

STUDIES ON THE RELATIONSHIP BETWEEN CERTAIN PROPERTIES
RHIZOSPHERE SOILS AND THE NUTRITION OF SORGHUM
(*Sorghum vulgare* Pers.)

Thesis submitted in part fulfilment of the requirements for the degree of
Doctor of Philosophy in Soil Science and Agricultural Chemistry
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CERTIFICATE

This is to certify that the thesis entitled '**STUDIES ON THE RELATIONSHIP BETWEEN CERTAIN PROPERTIES OF RHIZOSPHERE SOILS AND THE NUTRITION OF SORGHUM** (Sorghum vulgare Pers.) submitted in part fulfilment of the requirements for the degree of DOCTOR OF PHILOSOPHY IN SOIL SCIENCE AND AGRICULTURAL CHEMISTRY to the Tamil Nadu Agricultural University, Coimbatore is a record of *bona fide* research work carried out by Thiru.P.THYAGARAJAN under my supervision and guidance and that no part of this thesis has been submitted for the award of any other degree, diploma, fellowship or other similar titles and that the work has not been published in part or full in any scientific or popular journal or magazine.

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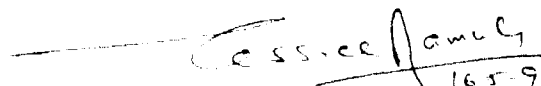


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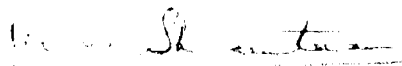
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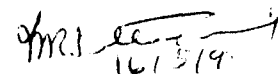
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ABSTRACT

STUDIES ON THE RELATIONSHIP BETWEEN CERTAIN PROPERTIES OF RHIZOSPHERE SOILS AND THE NUTRITION OF SORGHUM

(Sorghum vulgare Pers.)

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A detailed investigation was carried out to study the nutrient availability, transformation and mobility of plant nutrients in the root environment of sorghum crop with particular reference to nutrient flow rate and uptake of nutrients by sorghum (Sorghum vulgare Pers. Var. Co.24) grown in two major soil types of Tamil Nadu. A pot experiment, using black and red soils collected from Tamil Nadu Agricultural University farm, was carried out for investigating the above said characteristics. In addition, laboratory studies were conducted to study the root development and root exudation patterns of sorghum crop.

The results revealed that the sorghum plant root exuded relatively more number and greater quantity of amino acids and sugars at 30 days than at 15 and 45 days of crop growth thereby exhibiting decline in the quantity of exudates with advancement of crop growth. The presence of microorganisms and the root exudates accumulating within the vicinity of root environment played a vital role in the availability and transformation of plant nutrients in the rhizosphere region soils.

The black soil recorded higher availability of N, K, Fe and Cu nutrients. Phosphorus addition not only tended to decrease the availability of micronutrients, but also hindered the absorption as in the case of P-Fe and P-Mn interaction which proved antagonistic.

The transformation pattern of major nutrients depended on the initial fertility status of soil and type of soil. Under sterilized condition of the soil, the transformation pattern of major nutrients was found to be greatly decreased due to the absence of microorganisms and low availability of plant nutrients in the soil.

The flow rate of nutrients in the sorghum plant grown in the black soil was observed to be higher than that in the red soil due to higher fertility status of the black soil.

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The transformation pattern of major nutrients depended on the initial fertility status of soil and type of soil. Under sterilized condition of the soil, the transformation pattern of major nutrients was found to be greatly decreased due to the absence of microorganisms and low availability of plant nutrients in the soil.

The flow rate of nutrients in the sorghum plant grown in the black soil was observed to be higher than that in the red soil due to higher fertility status of the black soil.

The nutrient flow rate into the plant at vegetative stage was the most rapid and decreased with advancement of plant growth. The absence of microbial content due to sterilized condition of the soil brought forth many undesirable effects such as lowering of nutrient availability, lowering of nutrient transformation and mobility and interference with nutrient absorption. However, some of the nutrients viz., available Cu content in soil, N and P contents in the shoot, Fe, Mn, Cu and Zn contents both in root and shoot of the crop under sterilized condition were found to be higher than under normal condition of the soil, obviously attributed to the concentration effect. Though the sterilized condition interfered with nutrient availability by way of reducing nutrient content, it had little effect on the amount of nutrients entering into the root.

Most of the plant nutrients accumulated in the shoot relating to the black soil. The black soil produced relatively lesser shoot dry matter than the red soil and the absorbed nutrients tended to concentrate. The enhanced concentration of the plant nutrients in the shoot viz., N, P, Fe, Cu, Mn and Zn due to sterilized condition indicated that the amount of nutrients going into the plant system had not appreciably altered. Both under sterilized and normal conditions of the soil, sufficient nutrients moved into the system and got distributed over a large mass in the red soil and vice versa in the black soil.

The black soil was associated with reduced root growth and this resulted in higher concentration of the different plant nutrients. Under sterilized condition of the soil, root growth characteristics were found to be reduced in the black soil. The root growth parameters were observed to be more in the red soil than that in the black soil, mainly attributed to the light textured nature of the soil which helped in the easy penetration of roots for absorbing plant nutrients and water requirement.

The nutrient uptake both by shoot and grain is related not only to the yield of dry matter and grain but also to the nutrient availability in the rooting environment of the soil. Under sterilized condition of the soil, the uptake of macro and micronutrients both in the shoot and grain was depressed and this was annihilated by the absorption mechanism.

Sorghum responded to N fertilization and the response trend was found to be curvilinear. Phosphorus application at 50 kg ha⁻¹ level brought about yield improvement to the tune of 39.8 per cent over control. Although the black soil produced lesser amount of plant growth parameters, it favoured greater mobilization of plant nutrients through the root system as evidenced by the nutrient flow rate, thereby accounted for enhanced grain yield as compared to that of the red soil.

From the foregoing, it becomes apparent that

i) the rhizosphere region soil contributed much to the growth and nutrition of sorghum crop;

ii) the black soil provided relatively favourable environment for the nutrition and growth of sorghum crop;

iii) Sterilization of the soil had definite deleterious effects on the nutrient availability and concomittant plant growth; and

iv) While the response trend was curvilinear in respect of N application, the dose of 50 kg P_2O_5 ha⁻¹ accounted for increased sorghum grain yield.

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associated with significant 'F' values

ABBREVIATIONS USED

ha	= Hectare
kg	= Kilogram
g	= gram
mg	= milligram
µg	= microgram
ppm	= parts per million
ml	= millilitre
cm	= centimetre
m.e. 100 g ⁻¹ soil	= Milliequivalents per 100 g of soil
CEC	= Cation exchange capacity
AEC	= Anion exchange capacity
EC	= Electrical conductivity
N	= Nitrogen
P	= Phosphorus
K	= Potassium
Fe	= Iron
Mn	= Manganese
Cu	= Copper
Zn	= Zinc
Rh	= Rhizosphere region
NRh	= Non-rhizosphere region
St	= Sterilization
NSt	= Non-sterilization
S ₁	= Black soil
S ₂	= Red soil
St ₁	= Stage 1
St ₂	= Stage 2
St ₃	= Stage 3

Statistical analysis

S.E.	= Standard error of mean
C.D.	= Critical difference at 0.05 level
r	= Coefficient of simple correlation
*	= Significant at 0.05 level
**	= Significant at 0.01 level
NS	= Non-significant

CHAPTER I

INTRODUCTION

The growth of root and shoot is interdependent and their relationship is complex. Study of root of crops has been the subject not fully investigated largely because of difficulty of gaining access to and experimenting upon them in soil. Moreover, the study of rhizosphere by non-destructive methods has not been perfected. The term 'Rhizosphere' is applied, to an ill-defined narrow zone of soil (about 1-3 mm wide) surrounding the root and root hairs. Obsession that destructive methods will not provide full information to understand the complexity of the rhizosphere phenomena is another reason for such limited interest in this aspect. Only at the soil-root interface, the plants interact with the soil environment. If growth and nutrient uptake of plant in soil is to be understood and predicted, the physico-chemical and biological reactions that are taking place at the soil root interface are to be understood well. Hence the subject is receiving increasing attention now and the emphasis is being given on root behaviour and properties including their relationship with soil fertility.

Eversince the term, 'Rhizosphere' was introduced in 1904 by the German Botanist, Hiltner, to denote the region of the soil which is subject to the influence of plant root,

many scientists attempted to define it based on increasing scientific informations available at that time. However, the integral components of the rhizosphere are root, soil and microorganisms. These components, individually and collectively exert influence on the plant or crops. This calls for a system approach to understand the various aspects of the rhizosphere in its entirety and gestalt view to be taken.

Roots not only act as 'sink' only for nutrients transported to the root surfaces by mass flow and diffusion, but can also actively modify conditions within the rhizosphere by changing the pH and oxygen concentration, release of chelating and/or reducing substances and by root exudates as substrates for rhizosphere microorganisms. As rightly pointed out by Nye and Tinker (1977), the absorbing roots are often in a chemical environment, quite different from that of the bulk soils. Concentration of different nutrients in plants vary with the rate of plant growth and nutrient absorption as well as with the movement of the nutrients within and between different plant parts. Proper understanding of the pattern of accumulation of different nutrients by the plants is essential for planning a judicious fertilizer application schedule.

The dynamics and availability of nutrients in soils are determined not only by chemical equilibria and

binding of nutrients in the bulk soil, but also by nutrient mobility, root growth and root induced changes in the rhizosphere. At the soil-root interface, the availability of plant nutrients can be considerably influenced by many factors such as mobilization and immobilisation of nutrients, relative accumulation of ions at the root-soil interface, release of nutrients due to the changes in redox-potential etc. The ability of the microorganisms to change the chemical composition of rhizosphere and hence to alter the chemical availability of nutrients is a proven fact. Therefore, studying the chemistry of rhizosphere soils in relation to nutrient availability transformation and mobility is of paramount importance.

Among the soil orders of Tamil Nadu, Alfisols and Vertisols occupy major portion. They differ markedly in morphological and in physico-chemical properties. They occur both under dry and irrigated agriculture.

Due to differing morphological and physico-chemical properties, the nutrient availability, transformation of applied nutrients, native fertility of **soil** vary to a great extent in these two soil orders. Much informations on the above aspects in bulk soils of these soil orders are available through extensive research work in this aspect. However, informations in rhizosphere soils in these two major soil orders are few in relation to the above aspects.

According to projection by ICRISAT, there will be a deficit of 16.28 lakh tonnes at the current level of production by 1990 in the case of millets in Tamil Nadu. Among the millets, sorghum occupies the pride of place and is raised in Tamil Nadu in large areas as irrigated and rainfed crops. The deficit in the production of millets can be made good only by increasing the yield of sorghum, as bringing new area under sorghum cultivation in Tamil Nadu is not possible. Moreover scientific information in respect of rhizosphere chemistry with sorghum crop grown in major soils of the state-vertisols and Alfisols are scanty. Management practices and fertilization of sorghum crop will cause changes in the nutrient transformation and availability of plant nutrients and much work has not been done in this aspect. This study requires sufficient amount of soil sample from the rhizosphere region and because of lateral and secondary root system, sorghum plant provides an ideal situation for such study. In view of the above, the present study was taken up with the following objectives:

- i) To study root development pattern of sorghum crop;
- ii) To determine root exudation pattern at different stages of growth of sorghum crop;

- iii) To determine the transformation and availability of nutrients in the rhizosphere and non-rhizosphere soils as influenced by soil types, sterilization of soil and fertilization of sorghum crop;
- iv) To study the nutrient content and uptake pattern of plant nutrients by the various plant parts of the test crop, under varying soil types, levels of N and P fertilization and under two sets of soil conditions;
- v) To determine the nutrient flow rate in the plant at different stages of crop growth; and
- vi) To determine the root growth characteristics of the test crop.

CHAPTER 2

REVIEW OF LITERATURE

The experiment involved investigations on chemistry of rhizosphere soils in relation to nutrient availability and transformation of nutrients as also the mobility with the test crop of sorghum. The pertinent literature are reviewed and the salient aspects in relation to some specific topics are briefly summarised below:

2.1. Significance of rhizosphere

The root in soil is dynamic interacting three component system in series, i.e., the soil, a somewhat discontinuous microbial layer and the plant root itself. Only at the soil-root interface, the plant interacts with the soil environment. The soil environment and condition of the shoot affect the behaviour and properties of root. The soil-root interface viz., the rhizosphere is influenced by the elements of climate, by water on the soil surface and beneath the soil by chemical, physical and biological factors (Fig. 1).

Solute concentrations have been often shown to be greatly altered in the rhizosphere (Nye and Tinker, 1977) and there can be no doubt that absorbing roots are often in a chemical environment quite different from that of the bulk

soil. This establishes that nutrients can be depleted by uptake by the root, after which they are to be supplied by diffusion processes.

2.1.1. Definition of rhizosphere

In 1904, the German Botanist Hiltner introduced the term 'rhizosphere' to denote the region of the soil which is subject to the influence of plant roots. Rhizosphere is applied to an ill-defined narrow zone of soil (about 1-3 mm wide) surrounding the root and root hairs. Katznelson (1965) stated that the term 'rhizosphere soil' refers to the thin layer adhering to a root after the loose soil and clumps have been removed by shaking. The soil coating varies in thickness with the kind of root, and the nature and moisture conditions of the soil. This may influence the magnitude of the rhizosphere effect but will not obscure it nor alter its characteristic features. The degree of stimulation of activity in rhizosphere soil varied according to the stage of plant growth with maximum activity corresponding to the stage of maximum vegetative growth (Parkinson and Thomas, 1969).

Magyalogy and Hancock (1972) indicated that the zone of influence of below ground stems be designated as rhizosphere; the combining form from 'rhiza' (Greek) means 'root', a plant organ, anatomically and functionally distinct from the shoot. According to broader definition of Scott

(1977) the term 'soil-root interface' could imply merely the boundary between the outermost tissues and the particles of soil which are closest to them. Comparing non-rhizosphere and rhizosphere soil, he observed that the bulk of non-rhizosphere soil is not directly influenced by the growing roots except by the withdrawal of water and nutrients. However, the rhizosphere and the bulk soil merge into the other and the boundary between them cannot be rigidly defined. It is reasonable to assume, however, that the diameter of the rhizosphere atleast equals that of the cylinder of soil which the root hairs explore and into which they may release exudates. The living roots occupy only a small fraction of the total soil volume.

2.2. Bio-dynamics of root system

Newman (1969 c) concluded that the root systems were usually much more extensive than necessary for water uptake. Since the major resistance to the movement of water is associated with the root, the uptake of water per unit volume of soil would be proportional to rooting density, other factors being equal. Weatherly (1975) and Faiz et al. (1977) observed that the diameter of roots could decrease appreciably under water stress and suggested that the gap at the root-soil interface may contribute to the overall resistance under conditions of water stress.

Roots, however, do not act only as 'sink' for nutrients transported to the root surfaces by mass flow and diffusion (Brewster et al., 1976), but can also modify conditions within the rhizosphere by changing the pH and O₂ concentration, release of chelating and/or reducing substances and by root exudates as substrates for rhizosphere microorganisms. Long root hairs ensure better contact between soil and plant and improve water movement from fine soil pores to the plant.

Mucigel, occurring on the root-surface in the zone of differentiation, largely establishes the contact between growing roots and the solid matrix of the soil rather than the walls of the root cells themselves and also influences the transfer of nutrients to roots (Juniper and Bask, 1973).

2.3. Root exudate and rhizosphere effect

A wide range of compounds is exuded from intact plant roots and these exudates consist of soluble organic materials like aminoacids, sugars, organic acids, vitamins, nucleotides and many other unidentified substances and these are responsible for their rhizosphere effect. A compendium of the chemicals exuded by roots of different plants have been given in an excellent review by Rovira (1965).

Root exudate plays a major role influencing nutrient availability in the rhizosphere. Apical meristems of

roots produce continuously 'mucigel' which contains a substantial proportion of polygalacturonic acid, a quite effective substance in mobilizing both phosphorus and iron (Nagarajah et al., 1970). Root exudates seem to be responsible also for the ability of plant roots to take up micronutrients like zinc from soil layers with extremely low water availability (Nambiar, 1976). Root exudates with distinct chelating and/or reducing properties are released by roots in response to iron deficiency (Takagi, 1976; and Olsen et al., 1981). These root exudates enhance the iron mobilization from iron III oxides (Olsen et al., 1981) and manganese oxide (Marschner et al., 1982) which create manganese toxicity on calcareous soils (Moraghan, 1979). The organic acids present in the root exudates of wheat crop are responsible for dissolving manganese oxides (Godo and Reisenaner, 1980) and for mobilizing phosphate from root phosphate (Moghimi et al., 1978).

Balasubramaniam and Rangaswami (1969) found that sorghum (Sorghum vulgare pers.) exuded atleast 14 different amino acids and also reported the presence of glucose and absence of sucrose in the exudate.

2.3.1. Role of micoorganisms in the rhizosphere

Soil micoorganisms play a very significant role in making P available to plants by dephosphorylating P

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bearing organic compounds and also by bringing about favourable changes in soil reaction in the soil micro-environment leading to solubilization of inorganic phosphate sources. Besides, metabolic byproducts of soil microorganisms such as organic acids and humic substances, primarily emanating from organic matter decomposition, form complexes with iron and aluminium compounds, thereby reducing inorganic phosphate fixation to a remarkable degree and thus increasing its availability indirectly (Chhonkar, 1979; Wani, 1980; and Raj, 1981).

It has been observed that a reduction in soil organic P content is associated with a simultaneous increase in the number of microorganisms capable of dephosphorylating these substances (Halstead et al., 1963) showing inter alia, their involvement in the mineralization process. However, the significance of the direct involvement of soil microflora in the release of inorganic P from organic phosphatic compounds in soils is not clearly understood.

Soil microorganisms can oxidise divalent manganese, which is the most easily plant available form, to insoluble oxides. These oxides can supply manganese to plants at a low rate, but the overall effect is to diminish plant uptake (Bromfield, 1978).

Between 20-40 per cent of the photosynthetic products are translocated into the roots and utilized for root growth and respiration or released into the rhizosphere (rhizo deposition according to Sauerbeck and Johnen, 1976; Sauerbeck et al., 1981 and Barber and Martin, 1976). The majority of the rhizodeposition is utilized as substrate for the rhizosphere microorganisms. This high microbial activity at the root-soil interface has various effects on the dynamics of mineral nutrients in the rhizosphere and on the availability of nutrients for the plants. Higher rates of denitrification in the rhizosphere can be observed at low redox potentials (Trolldenier, 1971), particularly when root exudation is enhanced by deficiency of potassium or phosphorus (Kraffezyk and Trolldenier, 1979).

2.4. Dynamics of nutrients in the rhizosphere region of crops

Among the factors influencing the availability of plant nutrients, rhizosphere soil plays a significant role by interacting with nutrient diffusion phenomena, moisture relationship, etc. Depending on soil and plant factors, the ion concentration at the soil-root interface usually differs substantially from the bulk soil. Furthermore, at this interface root induced changes in pH and redox-potential and the release of organic compounds (root exudates) can considerably affect the solubility and availability of mineral nutrients (Marschner, 1983).

2.4.1. Mobility of nutrients

The two main driving forces by which the nutrients move towards plant root surface are mass flow and diffusion. The importance of nutrient mobility in soils for nutrient availability has been stressed by Barber (1962) in his theory on 'Mass flow-diffusion concept'.

2.4.1.1. Mass flow

At high water availability, nutrient ions which can diffuse freely in the soil, reach plants primarily by mass flow in the water, which move towards roots to satisfy the requirements of transpiration. Upon reaching the root surface, the nutrients may then be taken into the plant by the active uptake mechanisms (Barber, 1971). The localized enrichment with nutrients can modify root form and nutrient uptake. The accumulation of ions near the root surface (e.g., Calcium or Sulphate) may affect the mobility of other ions (Marschner, 1983). Wiersum (1961) stated that average distance over which nutrients are extracted from water saturated soil were P = 2.5 mm; Ca, Mg and Mn = 5 mm; K and Na = 7.5 mm and mobile ions = 20.0 mm. If water is absorbed by the plant roots relatively faster than ions (high transpiration rates in combination with high salt concentration in the soil solution) an accumulation of ions at the root surface can be predicted (Barber et al., 1963; Elgawhary et al., 1972; Renger and Strebel, 1976).

When the nutrients reach the root surface, the root must make a place for itself in the soil and in doing this, it will usually increase the bulk density of the soil immediately around the root. This causes a higher concentration of adsorbed ions in the rhizosphere than would be present if no change in bulk density occurred. This process of increasing nutrient availability has been called 'root interception' by Barber et al. (1963). If the processes do not supply the root with nutrients as fast as they are absorbed, the concentration at the root surface is reduced causing a concentration gradient along which nutrients diffuse to the root (Barber, 1971). Nutrients such as Ca and Mg usually reach the root by mass-flow particularly for plants which are not high calcium absorbers.

The chemical changes in the rhizosphere soil due to the action of the root are mainly a result of changes in the concentration of one ion in the soil affecting the solubility of a second ion. For example, calcium may accumulate in the soil near the root, by mass-flow, as more of calcium is moved to the root than it is absorbed (Riley and Barber, 1969). Conversely, there may be depletion of calcium when the absorption rate exceeds the rate of movement to the root by mass-flow (Barber and Ozanne, 1970). This wide variation in the level of the calcium ion plus its associated anion will frequently alter the solution level of ions such

as borate, phosphate and potassium (Barber, 1971). Where a larger quantity of the nutrient moves to the root by mass-flow than the root absorbs, the concentration at the root surfaces increases and this may increase uptake, however, above a certain concentration, increasing the concentration does not greatly increase uptake of many nutrients.

2.4.1.2. Diffusion

The other main driving force for nutrient movement towards plant root surface is diffusion, driven by ion uptake and a corresponding decline in the ion concentration at the root surface (depletion zone). When the mass-flow supplies only a small portion of the plant's requirement, diffusion becomes an important factor, the level of nutrients at the root surface will be less than that initially present in the soil (Barber, 1971). The importance of diffusion and its role in the nutrient supply to plant roots depends upon both soil and plant factors. Scott (1977) stated that the rate of absorption of nutrients ions by plants is dependent on the rate of diffusion of ions through the soil towards roots. He further showed that an appreciable volume of the root exterior to the endodermis is accessible to ions which enter by diffusion or mass flow. When the roots are transferred from a solution of lower to higher concentration, a rapid initial uptake of ions occurs at within a

period of 30 minutes because of the ready physical movement of ions into the free space. The influx of cations is greater than that of anions because of the predominance of negatively charged sites on the surface of cell walls. On most soils, almost all of the phosphorus will reach the root by diffusion. Potassium has also been frequently observed to move by diffusion. Most of the nutrients diffusing to the root come from soils within 3 mm of the root surface.

Renger et al. (1981) stated that the relative contribution of mass-flow and diffusion for ion transport to plant root surfaces also depends upon the plant species as both rates of transpiration and ion uptake vary considerably between species. Potassium transport to the root surfaces in maize is primarily by diffusion, but in onion, mass-flow is of major importance (Baligar and Barber, 1978). Since mass-flow and diffusion occur simultaneously in solute transport to the root surfaces, the term 'apparent mass flow' = transport of ions to the root-soil interface, has been recommended by Nye and Tinker (1977).

2.5. Changes of pH at the soil-root interface

Monitoring pH continuously in an undisturbed soil plant system supplied with ammonium, Schaller and Fischer (1981) demonstrated changes in pH at the soil-root interface

of peanut from 5.5 (bulk soil) to 3.5 (interface); with maize, however, pH remained as 5.5 or decreased only slightly. Plant species which show preferential uptake of cations over anions even with nitrate nitrogen supply are quite efficient in acidification of the rhizosphere and in utilization of rock phosphate (Fried, 1953; Raij and Diest, 1979). If the pH in the rhizosphere decreases, this leads to an increase in desorption of phosphorus, solubilization of non-exchangeable phosphorus and increase in P concentration in the rhizosphere soil solution. Enhanced H^+ efflux from roots corresponding to acidification of the rhizosphere is also a typical response of the so-called 'Fe-deficient' plant species to iron deficiency. These plant species are therefore able to dissolve and utilize effectively sparingly soluble iron-III compounds (Marschner et al., 1974) as long as the bicarbonate concentration in the rhizosphere does not counteract this acidification (Venkatraju and Marschner, 1981).

2.6. Availability and transformation of nitrogen in soils

It is well known that the concept of nutrient availability in the soil is a complex phenomena, much so with respect to nitrogen. Apart from physical disintegration and chemical decomposition, a matrix of microbial decomposition is also involved in the transformation processes of both native and added N forms.

2.6.1. Effect of N fertilization

2.6.1.1. Root system

The effect of N fertilization is reflected on the growth of the root system. Davidson (1969 b) reported that the size of the root systems relative to their shoots is commonly reduced when the external supply of N is raised thereby depressing the root/shoot ratio, though the actual weight of roots usually increases, but not as greatly as that of shoots.

2.6.1.2. Nutrient availability and transformation

Cooke (1962) indicated that the capacity of soils to supply the mobile anions viz., nitrate, sulphate and chloride that form very sparingly soluble compound is governed only by the total amounts present in the soil solution plus any added by fertilizers or mineralized by decomposing organic substances.

Ramalingam (1975) observed that soil application of N increased the available N in red soils of Coimbatore district when sorghum CSV-4 was grown. He further noted that the available nutrients were more during initial stages and the same decreases during post-harvest stage. The application of N resulted in significantly higher available N in soil at

70 and 120 kg N ha⁻¹ level than in 0 kg ha⁻¹. In contrast, the highest available P was recorded in the control plot of nitrogen. Again applied N did not produce significant difference in available K.

Viswanathan (1976) reported that available N of red soil ranged from 26 to 89 ppm and that of P ranged from 2.0 to 8.6 ppm. In case of available K, the values recorded were 78 and 120 ppm. The availability of all the major nutrients progressively decreased with advancement in crop growth. Durairaj Muthiah (1978) reported that available N status of soil increased progressively with increased dose of N in a field experiment conducted on red loam soil with three levels of N at 0, 60 and 120 kg ha⁻¹ with fine varieties of sorghum.

2.6.1.3. Changes in the rhizosphere zone

The immobilization of N by rhizosphere micro-organisms eventhough temporary, will reduce the amount available to the plant. Nitrogen losses by denitrification were demonstrated with N¹⁵ labelled nitrate to be greater with living root systems, owing to decreased oxygen tension in the rhizosphere and to root excretions that functioned as hydrogen donors for the large number of denitrifying bacteria in this zone (Woldendrop, 1962 and 1963).

Sapozhnikov et al. (1968) found by split plot technique that application of fertilizer N increased the plant utilization of soil N although there was no contact between the fertilizer and the soil. They attributed this to the increased metabolism of the fertilized plant and to the increased absorbing power of the root system, uptake of soil N, however was even higher when the fertilizer was placed in contact with the soil. Nitrogen transformations that were thought to take place at the root-soil interface of rice were mainly due to nitrogen fixation and N losses through the process of nitrification and denitrification in the root zone (Anon., 1964 and 1968).

Riley and Barber (1971) had attributed the influence of N additions on P uptake by plants growing in soil to increased plant growth, changes in root morphology, chemical changes in the soil and changes in the rate of P absorption by the root. Ammonium is often superior to NO_3^- in stimulating P uptake and this has been attributed to its effect on root morphology and on soil P solubility.

2.6.1.4. Dry matter production

Roy and Wright (1974) reported that the rate of dry matter accumulation in fertilized sorghum plants was rapid early in the season and continued almost linearly until

maturity stage but in unfertilized plants, it began to drop after 70 days. The application of 50 kg N ha^{-1} significantly increased the dry matter of whole plant by 26.0 per cent over control and further the application of N at 120 kg ha^{-1} increased the dry matter by 35.2 per cent. Ramalingam (1975) observed that dry matter production of sorghum variety CSV-4 was the lowest at the seedling stage and it increased at subsequent stages. The effect of N levels on dry matter production was significant. Increasing levels of N increased the dry matter subsequently.

2.6.1.5. Content of nutrients

Herron et al. (1963) indicated that the N content of sorghum was 3.1 per cent at flowering stage and 1.14 to 1.56 per cent of N was found to be present in grain. Kamalam (1964) reported a sudden decline in the N content of straw at maturity stage due to translocation of accumulated N to the grain sorghum. Kaf Kafi (1967) reported that the N content of leaves of sorghum plants receiving 160 kg N ha^{-1} was consistently higher than those of plants from unfertilized plots. He also reported that all the nutrients decreased after the appearance of flower primordia.

Srivastava (1967) tried three levels of N (0, 50 and 100 kg N ha^{-1}) and three levels of P_2O_5 (0, 50 and $100 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1}$) in sorghum and concluded that application of 50 kg N ha^{-1}

did not influence the N content and uptake upto first 30 days and differences in N content was noticed only on 60th day. Muthusamy (1972) observed that increasing doses of N increased the N content of plant materials due to better absorption of the nutrients by the extensive rooting system caused by higher doses of N.

Ramalingam (1975) recorded high N, P and K concentrations at seedling stages in CSV-4 sorghum and the concentration of nutrients decreased towards maturity stage. Viswanathan (1976) reported that K was absorbed only at initial stages and got diluted as dry matter increased.

2.6.1.6. Uptake of nutrients

Herron et al. (1963) and Roy and Wright (1974) observed that the application of N had significant effect in increasing the uptake of N in sorghum. The effect of N in increasing the N uptake by plants was the highest at maturity stage. Ramalingam (1975) reported that the application of 280 kg N ha⁻¹ recorded the highest uptake value. But at maturity stage, treatment of 140 kg N ha⁻¹ produced highest quantity of grain which contained higher N content than straw in sorghum.

The N uptake increased progressively with the increasing levels of N upto 180 kg ha⁻¹ in sorghum.

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Application of urea at the rate of 100 kg N ha^{-1} one as basal and another as split application to CSH-1 sorghum resulted in uptake values of 46.36 and 50.35 kg ha^{-1} respectively. They also tried in CSH-3 sorghum variety at Hissar experimental station four levels of N application viz., 0, 60, 90 and 120 kg N ha^{-1} and obtained uptake values of 16, 23, 29 and 30 kg N ha^{-1} respectively (Anon., 1972). Batley and Reynish (1976) stated that winter wheat fertilized with five levels of N in the range of 0 to 175 kg ha^{-1} showed increase in N content and uptake with increasing levels of N application. Singh et al. (1976) revealed that N uptake was enhanced with increasing rates of N application to rice.

2.6.1.7. Yield of sorghum

Thangavelu et al. (1968) reported that CSH-1 sorghum gave a grain yield of $2,310 \text{ kg ha}^{-1}$ and straw $15,880 \text{ kg ha}^{-1}$. Application of urea at the rate of 100 kg N ha^{-1} in two ways one as basal and another as split application to CSH-1 sorghum gave an yield of $5,116 \text{ kg ha}^{-1}$ and $4,569 \text{ kg ha}^{-1}$ respectively (Anon., 1972).

Ramalingam (1975) concluded that application of 140 kg N ha^{-1} increased the grain yield of CSV-4 and 130 kg N ha^{-1} was found to be the economic and optimum level. Rodge and Tok (1975) reported linear response of N upto 120 kg N ha^{-1}

which produced the highest grain yield of 5,183 kg ha⁻¹ and it was significantly superior to 0, 40 and 80 kg ha⁻¹ in sorghum. Similar observations were also recorded in CSH-5, CSH-6 by Bhalerao et al., (1976) and Surender Reddy and Reddy (1976).

2.6.2. Effect of sterilization on the N content in soil

Arunachalam (1975) reported that the organic carbon content increased in the rhizosphere with plant age, when compared to non-rhizosphere soils. It was higher in sterile soil than in non-sterile soil. The rhizosphere region of the black soil had higher organic carbon content than that of the red soil. He also observed that the rhizosphere samples obtained from sterile conditions had higher CEC than from non-sterile conditions. The CEC of soils increased with plant age. The total nitrogen content of rhizosphere samples from sterile soil was more than the non-sterile soil. The total nitrogen content in the black soil was more than the red soil and increased with plant age.

2.7. Availability and transformation of phosphorus in soils

A knowledge of phosphate adsorption characteristics is imperative for understanding the phosphorus availability and to suggest a proper P fertilizer dose. Transformation of

phosphorus in soil is believed to be a dynamic process, which is influenced by rhizosphere besides other soil and plant characteristics. The nature of initial reaction products resulting from the transformation of native and applied phosphorus under the influence of root exudates, the composition of which depends upon plant species, primarily determine the availability of phosphorus and hence its efficiency.

There are several mechanisms by which the plant root can modify the availability of phosphorus. Firstly, the release of phosphate from insoluble phosphates (Ca, Al, Fe) may be increased by the formation of soluble complexes between metal ions and metabolites either of microbial or plant origin (Barber, 1968). Secondly, organic acids found in root exudates that are capable of forming adsorption complexes and more particularly chelates are very effective competitors for phosphates adsorbed on kaolinite and aluminum oxides but less so on goethite (Nagarajah et al., 1970).

Lewis and Quirk (1967) concluded that over 94 per cent of the phosphate adsorbed by roots during four days had come from soil within 0.1 mm of it. The uptake of both phosphate and potassium can be restricted by the slow diffusion of these ions through the soil. Phosphorus is usually absorbed from a small cylinder of soil surrounding

the root, because P diffuses very slowly through the soil (Barber et al., 1963; Lewis and Quirk, 1967). If the form of N absorbed changes the pH of the rhizosphere soil, it will also change the availability of P (Miller et al., 1970).

Russel and Sanderson (1967) using photometers to treat portions of individual barley roots with ^{32}P phosphate showed that there was considerable leakage of ^{32}P from these portions of roots outside the photometers. They concluded that much of the leakage may have been due to diffusion along the cell-free space in the cortex rather than exudation of compounds incorporated into the vacuoles or cytoplasm.

Riley and Barber (1971) recognised that the rhizosphere microflora and exudates from the roots as factors influencing P availability (Nagarajah et al., 1968 and Taha et al., 1969). They also observed that extractable P values for the rhizoplane soil from the NO_3^- fertilized soybeans were not significantly different from those for the bulk soil due to leakage of P from damaged roots during separation of the rhizoplane soil.

Lewis and Quirk (1967) demonstrated that ~~phosphorus~~labelled with ^{32}P was rapidly removed by roots from within the root hair zone. Diffusion studies indicated that P

and K enter roots at a greater rate than could be explained by their diffusion in the bulk soil to the surface of the root itself. Boero and Thien (1978) reported that soil phosphatase was enriched upto 40 per cent by corn roots in the central core and to a lesser extent 5 mm away. No decrease in organic P levels in these zones was observed suggesting that enzyme activity was not limiting the mineralization of hydrolyzable phosphatase compounds.

Arunachalam (1975) reported that the available P of rhizosphere soil was higher than the non-rhizosphere soil and was more in non-sterile condition than under sterile condition. In general, the available P increased with plant age. Marschner (1983) reported that root induced pH changes of as much as 0.5 units were observed between the root core and the outer zones over the two week growing period. Available P levels increased as the root induced pH changes acidified the rhizosphere.

For phosphorus, clear evidence for a depletion zone around the roots has been postulated mainly by autoradiographic methods (Bhat and Nye, 1974). Claassen et al. (1981) and Hendricks et al. (1981) could demonstrate that plant roots decrease the concentration of the soil solution within the rhizosphere down to 1 μm phosphorus (Hendricks et al., 1981) 2-3 μm potassium (Jungk et al., 1982).

2.7.1. Effect of P fertilization on P availability and transformation

Large number of experiments have been conducted to study mainly the changes that occurred in respect of P availability when P was added alone or in combination with other fertilizers or manures. The effects of P application on P availability were studied earlier by Kothandaraman (1975) and Singaram (1988) and they found that direct application of P fertilizers increased the available P status. In red soils the residual effect was attributed to the resultant Fe-P and Ca-P formation in the course of time (Sherman, 1971). Phosphorus alone or along with N decreased the available K content of the soil as reported by Bhide and Motiramani (1964). Phosphorus added along with K also recorded an increase in the available P and organic carbon contents of the soil (Ramasamy and Raj, 1973).

Many investigations have been made on the changes in soil P during the conversion from dryness to submergence of soil (Patrick and Mahapatra, 1968; Mahapatra and Patrick, 1969; Islam, 1970; Kono and Kobo, 1970; Mandal and Khan, 1972; Ponnampereuma, 1972; Gupta and Kamal Nayan, 1975; Singh and Hariram, 1976 and Mandal, 1979). The transformation resulting from alternation of dryness and submergence induce an increased availability of soil P. Goswami and Banerjee (1978) considered the causes for this increase to be due to

of CO_2 in calcareous soil, (iii) reduction of $\text{FePO}_4 \cdot 2 \text{H}_2\text{O}$ to $\text{Fe}_3(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$ with higher solubility, (iv) higher solubilities of $\text{FePO}_4 \cdot 2 \text{H}_2\text{O}$ and $\text{AlPO}_4 \cdot 2 \text{H}_2\text{O}$, resulting from hydrolysis due to the increase of soil pH in acid and strongly acid soils, (v) release of phosphate ions from the exchange between organic anions and phosphate ions in Fe, Al, Phosphates, and (vi) increased diffusion of P under submerged conditions.

It is generally known that factors that may increase the availability of P disappear with the change in soil conditions from reduction to oxidation. However, some investigations have also found that this process can increase the availability of soil P (Savant et al., 1970). In this case the increase in available P may result from the mineralization of organic P in soil while the availability of iron and aluminium phosphate may be decreased.

Kumarasamy et al. (1973) reported that the abundant presence of CaCO_3 in calcareous soil of Coimbatore district coupled with high pH (8.2) would have rendered the P fraction unavailable to plants by converting the same into tricalcium phosphate. At this pH, the plants have preferred Fe-P and Al-P fractions to Ca-P fraction, since the former have remained in more available form than the latter. They also reported that in non-calcareous red soil (pH 7.0) all

the four fractions of P viz., Al-P, Fe-P, Ca-P and saloid-bound P were contributing significantly to the available phosphorus pool.

Kuo and Lotse (1973) studied the kinetics of P adsorption and found that the rate of P adsorption was rapid initially and decreased with prolonged time. Species and concentration of associated cations had greater effects on P sorption than pH, by minerals and soils over a pH range of 4 to 7. Higher P sorption was observed with Ca solutions and the increased sorption was greater when the pH and Ca concentrations were higher (Volkweiss et al., 1973). Singh and Hariram (1976) observed that the amount of added soluble P transformed into Ca-P was much less in laterite mar and alluvial soils in comparison to Al-P and Fe-P under both the moisture regimes. Sharma et al. (1980) reported that the conversion of added P into Al-P and Fe-P fractions in the acid soils of Himachala Pradesh is negatively associated with pH, indicating thereby an increase in Al-P and Fe-P fractions with decrease in pH from neutral to acidic range. They also reported that less amount of P transformed into Ca-P fraction in the soils of Himachala Pradesh can be ascribed to the absence of CaCO_3 in these soils.

Jain and Sarkar (1980) observed that a major portion of the applied phosphorus is transformed into Al-P and Fe-P

during the initial stages. They also reported that the transformation of Ca-P into Al-P and Fe-P in control plots seems to be brought about by the rhizosphere supplemented by the root exudates. A reverse mechanism i.e., conversion of Al-P and Fe-P into Ca-P seems to be operative between tillering and maturity stages. The plant feed initially on Al-P and Fe-P and subsequently on Ca-P.

Sharma and Saxena (1982) stated that phosphorus application @ 75 kg ha⁻¹ to pea (Pisum sativum) crop over control caused a significant increase in Olsen's P at maturity stage in both rhizosphere and non-rhizosphere regions. Olsen's P values were higher in rhizosphere as compared to those in non-rhizosphere regions and this is attributed to the solubilization of insoluble phosphate compounds because of organic acids as a result of increased microbial activity in the rhizosphere (Duff et al., 1963). Phosphate concentration in the rhizosphere is usually much lower than in soil solution (Lewis and Quirk, 1967).

Sharma and Saxena (1982) stated that the changes caused by inclusion of legume in a crop rotation have influence on the P availability in rhizosphere region because of the fact that P movement and absorption in soil occurs through diffusion and interception. Squalli and Nadir (1983) stated that conditions favouring the mobilisation of P are

almost the same as those favouring the mineralisation of N. At pH 6-7, rates of mineralisation of P increase more than that of N. Mineralization of both is favoured by alternate wetting and drying and by high temperature (40-60°C).

2.8. Availability and transformation of Potassium in soil

Potassium in readily available form in the soil exists in the soil solution in the ionic phase and in the exchangeable form. This availability is largely conditioned by pH of the soil, the total K content of soil and its colloidal content. The amount of readily available K depends upon the nature and concentration of competing cations and the nature of the exchange material.

Plants are able to utilize not only water soluble and exchangeable K, but also the non-exchangeable form of K. Schiffer and Schachtschabil (1967) called this form of K, the subsequently available one. Exchangeable K was the immediate source of K for plant uptake and the depletion was followed by replenishment from other sources of K in the soil preferably from non-exchangeable K. The non-exchangeable K content was higher in clay plus silt fraction rather than fine and coarse fractions (Jayaraj and Dhanapalan Mosi, 1973).

Selvaseelan et al. (1973) observed that black soil was significantly superior to red soil in the release of available K. About 2 per cent of the total K is in

exchangeable form. The highest amounts of exchangeable K was obtained in clay plus silt fractions of black soil followed by red, alluvial and laterite soils (Jayaraj and Dhanapalan Mosi, 1973). Generally, the K held at interlattice positions is K non-exchangeable and this form is not exchangeable by $\text{N.NH}_4\text{OAc}$ (Ramamurthy and Velayutham, 1976). The per cent utilization of fixed K decreased as the level of added K increased in rice crop (Ramanathan, 1977 and Nagarajan, 1980). The amount of water soluble K fraction in the major soil groups followed the order of alluvial < black < red < laterite (Ramanathan, 1977).

Though Barber et al. (1963) reported that diffusion is the major mechanism by which K reaches plant roots, Sekhon (1985) reported that root interception, mass flow and diffusion are the three mechanisms of movement of K to the plant roots.

The depletion zone around roots is also affected by the buffering capacity of a soil for nutrients and by the concentration gradient between the bulk soil solution and the soil solution at the root surface. For potassium with increasing clay content, the extension of the depletion zone decreases and the equilibrium concentration at the root surface increases (Jungk et al., 1982). In the same soil, increase in K concentration in the soil solution by

fertilizer application, for example, increases both the diffusion coefficient and the extension of the depletion zone around the roots.

The rate of diffusion is influenced by the content of soil moisture and the amount of exchangeable K. As the effective volume of soil moisture decreases, the cross sectional area for K diffusion becomes smaller, the diffusion path to the roots becomes more tortuous owing to increase in air space; both factors tend to decrease the rate of K diffusion (Sekhon, 1985).

2.9. Availability and transformation of micronutrients in soil

Total reserves and availability of micronutrients (B, Cl, Co, Cu, Fe, Mn, Mo, Zn) in soils are mostly inherited from parent materials and modified by weathering and leaching. Little was known of the ways in which these elements are held in soils (Cooke, 1962). Now the situation is better than in 1962.

2.9.1. Iron

Iron is one of the most abundant elements in soil. The available cations in soils are of two valencies Fe^{++} and Fe^{+++} . Their availability is largely controlled by oxidation-

reduction systems in the soil and higher concentration of heavy metals. The most readily available form of Fe taken by the plants from the soil is (Fe^{++}) ferrous iron (Kliman, 1937).

The available Fe content of soils have been reported to vary from 8.5 to 18.7 ppm in Gujarat alluvial soils (Rai et al., 1968); whereas it was 2.2 ppm in Himachal Pradesh soils (Takkar and Bhumbla, 1968); 2.7 to 17.3 ppm in Madhya Pradesh soils (Bansal et al., 1969); 0.6 to 8.7 ppm in deep black soils of Madhya Pradesh (Rai et al., 1970); 6 to 22 ppm in Tamil Nadu soils (Arunachalam and Dhanapalan Mosi, 1973); 0.30 to 32.0 ppm in soils of hilly tract of Tamil Nadu (Rajagopal et al., 1973); 0.02 to 2.4 ppm in Tamil Nadu soils (Rajagopal et al., 1975); traces to 1214 ppm in Indian soils (Randhawa and Takkar, 1975) and 4.8 to 23.4 ppm in Uttar Pradesh paddy soils (Singh and Patiram, 1975).

Sauchelli (1969) suggested that Fe was held as chelate by organic matter in soluble form and was easily available to crops. Mortvedt et al. (1977) stated that Fe is available to the plant in ferrous form and it is affected by oxidation-reduction processes in the soil such as pH, soil aeration (drainage) and CaCO_3 content. It is the free or active CaCO_3 which releases bicarbonate ion into the soil solution which decreases the solubility of iron (Hagen and

Tucker. 1982). Soil texture and organic matter content also affect iron availability (Silanpää, 1982),

Although total Fe content of Indian soils is fairly high, its availability to plants is very much restricted. On account of differences in the nature of soils and differential capacity of the plants to remove Fe from soil, its content in plants varies to a great deal. Chimanika (1969) reported the Fe content of IR 8 paddy grain as 26.6 to 35.4 ppm and straw and 429 to 722 ppm. In the case of Bajra, Karam Narain (1969) found the Fe content of grain and whole plant in both 'local' and 'Hybrid HB-1' cumbu to vary from 114 to 149 ppm and 126 to 166 ppm respectively. Mann (1969) reported that the Fe content of maize grain and straw ranged from 15.8 to 18.7 ppm and from 134.5 to 160.4 ppm respectively.

2.9.2. Manganese

The available Mn content has been reported to vary from 0.5 to 10.5 ppm in Tanjore soils of Tamil Nadu (Lakshmanan et al., 1972); 0.7 to 8.76 ppm in Tamil Nadu soils (Balaguru and Dhanapalan Mosi, 1972); 0.6 to 26.0 ppm in Tamil Nadu soils (Arunachalam and Dhanapalan Mosi, 1973); 1 to 180 ppm in hilly tracts of Tamil Nadu (Rajagopal et al., 1973); 0.5 to 50 ppm in saline alkali and sodic soils (Velayutham, 1974).

Manganese found in the soil solution is taken up by plants in the divalent form or adsorbed on the exchange complex (Anderson and Okhi, 1977). Manganese availability is much affected by oxidation-reduction conditions in the soil. Hagen and Tucker (1982) concluded that Mn deficiency would occur in well aerated alkaline and calcareous soils. Soil texture, organic matter content and electrical conductivity also affect Mn availability (Anderson and Okhi, 1977 and Sillanpää, 1982).

2.9.2. Copper

The available Cu content of West Indian soils ranged from 0.3 to 13.0 ppm (Neelakandan and Mehta, 1961); 0.83 to 3.10 ppm in Vidharbha soils (Kavimandan et al., 1964); 0.45 to 12.34 ppm in Madhya Pradesh soil (Agarwal and Mothiramani, 1966); 1.2 to 10.66 ppm in Uttar Pradesh soils (Mishra et al., 1969); 0.25 to 1.00 ppm in Madhya Pradesh soils (Singh and Jain, 1971); 0.16 to 0.60 ppm in Tamil Nadu soils (Balasundaram et al., 1973); 0.01 to 12.0 ppm in Tamil Nadu soils (Rajagopal et al., 1973).

Lindsay and Norwell (1969) reported that the precipitation of Cu compounds in calcareous soils was observed to be responsible for the reduced availability of

Cu. Krauskopf (1972) stated that Cu was precipitated as Cu_2O under alkaline or reduced environment.

Appavu (1976) reported that the mean values of available Cu content were 0.54 ppm for black soils; 0.69 ppm for alluvial soils; 0.56 ppm for red soils and 0.39 ppm for laterite soils; 0.51 and 0.53 ppm for red calcareous and non-calcareous soils respectively. Available Cu occurs mainly in the clay fraction (Khan, 1979) and irrigated sandy soils are likely to be low in available Cu. High organic matter, texture index, CEC and electrical conductivity were found to increase the availability of Cu (Sillanpää, 1982).

2.9.4. Zinc

The available Zn content was found to vary from 0.5 to 6.05 ppm in Gujarat soils (Mehta et al., 1964). Balasundaram et al. (1973) reported the value of 0.7 to 2.6 ppm of available Zn in soils of Tamil Nadu. Similar observation was also reported by Rajagopal et al. (1975).

Lindsay (1972) suggested that organic matter could interact with Zn in two ways viz., Zn from soluble organic matter could be mineralized and released, Zn becomes bound to organic matter and was made immobile. It may then be released

slowly. In the presence of high available phosphate, zinc might be partly precipitated as $\text{Zn}_3(\text{PO}_4)_2 \cdot 6 \text{H}_2\text{O}$. Zinc availability is low in calcareous soils presumably due to precipitation of zinc carbonate (Kalbasi *et al.*, 1978), soil texture, organic matter content, electrical conductivity and to a lesser extent, CEC also affect its availability (Sillanpää, 1982).

Conveyance of Zn to plant roots principally occurs by diffusion (Wilkinson, 1972 and Elgawhary *et al.*, 1972). Diffusion theory offers an additional advantage that Fick's law of Diffusion coupled with equation of continuity when solved under various boundary conditions can be used to calculate concentration of the nutrients at the root surface, depletion zone around the roots and uptake by the plants. Such studies have been conducted so far with P (Olsen and Watanabe, 1970) and Iron (O'Connor *et al.*, 1975).

2.10. Movement of water and salts into the roots

The passive movement of water into the roots in response to the respiration demand of the foliage depletes the soil of water in the immediate individual rootlets and of the rhizosphere generally; it decreases the soil water potential. Entry of water into a root or evaporation from the soil surface sets up a gradient which causes water to move from soil particle to particle towards the denuded zone (Winter, 1980).

Fairly large molecules can be incorporated into the root in the normal process of uptake for example, the common antibiotics such as terramycin and streptomycin with molecular weights upto 60. It has been advocated that even much larger molecules can pass into the root. The protein lysozyme of a molecular weight of about 15,000 is taken up by the undamaged roots under some circumstances by the suggested mechanism of pinocytosis (Burstrom, 1945 a).

Riely and Barber (1969) showed an approximate doubling of soluble salts in the rhizosphere soil around soybean (1-4 mm distance from the root) and approximately six fold increase at the rhizoplane and confirmed by experiments that the total salt movement to the roots by mass flow was greater than salt uptake by plants.

QUESTION 3

1. (10 marks) Consider the function

$$f(x) = \begin{cases} x^2 \sin\left(\frac{1}{x}\right) & x \neq 0 \\ 0 & x = 0 \end{cases}$$

(a) Show that f is differentiable at $x = 0$.

(b) Find $f'(0)$.

CHAPTER 3

MATERIALS AND METHODS

To elicit information on the chemistry of rhizosphere soils in relation to root development pattern, root exudation pattern, nutrient availability, transformation, flow rate and effect of crop nutrition, the following laboratory studies and pot culture studies were conducted with the test crop sorghum Co.24. The experimental details, analytical procedures adopted for analysing materials and also the statistical techniques used for studying the treatment effects are briefly summarised in this chapter.

3.1. Studies on the root development pattern in sorghum

The study was carried out as per procedure described by Fåhreaus Slide Technique (1957). The techniques used for this study involved the use of two glass plates of size 10x3cm. A surface sterilized sorghum seed was placed in between the two glass plates separately. The two glass plates were held together by means of rubber band at the two ends of the plate in such a way that the seed was not damaged. This arrangement was placed in a 100 cm³ beaker individually and a little quantity of Hoagland's No.2 nutrient solution with the following composition was added to the beaker till the surface of the solution was just below the position of the seed in between the two glass plates.

Hoagland's No.2 nutrient solution

1 M Calcium nitrate	5 ml
1 M Potassium nitrate	5 ml
1 M Magnesium sulphate	2 ml
1 M Potassium dihydrogen phosphate	1 ml
5000 ppm iron EDTA	1 ml
*Trace elements solution	1 ml

***Composition of the trace elements solution**

Manganous chloride	1.87 g
Boric acid	2.86 g
Zinc sulphate	0.22 g
Copper sulphate	0.08 g
Molybdic acid	0.09 g
Redistilled water	1000 ml

The entire arrangement was covered with a bell jar. After 3-4 days, the seed developed root and plumule. The morphological studies on the root system were made and presented in Fig.2.

3.2. Determination of root exudation pattern

The root exudates of sorghum plant was collected from the root exudation apparatus designed by Kandasamy et al. (1973). The exudation apparatus (Fig. 3) is useful to grow

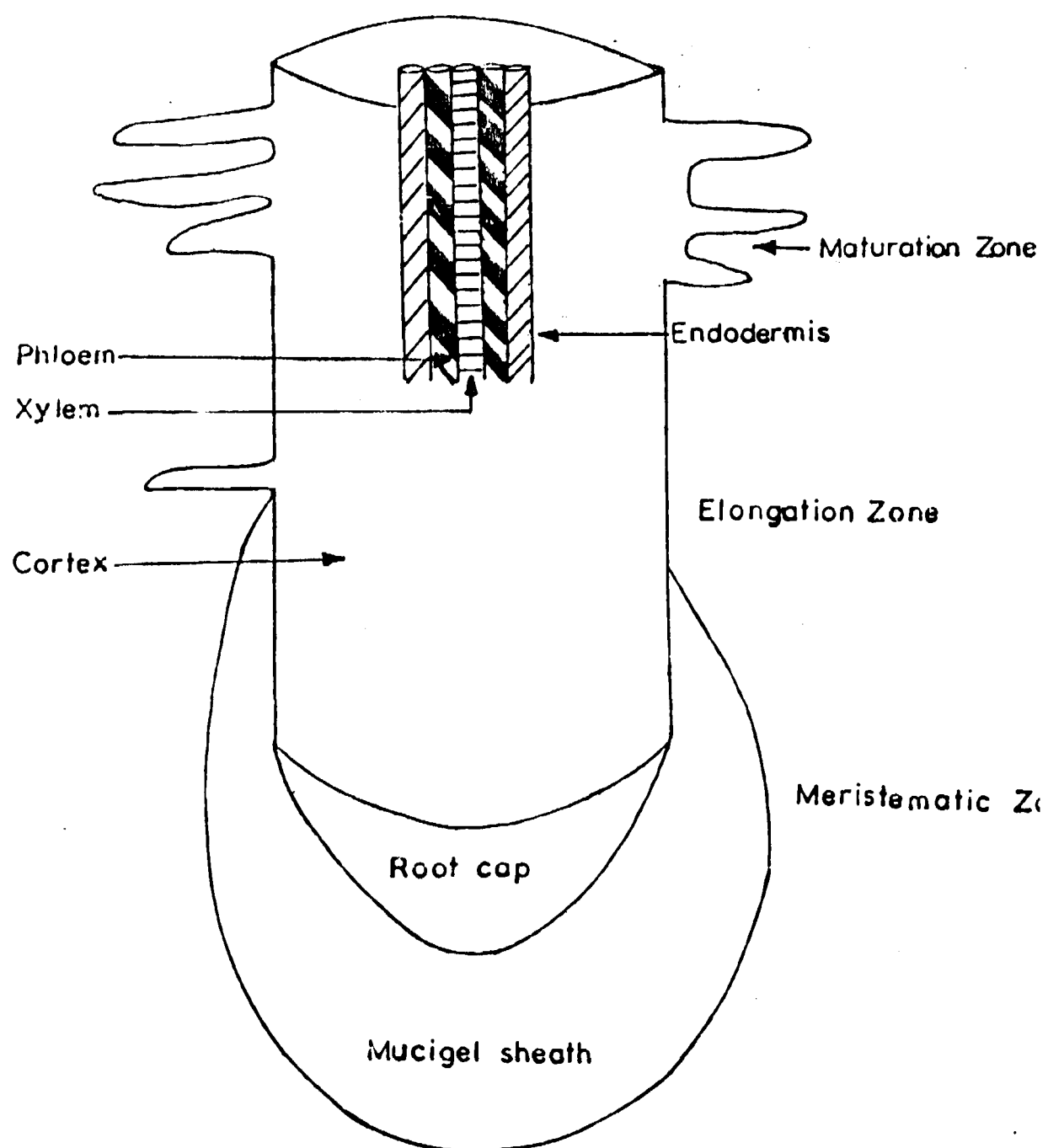


FIG. 2 LONGITUDINAL SECTION OF APICAL ZONE OF SORGHUM ROOT

plants over a period of 45 days with the root system under aseptic conditions at the same time exposing the shoot to the atmosphere and also useful to collect root exudates at periodical intervals without disturbing the root system.

The apparatus consists of an inverted 250 ml pyrex Erlenmeyer conical flask provided with stopcock at the bottom. One hole of 2.5 cm diameter at the centre and three holes of 0.5 cm diameter were made at the top. Through the central hole a glass tube of 7.0 cm in length was inserted so that about 4.0 cm length of the tube remained inside the flask thus forming a well. Through the other three holes, glass tubes of varying lengths were inserted for passing sterile air (T_1) for adding nutrient solution (T_2) and for the exit of the air (T_3). The flask was filled successively with acid washed quartz, quartz plus sand mixture and fine sand over a thin layer of glass wool each about 3 cm in depth and holes plugged with cotton wool. The apparatus was covered with a thick sheet of paper and sterilized at 20 psi for 30 minutes. Then the apparatus was taken out and covered with a black sheet of paper.

3.2.1. Techniques for the collection of root exudates

Sorghum Co.24 healthy seeds were surface sterilized with 0.1 per cent mercuric chloride solution and two seeds of sorghum were positioned aseptically on the sand in the

exudation apparatus. After addition of sterile nutrient solution of Hoagland and Arnon (1950) to the required level, the sand barrier was provided over the seeds. As the seedlings emerged out of the sand barrier, the microbial barrier was provided by placing a layer of 1 to 1.5 cm thickness of Dowex 50 x 12 (20-15 mesh) ion exchange resin which was previously washed with 0.1 N Hydrochloric acid followed by water and 0.2N mercuric chloride and sterile distilled water and dried at 50° C (Bradefute et al., 1962). Sterile cotton was also placed over the microbial barrier to ensure further aseptic conditions. All other openings were closed with sterile cotton. Air, freed from dust and microorganisms by passing through a trap containing cotton and bubbling through sterile water was injected through the opening continuously so that continuous bubbling of air in the nutrient solution was maintained. Nutrient solutions were changed at weekly intervals, utmost care being taken to prevent contamination during the process.

Darkness was provided to the root system during the experimental period by wrapping a thick black paper around the apparatus. The exudation apparatus was maintained at 23-25°C under artificial light (30,000 lux) during the period. Periodical checking of the exudation for any microbial contamination was done by plating 1 ml of the

exudate in appropriate medium. It was found possible to maintain complete sterility of the root system for not less than 45 days.

Exudates were collected from the plant at fortnightly intervals upto 45 days by opening the stop-cock and passed through ion exchange resin column for the separation of aminoacids and sugars.

3.2.2. Analysis of amino-acids and sugars in the root exudates

The amino acids and sugars contained in the root exudates were determined by following a modified procedure of Hussain and McKeen (1963). The root exudates were analysed by adsorption chromatography by passing through ion-exchange resin column and then eluting with a suitable solvent as detailed below:

For preparing the ion-exchange resin column, two glass tubes of 2.5 cm diameter and 15.0 cm long with a nozzle end were used. Glass wool occupying 1 cm of the bottom of the tube was passed with a blunt glass rod. In one of the tubes, the ion exchange resin, Dowex-50 $\times$ 8, 200-400 mesh in H^+ form was added to about 10 cm height and washed several times with distilled water. More glass wool was packed on top of the Dowex-50 column and was closed with a rubber stopper provided with a glass tubing for external

connection. In the other tube, Dowex 1 x 8, Cl^- form, 200-400 mesh was added in a similar manner. Both the columns were secured to a metal stand, keeping the Dowex column above the Dowex-50 column and were interconnected by plastic tubing. The resin column above was connected to a flask containing the exudates and the set up was arranged such that an automatic flow of the exudate would pass through the Dowex column and then through the Dowex-50 column. Uniform flow of the liquid was achieved by manipulating the screw type cock at the outlet. By this arrangement, it was possible to handle large volume of the exudation at a time. Such set was used for analysing exudates from the plant under test.

When the exudate was passed through the column, the anions in the exudate were adsorbed to the strongly basic Dowex-1 and the amino acids were adsorbed on Dowex-50 which is a strongly acidic, cation exchange resin. The effluent contained the sugars and were collected separately. When all the liquid had passed through the column, distilled water was added repeatedly to flush the resin column and Dowex-1 column was separated from the Dowex-50 column, which contained the adsorbed amino acids. Piperidine (0.1M) was used to elute amino acids from Dowex-50. The effluent containing sugars and piperidine amino acid solution were dried separately in vacuo at 40°C in a flash evaporator.

3.2.2.1. Chromatographic separation of amino acids

The dried material containing amino acids was dissolved in 0.2 ml of distilled water and this was used for the quantitative estimation of amino acids spectrophotometrically by the method of Block et al., (1958). One tenth ml of the concentrated solution was spotted on Whatman No.1 filter paper (25 cm x 25 cm) and developed ascendingly in n-butanol: acetic acid: water (9:1:2.2) for 20 hours. The chromatograms were air dried, sprayed with ninhydrin (0.5 g ninhydrin, 95 ml acetone and 5 ml water) and dried in an air oven at 60°C for 10 minutes. The amino acids were identified by their Rf values and estimated quantitatively after eluting in alcohol-buffer mixture for three hours. The concentrations were arrived at from a standard curve.

3.2.2.2. Chromatographic separation of sugars

One tenth ml of the concentrated root exudate was spotted on Whatman No.1 filter paper and ascendingly developed in n-butanol; acetic acid; water (4:1:5 organic phase) for 2 hours. After air drying, the chromatograms were sprayed with aniline hydrogen phthalate reagent as recommended by Partridge (1949) and dried in an oven at 100°C for 5-10 minutes, when the coloured spots appeared on white background. By comparing the colour of the spots and their Rf values with the spot developed by co-chromatography with standard sugar samples, the sugars in the root exudates of two plant species were identified.

The relative concentrations of the various sugars present on the chromatograms were estimated quantitatively after eluting the coloured spots in 4 ml of 3:2 mixture of alcohol and water and the colour intensity was read at 360 nm in a spectronic-20 spectrophotometer.

3.3. Details regarding soil samples

The soils used in the pot experiment represented typical black soil of Tamil Nadu collected from Eastern Block of Central Farm in Tamil Nadu Agricultural University campus, Coimbatore (Periyanaickenpalayam series). In this type of black soil, sorghum crop is mostly grown. The soil is classified, taxonomically as Typic ustivertept.

Red soil, which is one of the most important soil groups occupying the major portion of cultivated area in Tamil Nadu was collected from Millet Breeding Station in Tamil Nadu Agricultural University campus, Coimbatore (Palathurai series). The soil is classified taxonomically as Typic haplustalf. The details of the physico-chemical characteristics of the two soil types are given in Table 3.

3.3.1. Pot culture experiment

A pot culture experiment was conducted to study the nutrient availability, transformation, flow rate in the

rhizosphere region as compared to that of non-rhizosphere region as influenced by soil types, fertilization and sterilization. The details of treatments are given in Table 1.

Table 1. Details of the experiment

Crop: Sorghum Replication: 8 Design: CRBD Variety: Co.2

S.No.	Treatment combinations
1.	$S_1 N_0 P_0$
2.	$S_1 N_1 P_0$
3.	$S_1 N_2 P_0$
4.	$S_1 N_0 P_1$
5.	$S_1 N_1 P_1$
6.	$S_1 N_2 P_1$
7.	$S_2 N_0 P_0$
8.	$S_2 N_1 P_0$
9.	$S_2 N_2 P_0$
10.	$S_2 N_0 P_1$
11.	$S_2 N_1 P_1$
12.	$S_2 N_2 P_1$

S_1 : Black soil

S_2 : Red soil

N at 3 levels

N_0 : 0 kg N ha⁻¹
 N_1 : 50 kg N ha⁻¹ as urea
 N_2 : 100 kg N ha⁻¹

P at 2 levels

P_0 : 0 kg P₂O₅ ha⁻¹
 P_1 : 50 kg P₂O₅ ha⁻¹ as single super phosphate

K was uniformly added @ 50 kg K₂O ha⁻¹ as potassium chlori

Sets of soil: 2 (Sterilized and non-sterilized
i.e. normal condition)

Stages: 3 (30 days i.e., vegetative stage,
 60 days i.e., pre-flowering stage,
 90 days i.e., pre-harvest stage)

Site of collection of soil: 2 (Rhizosphere region and
 non-rhizosphere region).

The soil was processed, sieved in 6 mm sieve and
 filled in cleaned earthen pots of height 30 cm and dia.25 cm
 at the rate of 9 kg of soil per pot. The pot experiment
 consisted of 48 treatments viz., two types of soils (black
 and red), x two sets of soils (sterilized and non-sterilized).

i.e., normal condition) x three N levels (0, 50 and 100 kg N ha⁻¹) x two P levels (0, 50 kg P₂O₅ ha⁻¹) x two sampling zones (rhizosphere and non-rhizosphere soils).

For the purpose of sterilization, the required number of pots with the soil were sterilized in autoclave at 20 psi for 30 minutes, taking care that there is complete sterilization. Sorghum Co.24 seeds were sown in the pots at the rate of 3 seeds per pot and thinned later to maintain two plants per pot. The crop was fertilized at the dosage as indicated in Table 1 in the form of analytical grade chemicals as urea, single superphosphate and potassium chloride.

Out of eight replications maintained, two of the replications were utilized for collecting soil and plant samples representing vegetative stage; another set of two replications were utilized for collection of soil and plant samples representing preflowering stage; another set of two replications were utilized for collection of soil and plant samples representing pre-harvest stages and the remaining two replications were maintained upto harvest stage for recording the yield data and for other analyses.

At all stages of sampling, separate soil samples were collected to represent rhizosphere and non-rhizosphere soil samples. They were analysed for soil available nutrients and transformed forms of nutrients. The plant samples were analysed for nutrient contents apart from the routine biometric observations, viz., dry weight of root and shoot, diameter of root, number of roots per plant, total length of root and volume of root.

3.3.1.1. Method of collection of soil and plant samples

Rhizosphere and non-rhizosphere soil samples and plant samples were collected at three stages of crop growth i.e., at 30, 60 and 90 days after seeding (viz., vegetative, pre-flowering and heading, i.e., preharvest stages). At the particular stage of collecting the soil sample, the soil in the pot was depotted at field moisture capacity and the plants were carefully removed from the soil with the root system intact. The root was gently tapped to remove the loosely adhering soil. The strongly adhering soil to the root i.e., the particles of soil at the boundary of the outermost root tissue i.e., closest to the root tissues (0-5 mm distance from the root) were carefully removed and this was taken as rhizosphere soil (Riley and Barber, 1969 and 1971). The soil which lay outside the rhizosphere zone and is not directly influenced by growing

root except for the withdrawal of water and nutrients was collected as non-rhizosphere soil or arhizosphere soil. The root and shoot were separated. The root samples after the removal of rhizosphere soil were collected and the root growth measurements like root length, number of roots per plant, diameter of root, volume of root, weight of root and weight of shoot were recorded. Broken rootlets were recovered from the soil and added to the root sample. The root mass had been washed free of soil with tap water, distilled water, 0.5 N HCl and then with distilled water. The root and shoot were then dried under shade followed by oven drying at 70°C to a constant weight and the dry weight of the samples were recorded. The plant material samples and grain samples were ground to pass 20 mesh sieve and these were taken for chemical analysis.

3.4. Methods of chemical analysis of soil and plants

The laboratory analysis of rhizosphere and non-rhizosphere soil samples were conducted for the following determinations:

1. Analysis of soil samples for available nutrients viz., N, P, K, Fe, Mn, Cu and Zn.
2. Fractionation of soil samples for various forms of N, P and K.
3. Analysis of root, shoot and grain samples for N, P, K, Fe, Mn, Cu and Zn.

3.5. Preparation of soil samples

Excepting for certain determinations required under wet conditions, the collected rhizosphere and non-rhizosphere soil samples at the above said three stages were air dried under shade, gently pound with wooden mallet to pass through 2 mm sieve. The soil which passed through 2 mm sieve were stored in polythene bottles for further analysis. Specific soil preparations for individual chemical analyses were followed whenever necessary. Besides, the soil material passing through a 150 mesh plastic sieve was used for micronutrient analysis.

3.5.1. Estimation of available nutrients

3.5.1.1. Available nitrogen

This was done by alkaline permanganate method of Subbiah and Asija (1956).

3.5.1.2. Available phosphorus

0.5 N - NaHCO_3 (pH 8.5) was used as extractant (Olsen's P) for estimating the soil available P using Spectronic 2000 colorimeter as described by Jackson (1973).

3.5.1.3. Available potassium

This was estimated by the procedure outlined by Toth and Prince (1949) using Corning 400 Flame photometer.

3.5.1.4. Available micronutrients (Fe, Mn, Cu and Zn)

The available micronutrients were extracted with DTPA (Diethylene Triamine Penta Acetic Acid) extractant adjusted to pH 7.3 at 1:2 ratio after shaking for two hours, filtering and available Fe, Mn, Cu and Zn were estimated in the extract using Pye Unicam Atomic Absorption Spectrophotometer (Lindsay and Norvell, 1969).

3.6. Fractionation of soil samples for various forms of N, P and K

3.6.1. Fractionation of N

3.6.1.1. Exchangeable NH_4^+ nitrogen

Ammoniacal N was determined in 1 N KCl extractant of the soil with Kjeldahl's distillation apparatus (Bremner and Shaw, 1955).

3.6.1.2. Nitrate nitrogen

An aliquot of the above soil extract was distilled with ignited MgO and Devardas' alloy in Kjeldahl's apparatus as described by Bremner and Shaw (1955).

3.6.2. Fractionation of soil inorganic P

Inorganic phosphorus fractions of soil samples were estimated by the modified procedure of Chang and Jackson

(1957) and after Petersen and Corey (1966) as outlined by Hesse (1971). The following fractions were determined in rhizosphere and non-rhizosphere soil samples.

3.6.2.1. Saloid-bound P

One g of 0.15 mm soil was placed in a 100 cm³ polypropylene centrifuge tube 50 cm³ of 1 M.NH₄Cl solution was added and shaken for 30 minutes and centrifuged. Phosphorus was then estimated in the centrifugate by chloromolybdo-phosphoric blue colour method (Jackson, 1973) and expressed as saloid-P.

3.6.2.2. Aluminium-bound P (Al-P)

To the soil previously extracted with ammonium chloride, 50 cm³ of 0.5 M.NH₄F solution made to pH 8.2 with NH₄OH was added and shaken for one hour and centrifuged. Phosphorus in the solution after decolourizing with activated carbon was estimated as in Saloid-P in the presence of boric acid (0.5% level) to prevent the interference of fluoride ions and expressed as Aluminium-bound P (Jackson, 1973).

3.6.2.3. Iron-bound P (Fe-P)

The residue from the second step was washed twice with 25 ml portions of saturated NaCl solution and centrifuged each time ~~to~~ recover the soil. The soil was added

with 50 cm³ of 0.1 N.NaOH and shaken for 17 hours and centrifuged. Then five drops of concentrated H₂SO₄ were added to the solution and centrifuged. After flocculation of organic matter, the solution was decolourized by activated phosphorus free carbon and phosphorus was estimated by sulfomolybdo-phosphoric blue colour method (Jackson, 1973).

3.5.2.4. Calcium-bound P (Ca-P)

The residue from previous extraction was washed twice with 25 cm³ portion of saturated NaCl solution. The washed residue was suspended in 50 cm³ of 0.5 N H₂SO₄ and shaken for one hour and centrifuged. The residue was discarded. The phosphorus was estimated by sulfomolybdo-phosphoric blue colour method (Jackson, 1973).

3.6.3. Fractionation of soil potassium

Different forms of soil potassium were estimated in the soil samples using the following methods.

3.6.3.1. Water soluble-K

The method of Toth and Prince (1949) was followed.

Ten g of soil was shaken with 25 cm³ of distilled water for 10 minutes, centrifuged and the clear supernatant liquid filtered. The filtrate was collected in a 100 cm³

volumetric flask. Three additional extractions were made in the same manner and the combined extracts diluted to 100 cm³ with distilled water. The solution was mixed well and K determined using Corning 400 Flame photometer by comparing the emission intensity with that from standards made in distilled water and this gives the water soluble-K.

3.6.3.2. Exchangeable-K

The method of Pratt (1965) was followed.

Ten g of soil was shaken with 25 cm³ of N.N.NH₄OAc in a 50 cm³ centrifuge tube, centrifuged and the clear supernatant liquid filtered. The filtrate was collected in a 100 cm³ volumetric flask. Three additional extractions were made in the same manner and the combined extracts diluted to 100 cm³ with N.N.NH₄OAc. The solution was mixed well and K determined using Corning 400 flame photometer by comparing the emission intensity with that from standards made in N.N.NH₄OAc solution. The difference between this and the water soluble-K was taken as the exchangeable-K.

Since the water soluble K formed only a fraction of the exchangeable-K, the latter was considered as available K.

3.6.3.3. HNO₃ extractable -K (Non-exchangeable-K)

1 N.HNO₃ extractable K was determined by employing the method of Wood and De Turk (1941).

Two g of finely ground soil was boiled for 10 minutes with 25 cm³ of N.HNO₃ acid in 100 cm³ Erlenmeyer flask. The contents were filtered and the clear filtrate was collected in a 100 cm³ volumetric flask. The soil was washed four times with 15 cm³ portions of 0.1 N HNO₃ and the leachings were collected in the volumetric flask. After cooling, the solution was mixed well and K determined using Corning 400 flame photometer by comparing the emission intensity with that from standards made in N.HNO₃ acid. The difference between this and the water soluble plus exchangeable-K was taken as the non-exchangeable-K.

3.7. Determination of root growth characteristics

The root system of the above said sorghum plant, after the removal of rhizosphere soil, was separated. The volume of the root was measured by the method of displacement, when the root bunches were immersed in water contained in a measuring cylinder (Jena et al., 1980). The mass of the root was estimated by means of Metler top pan balance E 200. The diameter of the root samples was measured with the help of a microscope by taking cross sections at five different places in the root portion and the mean of these five diameters was taken into account (Patel and Ghildyal, 1980). The total root length was then calculated assuming the root to be cylindrical by using

the relationship $V = \pi r^2 L$ where V is the volume of root (cm^3), r the radius of the root (cm) and L the length of root (cm) (Patel and Ghildyal, 1980).

3.8. Analysis of plant samples

The root and shoot samples collected at different growth stages as well as the grain samples were separately analysed for N, P, K, Fe, Mn, Cu and Zn.

3.8.1. Preparation of the samples

The root and shoot were separated and washed successively in 0.1 N.HCl distilled water and redistilled deionized water. After recording their wet and dry weights, the samples were prepared for subsequent analysis. The cleaned samples were ground to fine powder mechanically to pass through 20 mesh sieve.

3.8.1.1. Nitrogen

Nitrogen in the root, shoot and grain samples was estimated in di-acid extract (sulphuric; perchloric acid 5:1) (Piper, 1966).

3.8.1.2. Phosphorus

Phosphorus in plant samples was extracted using triple acid mixture of HNO_3 , H_2SO_4 and HClO_4 in the proportion

of 9:1:3 and estimated by Vanadomolybdo-phosphoric method (Jackson, 1973) using Speetronic-2000 colorimeter.

3.8.1.3. Potassium

Potassium in the digested extract was determined using Corning 400 flame photometer, after neutralising with NH_4OH and after diluting it suitably.

3.8.1.4. Micronutrients (Fe, Mn, Cu and Zn)

The micronutrients, viz., Fe, Mn, Cu and Zn contents were estimated in the digested extracts using an Atomic Absorption Spectrophotometer (Pye Unicam Model) at the corresponding wavelengths of the element.

3.9. Determination of nutrient flow rate or uptake rate or flux

The rate of uptake of nutrients per meter of root was calculated using the following equation as used by Warncke and Barber (1974).

$$I = \frac{(U_2 - U_1) \left(\ln \frac{L_2}{L_1} \right)}{(t_2 - t_1) (L_2 - L_1)}$$

where I is the flux/meter of root or nutrient uptake rate, U is the amount of nutrient in the plant, t is the time and L is the root length. The subscripts 1 and 2 refer to the initial and final harvest respectively.

The equation reflects the exponential nature of root growth. Since root length reached a maximum at 80 days, this equation was used only upto 60 days. For the calculation of flux per meter of root for the 90 days, mean root length $\frac{L_1 + L_2}{2}$ was used as the root length value instead of $\frac{(\ln L_2 - \ln L_1)}{(L_2 - L_1)}$. The data reported based on this method of calculation, nutrient flux expressed as moles was calculated by dividing grams of nutrient uptake by the atomic weight of the concerned nutrient element.

3.10. Uptake of nutrients

This was worked out by multiplying the dry matter yield by the corresponding nutrient content.

3.11. Statistical analysis

The analytical data of the soil and plant samples and various other biometric characters such as grain yield, number of roots/plant, length of root, volume of root, diameter of root, weight of root and weight of shoot were subjected to statistical scrutiny as per the procedure given by Panse and Sukhatme (1978) to find out the influence of various treatments on the nutrient availability, transformation pattern and flow rate in the plant. Simple correlation as well as fitting up of regression equations were deduced as per the procedure described by Panse and Sukhatme (1978).

CHAPTER 4

RESULTS

The results obtained from the studies on the pattern of root development, root exudation and analysis of both soil and plant samples as well as the results of statistical analysis of the experimental data of the present investigation are presented in this chapter.

4.1. Root development pattern in sorghum

As already indicated, the root development of any plant assumes considerable significance in the utilization pattern of the nutrients available in the soil. Therefore, the root development pattern studies in sorghum were carried out as per procedure described by Fahreaus Slide Technique (1957). The root pattern was similar to that of already established for this crop.

4.2. Root exudation pattern of sorghum

The pattern of root exudation in the sorghum crop was thought to be of interest and root exudation studies were carried out as per details already furnished in Chapter 3.

The root exudates were collected at 15, 30 and 45 days growth stages of sorghum and studied for the nature of

root exudate. The qualitative and quantitative nature of the root exudate of sorghum crop at three different stages of plant growth are summarized in Tables 2(a) to 2(c).

4.2.1. Exudation pattern of sorghum plant at different stages of plant growth

In all, 16 amino acids were identified from the root exudate of sorghum plant. Seven amino acids on 15th day, 11 amino acids on 30th day and 10 amino acids on 45th day were detected from sorghum root exudate. Aspartic acid, glutamic acid, leucine and serine were found to be exuded by the plant irrespective of the stage of plant growth. In general, the number of amino acids exuded increased upto 30 days of plant growth after which it declined. In all, three sugars and two organic acids were identified from the exudate. Glucose and fructose were invariably present in the exudate at three stages, but declined at 45th day. Xylose was detected in the exudate in the later stages of plant growth viz., from the 30th day onwards. The organic acids were found to be present at 15 and 30 days of plant growth.

4.3. Influence of soil types, sterilization and fertilizer application on nutrient environment in the rhizosphere and non-rhizosphere region soils

Representative black and red soil (Periyanaickenpalayam series and Palathurai series respectively) collected

TABLE 2(a). EXUDATION PATTERN OF AMINO ACIDS THROUGH ROOT OF
SORGHUM PLANT ($\mu\text{g/plant}$)

S.No.	Amino acid	Age of the plant in days		
		15	30	45
1.	Alanine	-	+	-
2.	Asparagine	+++	-	-
3.	Aspartic acid	+++	+++	+++
4.	Cystine	++	-	+
5.	Glutamic acid	+++++	+++++	++++
6.	Glycine	-	+	-
7.	Histidine	-	-	-
8.	Leucine	+	+	T
9.	Lysine	-	-	-
10.	Methionine	-	T	T
11.	Phenylalanine	-	+	T
12.	Proline	-	+	++
13.	Serine	++	++	+
14.	Threonine	++	+	-
15.	Tryptophan	-	+	T
16.	Tyrosine	-	-	+
17.	Unidentified	1	-	1

+ : 0.1 to 0.2 $\mu\text{g/plant}$
 ++ : 0.2 to 0.3 "
 +++ : 0.3 to 0.4 "
 ++++ : 0.4 to 0.5 "
 +++++ : 0.5 to 0.6 "
 - : Not detectable
 T : Present in traces

TABLE 2(b). EXUDATION PATTERN OF SUGARS THROUGH ROOT OF
SORGHUM PLANT ($\mu\text{g/plant}$)

Sugars	Age of the plant in days		
	15	30	45
Glucose	++++	++++	+++
Fructose	+++	+++	+
Xylose	-	+	+
Sucrose	-	-	-

+ : 10 to 20 $\mu\text{g/plant}$
 ++ : 20 to 30 "
 +++ : 30 to 40 "
 ++++ : 40 to 50 "
 - : Not detectable

TABLE 2(c). EXDUATION PATTERN OF ORGANIC ACIDS THROUGH ROOT
OF SORGHUM PLANT ($\mu\text{g/plant}$)

Organic acids	Age of the plant in days		
	15	30	45
Tartaric acid	++	++	-
Oxalic acid	+++	++	-

++ : 20 to 30 $\mu\text{g/plant}$

+++ : 30 to 40 "

- : Not detectable

from Tamil Nadu Agricultural University Campus (Coimbatore) were used for the pot experiment. There were considerable differences in the physico-chemical properties of these two soils and as such helped to study the effect of treatments under varied soil situations (Table 3). As already indicated, this experiment carried 48 treatments (two soils, sterilized and unsterilized, three levels of N and two levels of P and rhizosphere region and non-rhizosphere region). Eight sets of such treatments were maintained to represent two replications per stage of collection viz., 30, 60 and 90 days. The final two sets of replications were used for recording grain and straw yield.

4.4. Studies of the effect on soil properties

4.4.1. Effect on availability of N, P and K in soils (Fig.4)

4.4.1.1. Effect on available N (Table 4)

Individual effects

i) Rhizosphere: The mean value for this main effect ranged from 83.2 to 108.9 ppm. At all the three stages of crop growth, the rhizosphere soil recorded higher available N content than non-rhizosphere soil.

ii) Sterilization: The mean value for this main effect ranged from 77.8 to 105.9 ppm. Under sterilized condition higher available N content was recorded at 30th day

TABLE 3. PHYSICO-CHEMICAL CHARACTERISTICS OF THE INITIAL SOIL SAMPLES COLLECTED FROM THE TNAU FARM, COIMBATORE (Pot Study)

A: BLACK SOIL COLLECTED FROM EASTERN BLOCK OF TNAU FARM, COIMBATORE
PERIANAYAKKANPALAYAM SERIES

Taxonomic classification: Typic ustivertep

B: RED SOIL, COLLECTED FROM MILLET BREEDING STATION, COIMBATORE
PALATHURAI SERIES

Taxonomic classification : Typic haplustalf

Heads of analysis	Values	
	A	B
<u>A. Textural composition</u>		
Clay (per cent)	43.7	7.7
Silt (per cent)	9.2	25.5
Fine sand (per cent)	19.2	42.5
Coarse sand (per cent)	27.5	23.7
Textural class	Clay loam	Sandy loam
<u>B. Chemical properties</u>		
a. Moisture (per cent)	5.32	4.12
b. Total N (ppm)	1050	720.0
c. Available N (ppm)	97.60	85.60
d. Ammoniacal nitrogen (ppm)	24.25	20.15
e. NO_3 - N (ppm)	19.75	15.82
f. Total P (ppm)	765.0	875.0
g. Available P (ppm)	1.25	2.32
h. Saloid - P (ppm)	4.15	8.67
i. Al-P (ppm)	5.67	4.72
j. Fe-P (ppm)	41.6	52.25
k. Ca-P (ppm)	7.67	6.56
l. Total K (ppm)	2765	2325
m. Available K (ppm)	235.0	168.0
n. Water soluble K (ppm)	57.0	43.0
o. HNO_3 extractable-K (ppm)	325.0	265.0
p. Total Fe (ppm)	1280	1300.0
q. Available Fe (ppm)	4.60	6.30
r. Total Mn (ppm)	490.0	380.0
s. Available Mn (ppm)	16.50	20.6
t. Total Cu (ppm)	20.0	19.0
u. Available Cu (ppm)	0.75	1.27
v. Total Zn (ppm)	40.0	150.0
w. Available Zn (ppm)	0.30	0.42
<u>C. Physico-chemical properties</u>		
i) pH	8.10	7.65
ii) EC (m.mhos cm^{-1})	0.62	0.45
iii) Cation exchange capacity (m.e 100^{-1} g soil)	36.60	16.50

than under non-sterilized condition and decreased with advancement of crop growth.

iii) Soil type: The mean value for this main effect ranged from 82.6 to 110.4 ppm. In the case of black soil, the available N content increased upto 60th day and thereafter declined. In the case of red soil, the available N content decreased with stage and the decrease in the third stage was insignificant when compared to the second stage. However in the third stage, the red soil registered more of available N content than the black soil.

iv) P levels: The mean value for this main effect ranged from 80.0 to 108.2 ppm. Phosphorus application did not increase the available N status at the earlier stages but increased at near about harvest.

v) N levels: The mean value for this main effect ranged from 83.3 to 104.8 ppm. Nitrogen application at all levels did not increase the available N status of the soil.

Interaction effects

At 30th day, the interactions viz., Rh x S, Rh x N, S x P, S x N and P x N were significant. The salient inferences drawn from the interaction effects are: (i) in both the rhizosphere and non-rhizosphere soils, the black soil

TABLE 4. EFFECT OF TREATMENTS ON AVAILABLE N IN RHIZOSPHERE AND
NON-RHIZOSPHERE REGIONS OF SORGHUM IN BLACK AND RED SOILS (ppm)

Treatments (1)	30 days (2)	60 days (3)	90 days (4)
Rh	108.9	110.0	86.0
NRh	95.7	90.7	83.2
St	105.9	104.2	91.4
NSt	98.7	96.5	77.8
S ₁	110.4	112.8	82.6
S ₂	94.2	87.9	86.6
P ₀	108.2	104.0	80.0
P ₅₀	96.4	96.7	89.3
SE	1.9	1.6	1.4
CD	5.5	4.5	3.9
N ₀	104.4	104.8	85.1
N ₅₀	102.7	100.0	85.3
N ₁₀₀	100.0	96.3	83.3
SE	2.4	2.0	1.7
CD	6.7	5.5	4.8
Rh x St	110.8	115.6	97.1
Rh x NSt	107.1	104.4	75.0
NRh x St	101.1	92.8	85.8
NRh x NSt	90.3	88.6	80.6
Rh x S ₁	120.4	133.0	82.3
Rh x S ₂	97.5	86.9	89.8
NRh x S ₁	100.4	92.6	82.9
NRh x S ₂	91.0	88.9	83.5
Rh x P ₀	115.9	118.0	80.6
Rh x P ₅₀	102.0	102.0	91.5
NRh x P ₀	100.5	90.1	79.4
NRh x P ₅₀	90.8	91.4	87.0
St x S ₁	109.3	117.6	86.3
St x S ₂	88.1	90.8	96.6
NSt x S ₁	111.5	108.0	78.9
NSt x S ₂	100.4	85.0	76.6

Contd.,

(1)	(2)	(3)	(4)
St x P ₀	112.4	110.2	83.5
St x P ₅₀	99.4	98.3	99.4
NSt x P ₀	104.0	97.9	76.4
NSt x P ₅₀	93.4	95.1	79.2
S ₁ x P ₀	113.4	119.6	81.3
S ₁ x P ₅₀	107.4	106.0	84.0
S ₂ x P ₀	103.0	88.5	78.7
S ₂ x P ₅₀	85.5	87.4	94.6
SE	2.7	2.3	2.0
CD	7.7	6.4	5.6
Rh x N ₀	119.1	113.3	85.9
Rh x N ₅₀	104.0	109.4	88.1
Rh x N ₁₀₀	104.8	107.4	84.0
NRh x N ₀	89.7	96.3	84.2
NRh x N ₅₀	101.3	90.6	82.4
NRh x N ₁₀₀	96.1	85.3	83.0
St x N ₀	106.0	104.8	92.9
St x N ₅₀	108.6	110.0	91.2
St x N ₁₀₀	103.2	98.0	90.3
NSt x N ₀	102.8	104.9	77.3
NSt x N ₅₀	96.7	90.0	79.3
NSt x N ₁₀₀	96.7	94.7	76.8
S ₁ x N ₀	104.1	119.4	84.0
S ₁ x N ₅₀	114.4	109.3	81.5
S ₁ x N ₁₀₀	112.7	109.7	82.3
S ₂ x N ₀	104.7	90.2	86.1
S ₂ x N ₅₀	90.9	90.6	89.0
S ₂ x N ₁₀₀	87.1	82.9	84.8
N ₀ x P ₀	106.7	104.7	81.8
N ₀ x P ₅₀	102.1	104.5	88.4
N ₅₀ x P ₀	113.5	104.5	79.4
N ₅₀ x P ₅₀	91.8	95.5	91.0
N ₁₀₀ x P ₀	104.4	102.9	78.8
N ₁₀₀ x P ₅₀	95.4	89.7	88.3
SE	3.3	2.8	2.4
CD	9.5	7.8	6.8

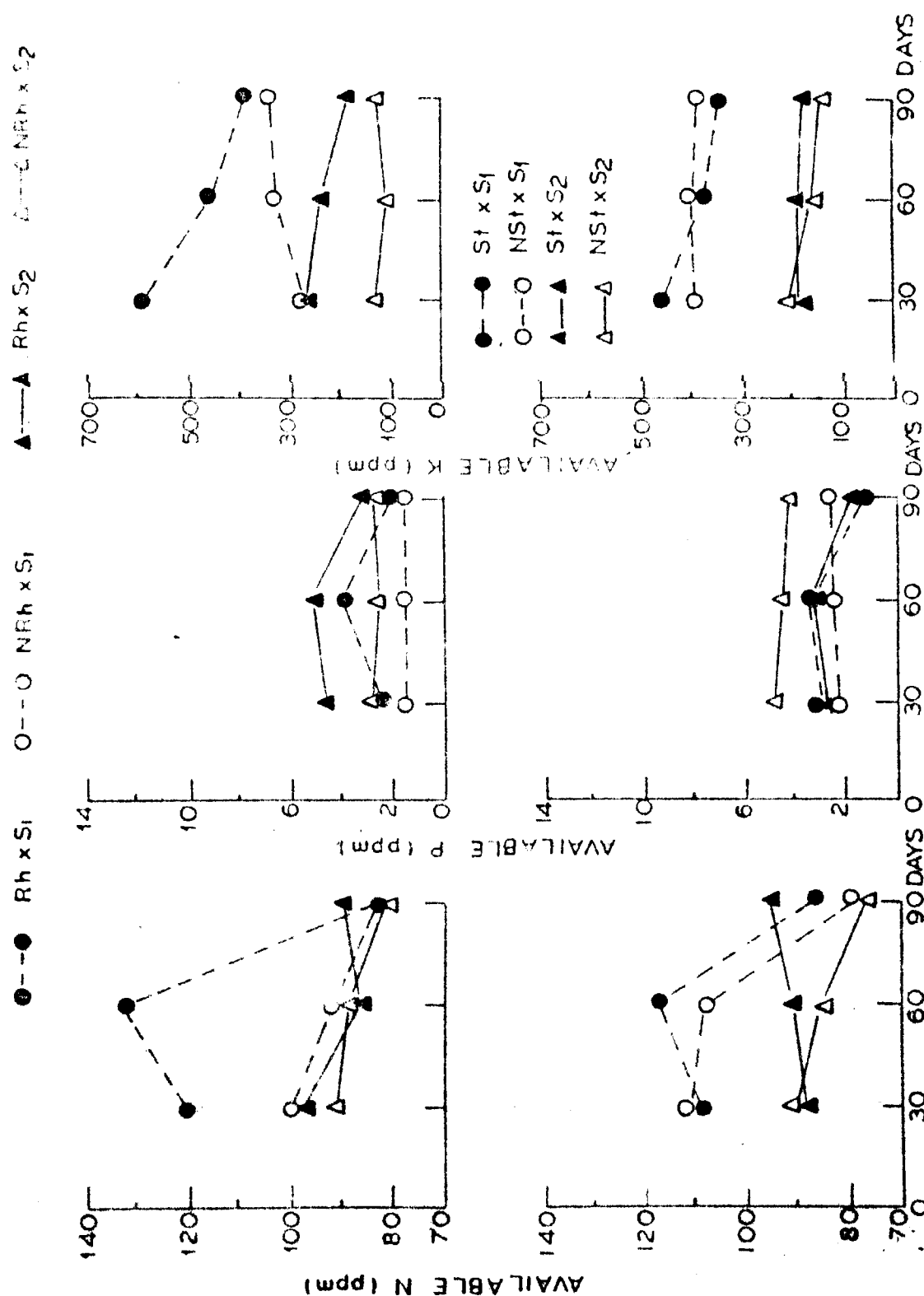


FIG-4 AVAILABILITY OF MAJOR NUTRIENTS AS INFLUENCED BY RHIZOSPHERE, SOIL TYPES AND STERILIZATION AT DIFFERENT STAGES OF CROP GROWTH

recorded significantly higher available N content than the red soil and the available N content in the rhizosphere soil was more in both the soils than in the non-rhizosphere soils;; (ii) the available N content was more in the rhizosphere soil irrespective of the levels of N tried; (iii) irrespective of P application, the black soil registered higher available N content than the red soil and in both the soils, P application did not enhance the available N content; (iv) the available N content in the black soil was influenced by the N application, but that was on par with control and in the red soil, levels of N did not have any influence in increasing the available N content; and (v) the combined application of $N_{50}P_0$ and N_0P_{50} recorded higher available N content, but on par with other combined applications.

At 60th day, the interactions viz., St x P, St x N, Rh x S, Rh x P and S x P were found to be significant. The salient inferences drawn are: (i) the levels of N and P tried did not increase the available N content under both the sterilized and unsterilized conditions; (ii) at N_0 level, the unsterilized i.e., normal soil, was on par with sterilized soil; (iii) at N_{50} and N_{100} levels, under sterilized condition of the soil higher available N content was recorded than the normal soil and that attained the level

of significance only at N_{50} level; (iv) irrespective of P application the available N content was more under unsterilized condition and at P_0 level, the differences were significant; (v) in the black soil, the available N content was significantly superior in the rhizosphere region than the red soil, while in the red soil in both the rhizosphere and non-rhizosphere soils, the available N content was more or less the same; and (vi) irrespective of P application, the rhizosphere soil recorded significantly higher available N content.

At 90th day, the interactions viz., St x Rh, St x S, St x P and S x P were significant. The important inferences are (i) under sterilized condition, the available N content was higher in the rhizosphere soil than that in the non-rhizosphere soil, in the red soil than in the black soil and at P_{50} level than at P_0 level. The above trend was completely reversed under non-sterilized condition; (ii) the content of available N was not increased in both the soil types and at both the levels of P application; (iii) within the soil types, generally P_{50} level registered higher available N content than P_0 level but the significance was observed only in the red soil; and iv) at P_0 level the black soil was on par with the red soil whereas at P_{50} level, the red soil recorded higher available N content than the black soil.

4.4.1.2. Effect on available phosphorus (Table 5)

Individual effects

i) Rhizosphere: The mean value for the main effect ranged from 2.12 to 4.81 ppm and at all stages of crop growth, the rhizosphere soil contained significantly higher available P content than the non-rhizosphere soil.

ii) Sterilization: The mean value ranged from 1.60 to 3.48 ppm and the sterilized condition brought about a significant depression in the available P content at all stages of crop growth.

iii) Soil types: The mean available P content for the soil types ranged from 1.83 to 3.91 ppm. For any given growth stage, the red soil was found to contain more available P than the black soil.

iv) P levels: The status of available P was higher in P applied treatments during all the three stages than in no P treatment.

v) N levels: At 30th day, the effect due to addition of N at all levels remained on par. With advancement in crop growth period, the added N levels caused depression of available P. But this effect was reversed at 90th day.

TABLE 5. EFFECT OF TREATMENTS ON AVAILABLE P IN RHIZOSPHERE AND NON-RHIZOSPHERE REGIONS OF SORGHUM IN BLACK AND RED SOILS (ppm)

Treatments (1)	30 days (2)	60 days (3)	90 days (4)
Rh	4.08	4.81	2.57
NRh	2.12	2.12	2.37
St	2.78	3.44	1.60
NSt	3.43	3.48	3.34
S ₁	2.56	3.01	1.83
S ₂	3.65	3.91	3.10
P ₀	2.24	2.90	1.84
P ₅₀	3.97	4.03	3.09
SE	0.12	0.15	0.08
CD	0.35	0.42	0.24
N ₀	3.17	3.85	2.24
N ₅₀	3.08	3.31	2.59
N ₁₀₀	3.07	3.23	2.57
SE	0.15	0.18	0.10
CD	0.43	0.51	0.29
Rh x St	3.69	5.17	1.97
Rh x NSt	4.48	4.44	3.17
NRh x St	1.97	1.72	1.22
NRh x NSt	2.38	2.53	3.51
Rh x S ₁	3.47	4.37	1.78
Rh x S ₂	4.69	5.24	3.36
NRh x S ₁	1.64	1.66	1.89
NRh x S ₂	2.61	2.59	2.85
Rh x P ₀	2.94	4.30	2.02
Rh x P ₅₀	5.22	5.31	3.12
NRh x P ₀	1.54	1.50	1.66
NRh x P ₅₀	2.70	2.74	3.07
St x S ₁	2.89	3.42	1.16
St x S ₂	2.67	3.47	2.04
NSt x S ₁	2.22	2.61	2.51
NSt x S ₂	1.63	4.35	4.16

Contd.

(1)	(2)	(3)	(4)
St x P ₀	1.77	2.75	1.16
St x P ₅₀	3.70	4.14	2.04
NSt x P ₀	2.70	3.05	2.53
NSt x P ₅₀	4.15	3.92	4.15
S ₁ x P ₀	1.71	2.34	1.50
S ₁ x P ₅₀	3.40	3.69	2.17
S ₂ x P ₀	3.77	3.45	2.19
S ₂ x P ₅₀	4.53	4.37	4.02
SE	0.17	0.21	0.12
CD	0.49	0.59	0.33
Rh x N ₀	4.49	5.20	2.25
Rh x N ₅₀	3.72	4.87	2.84
Rh x N ₁₀₀	4.04	4.34	2.62
NRh x N ₀	1.84	2.51	2.24
NRh x N ₅₀	2.43	1.74	2.35
NRh x N ₁₀₀	2.11	2.11	2.52
St x N ₀	2.38	3.73	1.48
St x N ₅₀	3.08	3.49	1.69
St x N ₁₀₀	2.89	3.11	1.63
NSt x N ₀	3.95	3.98	3.01
NSt x N ₅₀	3.07	3.12	3.50
NSt x N ₁₀₀	3.26	3.34	3.51
S ₁ x N ₀	2.20	3.62	1.47
S ₁ x N ₅₀	2.78	2.36	2.04
S ₁ x N ₁₀₀	2.69	3.07	1.99
S ₂ x N ₀	4.13	4.09	3.01
S ₂ x N ₅₀	3.37	4.26	3.15
S ₂ x N ₁₀₀	3.46	3.38	3.15
N ₀ x P ₀	2.67	3.24	1.46
N ₀ x P ₅₀	3.67	4.47	3.03
N ₅₀ x P ₀	2.10	2.82	2.12
N ₅₀ x P ₅₀	4.05	3.79	3.07
N ₁₀₀ x P ₀	1.96	2.63	1.95
N ₁₀₀ x P ₅₀	4.19	3.82	3.19
SE	0.21	0.26	0.14
CD	0.60	0.73	0.41

Interaction effects

At 30th day, the various interactions viz., St x N, St x S, Rh x P, Rh x N, S x N and P x N indicated statistical significance. For any given level of N, the application of P favoured, greater accumulation of available P and irrespective of P application, the rhizosphere soil recorded higher accumulation of available P content than the non-rhizosphere soil.

At 60th day, the interactions viz., St x Rh, St x S and S x N indicated statistical significance. The salient inferences from the above are: (i) sterilization caused greater accumulation of P in the rhizosphere soil (ii) in the black soil, sterilization favoured greater accumulation of available P as against a reverse effect associated with the red soil; and (iii) in the red soil, higher level of N tended to depress the available P status.

At 90th day, the interactions viz., St x Rh, St x S, St x P, Rh x S and S x P attained statistical significance. The important inferences drawn are: (i) the sterilized condition tended to enhance available P in the rhizosphere soil; (ii) the sterilized condition had similar effect in both the soil types; (iii) irrespective of sterilization, addition of P enhanced the available P status in the soils; in both rhizosphere and non-rhizosphere soils the red soil

contained more available P as compared to the black soil; and (iv) the effect P addition in enhancing the available P status was observed in both the soil types.

4.4.1.3. Effect of available K (Table 17)

The exchangeable-K is taken as available-K since the water soluble K recorded only very little fraction. The exchangeable K is dealt in detail under effect on K transformation.

4.4.2. Effect on availability of micronutrients in soils (Fig.5)

4.4.2.1. Effect on available Fe (Table 6)

Individual effects

i) Rhizosphere: The mean value for this main effect ranged from 5.15 to 20.58 ppm. The rhizosphere soil recorded higher values of available Fe content at all the three stages of crop growth than the non-rhizosphere soil.

ii) Sterilization: The mean value for this main effect ranged from 5.36 to 18.85 ppm. Under sterilized condition the available Fe content decreased at all the three stages of crop growth.

iii) Soil types: The mean values for this main effect ranged from 5.48 to 18.68 ppm. The black soil recorded

TABLE 6. EFFECT OF TREATMENTS ON AVAILABLE Fe IN RHIZOSPHERE AND
NON-RHIZOSPHERE REGIONS OF SORGHUM IN BLACK AND RED SOILS (ppm)

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Treatments (1)	30 days (2)	60 days (3)	90 days (4)
Rh	6.43	20.58	20.30
NRh	5.15	9.94	15.26
St	5.36	11.67	16.91
NSt	6.22	18.85	18.64
S ₁	5.48	16.11	18.68
S ₂	6.10	14.41	16.87
P ₀	5.57	14.70	18.00
P ₅₀	6.01	15.82	17.55
SE	0.08	0.42	0.40
CD	0.24	1.19	1.12
N ₀	5.95	16.05	18.47
N ₅₀	5.92	14.55	17.15
N ₁₀₀	5.50	15.17	17.71
SE	0.10	0.51	0.48
CD	0.29	1.46	1.38
Rh x St	6.07	17.92	18.73
Rh x NSt	6.78	23.24	21.88
NRh x St	4.64	5.42	15.10
NRh x NSt	5.67	14.47	15.41
Rh x S ₁	6.17	21.64	21.70
Rh x S ₂	6.69	19.51	18.90
NRh x S ₁	4.80	10.57	15.67
NRh x S ₂	5.51	9.31	14.85
Rh x P ₀	6.14	20.52	21.29
Rh x P ₅₀	6.71	20.64	17.31
NRh x P ₀	5.01	8.87	14.72
NRh x P ₅₀	5.30	11.01	15.79
St x S ₁	4.97	13.36	19.12
St x S ₂	5.73	9.98	14.71
NSt x S ₁	6.00	18.86	18.24
NSt x S ₂	6.46	18.85	19.04

Contd.,

(1)	(2)	(3)	(4)
St x P ₀	4.92	11.97	16.79
St x P ₅₀	6.22	11.37	17.04
NSt x P ₀	6.23	17.42	19.22
NSt x P ₅₀	6.21	20.28	18.06
S ₁ x P ₀	5.34	14.21	19.05
S ₁ x P ₅₀	5.62	18.01	18.31
S ₂ x P ₀	5.81	15.19	16.96
S ₂ x P ₅₀	6.39	13.64	16.80
SE	0.12	0.59	0.56
CD	0.34	1.68	1.59
Rh x N ₀	6.81	22.12	21.69
Rh x N ₅₀	6.40	19.60	19.13
Rh x N ₁₀₀	6.06	20.01	20.08
NRh x N ₀	5.09	9.98	15.26
NRh x N ₅₀	5.42	9.51	15.17
NRh x N ₁₀₀	4.94	10.34	15.34
St x N ₀	5.43	12.05	17.87
St x N ₅₀	5.50	10.51	14.78
St x N ₁₀₀	5.14	12.44	18.09
NSt x N ₀	6.47	20.05	19.08
NSt x N ₅₀	6.33	18.60	19.52
NSt x N ₁₀₀	5.87	17.90	17.33
S ₁ x N ₀	5.42	17.52	19.40
S ₁ x N ₅₀	5.83	15.29	17.06
S ₁ x N ₁₀₀	5.20	15.51	19.59
S ₂ x N ₀	6.48	14.58	17.55
S ₂ x N ₅₀	6.00	13.81	17.24
S ₂ x N ₁₀₀	5.81	14.84	15.83
N ₀ x P ₀	5.46	14.76	17.89
N ₀ x P ₅₀	6.45	17.35	19.06
N ₅₀ x P ₀	5.59	12.68	17.40
N ₅₀ x P ₅₀	6.24	16.42	16.90
N ₁₀₀ x P ₀	5.68	16.65	18.73
N ₁₀₀ x P ₅₀	5.33	13.70	16.69
SE	0.15	0.72	0.68
CD	0.42	2.06	1.95

higher amount of available Fe at 60 and 90 days of crop growth while the reverse was the case at 30 days.

iv) P levels: The mean value for this main effect ranged from 5.57 to 18.0 ppm. Phosphorus application increased the available Fe content.

v) N levels: The mean value for this main effect ranged from 5.50 to 18.47 ppm. Application of N at both the levels did not influence the available Fe content. The available Fe content decreased with N levels at 30 and 90 days of crop growth, while at 60 days, N_0 and N_{100} levels and N_{100} and N_{50} levels were on par.

Interaction effects

At 30th day, the interactions viz., St x P, Rh x N, S x N and P x N showed significance. The salient points of the inferences draw are; (i) P fertilization interacted significantly with sterilization and levels of N; (ii) P fertilization had positive effect of Fe availability under sterilized condition; (iii) Further, N application at higher level decreased Fe availability with P fertilization; and (iv) a stepwise reduction in Fe availability took place for each N addition in the rhizosphere soil as well as in the red soil.

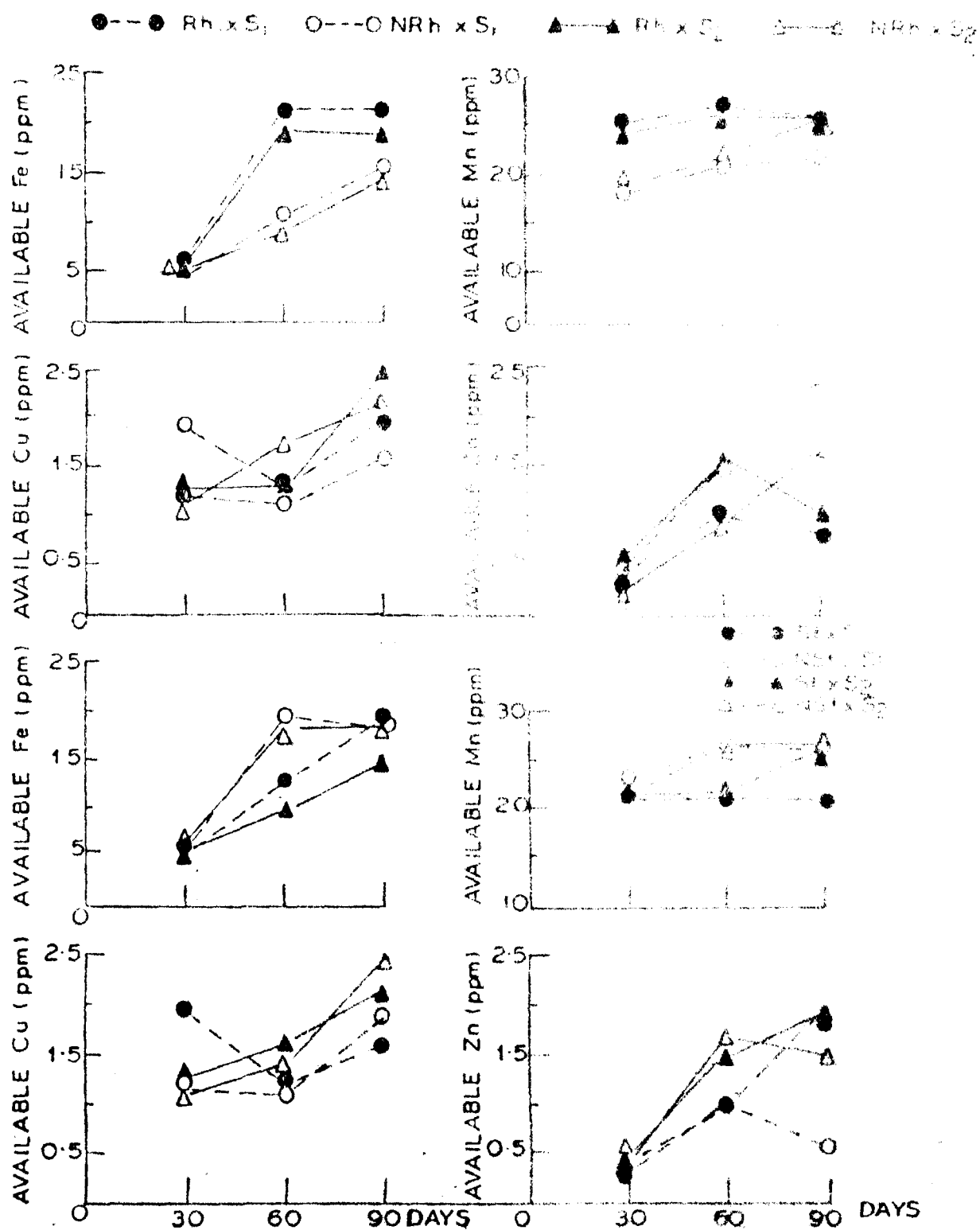


FIG.5 AVAILABILITY OF MICRONUTRIENTS AS INFLUENCED BY RHIZOSPHERE, SOIL TYPES AND STERILIZATION AT DIFFERENT STAGES OF CROP GROWTH

At 60th day, the interactions viz., St x Rh, St x S, St x P, S x P and P x N showed statistical significance. The salient inferences are: (i) in contrast to 30th day, P application helped to increase Fe availability only under non-sterilized condition; (ii) increased Fe availability for P addition was observed only in the black soil, while it was reduced for the same in the red soil; and (iii) similar to that of results obtained at 30th day, Fe availability was reduced at higher levels of N in the presence of P application.

At 90th day, the interaction involving soil with sterilization and soil with nitrogen attained significance. The salient inferences drawn are: (i) in the black soil, under sterilized condition of the soil Fe availability was not increased but in the red soil, it had a positive effect; (ii) differences were not conspicuous for Fe availability in the two soil types due to N addition at 50 kg level, but at 100 kg level the black soil had more Fe availability than its counterpart.

4.4.2.2. Effect on available Mn (Table 7)

Individual effects

i) Rhizosphere: The mean values for this main effect ranged from 18.58 to 26.80 ppm. The rhizosphere **soil**

showed higher accumulation of available Mn than the non-rhizosphere soil.

ii) Sterilization: The mean value for this main effect fell within the range of 21.24 to 26.63 ppm. The sterilized condition of the soil significantly decreased the available Mn content at all the three stages of crop growth.

iii) Soil types: The mean value for this main effect ranged from 21.66 to 26.19 ppm. The red soil enhanced the available Mn content only at 90 days of crop growth.

iv) P levels: The mean values for this main effect ranged from 21.03 to 25.24 ppm. Application of P increased the availability of Mn only at 30 and 60 days of crop growth period.

v) N levels: The mean values for this main effect ranged from 21.37 to 25.58 ppm. At 60 days of crop growth period, N at 100 kg level increased the available Mn content, while at 90 days N at 50 kg level increased the available Mn content. There was no significant difference among the N levels tried at 30 days of growth period.

TABLE 7. EFFECT OF TREATMENTS ON AVAILABLE Mn IN RHIZOSPHERE AND NON-RHIZOSPHERE REGIONS OF SORGHUM IN BLACK AND RED SOILS (ppm)

Treatments (1)	30 days (2)	60 days (3)	90 days (4)
Rh	24.92	26.80	25.84
NRh	18.58	21.66	24.15
St	21.24	21.83	23.53
NSt	22.26	26.63	26.47
S ₁	21.84	24.24	23.81
S ₂	21.66	24.21	26.19
P ₀	21.03	24.12	24.76
P ₅₀	22.48	24.34	25.24
SE	0.29	0.32	0.07
CD	0.83	0.92	0.21
N ₀	21.68	23.69	24.85
N ₅₀	22.20	23.42	25.00
N ₁₀₀	21.37	25.58	25.14
SE	0.36	0.32	0.09
CD	1.01	0.92	0.25
Rh x St	24.74	25.68	25.29
Rh x NSt	25.10	27.91	26.40
NRh x St	17.74	17.98	21.77
NRh x NSt	19.43	25.34	26.53
Rh x S ₁	25.58	27.19	25.42
Rh x S ₂	24.27	26.40	26.27
NRh x S ₁	18.11	21.30	22.20
NRh x S ₂	19.06	22.03	26.10
Rh x P ₀	23.94	27.12	25.40
Rh x P ₅₀	25.90	26.47	26.29
NRh x P ₀	18.11	21.13	24.11
NRh x P ₅₀	19.05	22.20	24.19
St x S ₁	20.88	21.60	21.18
St x S ₂	21.60	22.05	25.89
NSt x S ₁	22.80	26.89	26.45
NSt x S ₂	21.73	26.38	26.48

Contd.,

(1)	(2)	(3)	(4)
St x P ₀	20.09	21.45	23.03
St x P ₅₀	22.39	22.21	24.03
NSt x P ₀	21.96	26.80	26.48
NSt x P ₅₀	22.56	26.46	26.45
S ₁ x P ₀	20.96	24.07	23.30
S ₁ x P ₅₀	22.72	24.42	24.32
S ₂ x P ₀	21.09	24.17	26.22
S ₂ x P ₅₀	22.23	24.25	26.16
SE	0.41	0.46	0.10
CD	1.17	1.30	0.29
Rh x N ₀	22.50	26.11	25.92
Rh x N ₅₀	25.30	26.03	25.76
Rh x N ₁₀₀	23.97	28.24	25.85
NRh x N ₀	17.87	21.26	23.79
NRh x N ₅₀	19.10	20.80	24.24
NRh x N ₁₀₀	18.78	22.92	24.43
St x N ₀	22.43	21.77	23.25
St x N ₅₀	21.36	21.21	23.55
St x N ₁₀₀	19.94	22.49	23.79
NSt x N ₀	20.93	25.60	26.45
NSt x N ₅₀	23.05	25.62	26.45
NSt x N ₁₀₀	22.81	28.67	26.49
S ₁ x N ₀	22.04	22.90	23.51
S ₁ x N ₅₀	22.23	22.70	23.76
S ₁ x N ₁₀₀	21.25	27.13	24.17
S ₂ x N ₀	21.32	24.47	26.20
S ₂ x N ₅₀	22.17	24.13	26.25
S ₂ x N ₁₀₀	21.50	24.03	26.11
N ₀ x P ₀	19.68	23.12	24.52
N ₀ x P ₅₀	23.68	23.20	25.19
N ₅₀ x P ₀	22.02	26.04	24.66
N ₅₀ x P ₅₀	22.39	24.25	25.35
N ₁₀₀ x P ₀	21.39	23.64	25.10
N ₁₀₀ x P ₅₀	21.36	25.12	25.18
SE	0.50	0.56	0.13
CD	1.44	1.59	0.36

Interaction effects

At 30th day, the interactions viz., St x S, St x P, St x N, Rh x S and P x N showed statistical significance. The important inferences drawn are: (i) availability of Mn in soil was increased by the combined effect of P under sterilized condition and was decreased due to combined effect of N application under sterilized condition; and (ii) similar positive influences on Mn availability observed for P application was confined under sterilized condition and also without N application.

At 60th day, among the different interactions, the effect of N fertilization on Mn availability differed for soils, since at N_0 and N_{50} levels, Mn availability was more in the red soil, but at N_{100} kg level, the black soil showed higher value of Mn availability.

At 90th day, all the interactions excepting Rh x P were significant. The important inferences drawn are: (i) available Mn was observed to a higher extent in the rhizosphere soil in the black soil than that in the red soil and also due to P addition in the black soil and the red soil contained more Fe availability under sterilized condition; (ii) while N application had not significantly altered the Mn availability in the rhizosphere soil in the

black soil and without P application, the same got increased in the non-rhizosphere soil due to N fertilization; and (iii) the red soil was associated with significantly higher available Mn content irrespective of P application.

4.4.2.3. Effect on available Cu (Table 8)

Individual effects

i) Rhizosphere: The mean value for this main effect ranged from 1.17 to 2.21 ppm. The rhizosphere soil showed higher accumulation of available Cu content at 30 and 90 days of crop growth than the non-rhizosphere soil and the trend got reversed at 60 days of crop growth.

ii) Sterilization: The mean value for this main effect ranged from 1.13 to 2.19 ppm. Under sterilized condition of the soil available Cu content was enhanced at all the three stages of crop growth.

iii) Soil types: The mean value for this main effect ranged from 1.16 to 2.30 ppm. The black soil showed higher available Cu content at 30 days and 90 days of crop growth than the red soil and the trend got reversed at 60 days of crop growth.

iv) P levels: The mean value for this main effect ranged from 1.33 to 2.17 ppm. On par concentrations of

TABLE 8. EFFECT OF TREATMENTS ON AVAILABLE Cu IN RHIZOSPHERE AND NON-RHIZOSPHERE REGIONS OF SORGHUM IN BLACK AND RED SOILS (ppm)

Treatments (1)	30 days (2)	60 days (3)	90 days (4)
Rh	1.58	1.30	2.21
NRh	1.17	1.38	1.89
St	1.62	1.40	1.90
NSt	1.13	1.27	2.19
S ₁	1.56	1.16	1.80
S ₂	1.20	1.52	2.30
P ₀	1.37	1.33	2.17
P ₅₀	1.38	1.35	1.92
SE	0.04	0.03	0.03
CD	0.10	0.09	0.09
N ₀	1.40	1.25	2.06
N ₅₀	1.36	1.46	2.13
N ₁₀₀	1.37	1.30	1.95
SE	0.04	0.04	0.04
CD	0.12	0.11	0.11
Rh x St	1.97	1.56	2.13
Rh x NSt	1.19	1.04	2.28
NRh x St	1.27	1.25	1.67
NRh x NSt	1.08	1.50	2.11
Rh x S ₁	1.89	1.26	1.96
Rh x S ₂	1.27	1.34	2.45
NRh x S ₁	1.23	1.06	1.63
NRh x S ₂	1.12	1.69	2.14
Rh x P ₀	1.58	1.26	2.33
Rh x P ₅₀	1.58	1.33	2.08
NRh x P ₀	1.17	1.40	2.01
NRh x P ₅₀	1.18	1.36	1.77
St x S ₁	1.95	1.20	1.66
St x S ₂	1.29	1.61	2.14
NSt x S ₁	1.17	1.12	1.93
NSt x S ₂	1.10	1.43	2.45

Contd.,

(1)	(2)	(3)	(4)
St x P ₀	1.62	1.31	1.97
St x P ₅₀	1.62	1.49	1.84
NSt x P ₀	1.13	1.35	2.37
NSt x P ₅₀	1.14	1.20	2.01
S ₁ x P ₀	1.51	1.14	1.97
S ₁ x P ₅₀	1.61	1.18	1.62
S ₂ x P ₀	1.24	1.52	2.37
S ₂ x P ₅₀	1.15	1.51	2.23
SE	0.05	0.04	0.04
CD	0.14	0.12	0.12
Rh x N ₀	1.68	1.19	2.10
Rh x N ₅₀	1.58	1.45	2.20
Rh x N ₁₀₀	1.48	1.25	2.32
NRh x N ₀	1.13	1.31	2.01
NRh x N ₅₀	1.14	1.48	2.06
NRh x N ₁₀₀	1.25	1.35	1.59
St x N ₀	1.67	1.29	1.93
St x N ₅₀	1.59	1.53	1.95
St x N ₁₀₀	1.60	1.39	1.82
NSt x N ₀	1.14	1.39	2.18
NSt x N ₅₀	1.13	1.40	2.31
NSt x N ₁₀₀	1.13	1.21	2.08
S ₁ x N ₀	1.50	1.06	1.89
S ₁ x N ₅₀	1.55	1.25	1.82
S ₁ x N ₁₀₀	1.62	1.17	1.68
S ₂ x N ₀	1.31	1.44	2.23
S ₂ x N ₅₀	1.18	1.68	2.44
S ₂ x N ₁₀₀	1.11	1.43	2.22
N ₀ x P ₀	1.27	1.33	2.14
N ₀ x P ₅₀	1.54	1.17	1.98
N ₅₀ x P ₀	1.40	1.49	2.16
N ₅₀ x P ₅₀	1.32	1.43	2.10
N ₁₀₀ x P ₀	1.45	1.17	2.21
N ₁₀₀ x P ₅₀	1.28	1.43	1.69
SE	0.06	0.05	0.05
CD	0.17	0.15	0.15

available Cu content were recorded for added P level at all the three stages of crop growth.

v) N levels: The mean value for this main effect ranged from 1.25 to 2.13 ppm. The N application at 50 kg level increased the available copper content at 60 days and 90 days of crop growth and there was no significant difference at 30 days of crop growth.

Interaction effects

At 30th day, the interactions viz., Rh x N and S x N showed statistical significance wherein availability of Cu was reduced due to N application in the rhizosphere soil while N application in the black soil increased the same.

At 60th day, the interactions viz., St x Rh, St x P, Rh x S and P x N showed statistical significance. The salient points of inferences drawn are: (i) the availability of Cu was more in the rhizosphere soil than that in the non-rhizosphere soil due to sterilized condition while under non-sterilized condition, it was distinctly more in the non-rhizosphere soil than that in the rhizosphere soil (ii) availability of Cu was increased only under sterilized condition due to P addition; (iii) availability of Cu was more in the rhizosphere soil and in the black soil while in

the red soil similar trend as that of main effect was observed; and (iv) at added P level, availability of Cu was more due to N addition at two levels than at N_0 level.

At 90th day, the interactions viz., St x Rh, St x P, Rh x N, S x P and P x N were significant. The salient inferences drawn are: i) as against the main effect, availability of Cu was decreased under the sterilized condition of the soil, irrespective of rhizosphere or non-rhizosphere soil and P application; ii) N application particularly at 100 kg level increased Cu availability in the rhizosphere soil; iii) due to P addition available Cu was reduced in both the soils; and iv) Cu availability was reduced by the combined application of P with N at higher level.

4.4.2.4. Effect on available Zn (Table 9)

Individual effects

i) Rhizosphere: The mean value for this main effect ranged from 0.31 to 2.06 ppm. The rhizosphere soil showed significantly higher accumulation of available Zn at 30 days of crop growth and the trend got reversed at 90 days stages. At 60 days of crop growth, there was no significant differences between rhizosphere and non-rhizosphere soils.

ii) Sterilization: The mean value for this main effect ranged from 0.37 to 1.94 ppm. Under sterilized condition of the soil enhanced concentration of available Zn was recorded at 30 and 90 days, but at 60 days stage, there was no significant difference between sterilized and normal soils.

iii) Soil types: The mean value for this main effect ranged from 0.35 to 1.70 ppm. The red soil registered higher accumulation of available Zn at all the three stages of crop growth.

iv) P levels: The mean value for the main effect fell within the range of 0.39 to 1.52 ppm. The beneficial effect of P application in enhancing the available zinc content was significantly visible only at 60 days of crop growth and the effect of P application was not observed at 30 and 90 days of crop growth.

v) N levels: The mean value for this main effect ranged from 0.38 to 1.58 ppm. N₅₀ level enhanced the available Zn content only at 90 days of crop growth, but significant differences were not observed due to N application at two levels at 30 and 60 days of crop growth. The effect of N in increasing the availability of Zn was observed only at later stages of crop growth.

TABLE 9. EFFECT OF TREATMENTS ON AVAILABLE Zn IN RHIZOSPHERE AND
NON-RHIZOSPHERE REGIONS OF SORGHUM IN BLACK AND RED SOILS (ppm)

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Treatments (1)	30 days (2)	60 days (3)	90 days (4)
Rh	0.50	1.30	0.90
NRh	0.31	1.27	2.06
St	0.44	1.22	1.94
NSt	0.37	1.34	1.02
S ₁	0.35	0.97	1.26
S ₂	0.46	1.60	1.70
P ₀	0.39	1.20	1.44
P ₅₀	0.42	1.37	1.52
SE	0.02	0.05	0.06
CD	0.05	0.13	0.18
N ₀	0.42	1.28	1.38
N ₅₀	0.42	1.38	1.58
N ₁₀₀	0.38	1.20	1.48
SE	0.02	0.06	0.08
CD	0.06	0.16	0.22
Rh x St	0.58	1.51	1.42
Rh x NSt	0.43	1.08	0.38
NRh x St	0.31	0.94	2.46
NRh x NSt	0.30	1.61	1.67
Rh x S ₁	0.45	1.03	0.81
Rh x S ₂	0.55	1.57	1.00
NRh x S ₁	0.25	0.92	1.71
NRh x S ₂	0.36	1.62	2.41
Rh x P ₀	0.49	1.21	0.90
Rh x P ₅₀	0.52	1.38	0.90
NRh x P ₀	0.30	1.19	1.97
NRh x P ₅₀	0.31	1.35	2.15
St x S ₁	0.41	0.96	1.98
St x S ₂	0.48	1.49	1.90
NSt x S ₁	0.30	0.98	0.54
NSt x S ₂	0.43	1.71	1.51

Contd.,

(1)	(2)	(3)	(4)
St x P ₀	0.38	0.94	1.97
St x P ₅₀	0.51	1.51	1.91
NSt x P ₀	0.41	1.47	0.90
NSt x P ₅₀	0.32	1.22	1.14
S ₁ x P ₀	0.34	0.79	1.26
S ₁ x P ₅₀	0.45	1.16	1.25
S ₂ x P ₀	0.37	1.62	1.61
S ₂ x P ₅₀	0.46	1.58	1.79
SE	0.02	0.07	0.09
CD	0.06	0.19	0.25
Rh x N ₀	0.44	1.29	0.81
Rh x N ₅₀	0.58	1.45	1.08
Rh x N ₁₀₀	0.49	1.16	0.80
NRh x N ₀	0.40	1.27	1.96
NRh x N ₅₀	0.26	1.30	2.08
NRh x N ₁₀₀	0.26	1.24	2.15
St x N ₀	0.51	1.56	1.88
St x N ₅₀	0.48	1.12	2.10
St x N ₁₀₀	0.34	1.00	1.83
NSt x N ₀	0.33	1.00	0.89
NSt x N ₅₀	0.36	1.63	1.06
NSt x N ₁₀₀	0.41	1.41	1.12
S ₁ x N ₀	0.30	0.82	1.31
S ₁ x N ₅₀	0.41	1.12	1.36
S ₁ x N ₁₀₀	0.35	0.98	1.11
S ₂ x N ₀	0.54	1.74	1.45
S ₂ x N ₅₀	0.43	1.63	1.81
S ₂ x N ₁₀₀	0.40	1.42	1.84
N ₀ x P ₀	0.43	1.23	1.57
N ₀ x P ₅₀	0.41	1.32	1.19
N ₅₀ x P ₀	0.40	1.25	1.54
N ₅₀ x P ₅₀	0.44	1.50	1.63
N ₁₀₀ x P ₀	0.36	1.13	1.20
N ₁₀₀ x P ₅₀	0.39	1.28	1.75
SE	0.03	0.08	0.11
CD	0.08	0.23	0.31

Interaction effects

At 30th day, the interactions viz., St x P, St x N, Rh x N and S x N were significant. The important inferences drawn are: (i) P addition had a positive effect on Zn availability only under sterilized condition and it caused reduction under non-sterilized condition and the sterilized condition of the soil proved to be beneficial on Zn availability only at N_0 and N_{50} levels; (ii) Zn availability was more in the rhizosphere soil than that in the non-rhizosphere soil under all levels of added N; and (iii) the differences in Zn availability that existed between the red and black soils in the absence of added N, got nullified due to N addition.

At 60th day, among the different interactions, the interactions viz., St x P, St x N, S x P and S x N showed marked variations similar to that of the trend observed at 30th day. The salient inferences drawn are: (i) Zn availability was increased due to P fertilization under sterilized condition, but it was more under non-sterilized condition at N_{50} level; (ii) P application had a positive influence only in the black soil; and (iii) similarly N application at 50 kg level exhibited a positive effect on Zn availability in the black soil while the trend got reversed in the red soil.

At 90th day, the important inferences from the interactions include are: (i) Zn availability was more in the red soil than that in the black soil due to N addition at both the levels; and (ii) the beneficial effect of P addition on Zn availability was felt at N_{100} level, but at N_0 level P application reduced Zn availability.

4.5. Effect on transformation of N, P and K in soils

4.5.1. Effect on N transformation (Fig.6)

4.5.1.1. Ammoniacal-N (NH_4 -N) (Table 10)

Individual effects

i) Rhizosphere: The mean value of NH_4 -N content ranged from 6.9 to 59.9 ppm. At 30th day, the rhizosphere soil was found to contain significantly higher amount of NH_4 -N (33.0 ppm) than the non-rhizosphere soil (14.9 ppm). At 60th day, more NH_4 -N accumulation was observed in the non-rhizosphere soil (59.6 ppm) than that in the rhizosphere soil (33.8 ppm). However with advancement in time i.e., at 90th day the trend was reversed with considerable reduction in either case.

ii) Sterilization: The mean NH_4 -N content ranged from 7.3 to 51.2 ppm during different growth stages. For any stage, the effect of sterilization resulted in reduced

TABLE 10. EFFECT OF TREATMENTS ON $\text{NH}_4\text{-N}$ IN RHIZOSPHERE AND NON-RHIZOSPHERE
REGIONS OF SORGHUM IN BLACK AND RED SOILS (ppm)

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Treatments (1)	30 days (2)	60 days (3)	90 days (4)
Rh	33.0	33.8	10.4
NRh	14.9	59.6	6.9
St	21.3	42.2	7.3
NSt	26.6	51.2	10.0
S ₁	25.7	42.9	7.1
S ₂	22.2	50.5	10.2
P ₀	26.5	53.5	9.3
P ₅₀	21.4	39.9	8.0
SE	1.3	2.0	0.5
CD	3.6	5.6	1.5
N ₀	24.1	44.7	7.7
N ₅₀	23.9	45.1	9.0
N ₁₀₀	23.8	50.3	9.3
SE	1.6	2.4	0.6
CD	4.4	6.8	1.8
Rh x St	36.1	36.5	7.1
Rh x NSt	29.9	31.2	13.7
NRh x St	6.4	65.8	7.6
NRh x NSt	23.4	53.3	6.2
Rh x S ₁	35.5	27.5	7.7
Rh x S ₂	30.6	40.2	13.1
NRh x S ₁	16.0	58.4	6.5
NRh x S ₂	15.7	60.7	7.3
Rh x P ₀	37.7	41.8	12.4
Rh x P ₅₀	28.4	25.9	8.4
NRh x P ₀	15.4	65.2	6.1
NRh x P ₅₀	14.4	53.9	7.6
St x S ₁	22.0	42.3	6.3
St x S ₂	20.5	60.0	8.3
NSt x S ₁	29.4	43.6	7.8
NSt x S ₂	23.9	40.9	12.1

Contd.,

(1)	(2)	(3)	(4)
St x P ₀	24.5	57.0	6.4
St x P ₅₀	17.9	45.3	8.2
NSt x P ₀	28.5	50.0	12.2
NSt x P ₅₀	24.8	34.5	7.8
S ₁ x P ₀	28.4	45.7	6.6
S ₁ x P ₅₀	23.1	40.2	7.6
S ₂ x P ₀	24.7	61.3	12.0
S ₂ x P ₅₀	19.6	39.6	8.4
SE	1.8	2.8	0.7
CD	5.1	7.9	2.1
Rh x N ₀	34.3	31.5	9.9
Rh x N ₅₀	33.5	35.2	10.5
Rh x N ₁₀₀	31.2	34.8	10.8
NRh x N ₀	13.9	57.8	5.5
NRh x N ₅₀	14.3	55.0	7.4
NRh x N ₁₀₀	16.4	65.8	7.7
St x N ₀	25.7	47.4	6.6
St x N ₅₀	19.6	49.0	7.4
St x N ₁₀₀	18.4	57.0	7.9
NSt x N ₀	22.4	41.9	8.8
NSt x N ₅₀	28.2	41.2	10.5
NSt x N ₁₀₀	29.3	43.6	10.6
S ₁ x N ₀	22.3	44.6	6.3
S ₁ x N ₅₀	25.5	43.8	7.8
S ₁ x N ₁₀₀	29.4	40.5	7.1
S ₂ x N ₀	25.9	44.8	9.1
S ₂ x N ₅₀	22.3	46.4	10.1
S ₂ x N ₁₀₀	18.2	60.2	11.4
N ₀ x P ₀	27.2	48.9	9.7
N ₀ x P ₅₀	21.0	40.5	5.7
N ₅₀ x P ₀	26.7	50.7	8.3
N ₅₀ x P ₅₀	26.7	39.5	9.6
N ₁₀₀ x P ₀	25.7	60.9	9.8
N ₁₀₀ x P ₅₀	21.9	39.8	8.7
SE	2.2	3.4	0.9
CD	6.2	9.7	2.6

accumulation of $\text{NH}_4\text{-N}$ content. But at 60th day, there was greater accumulation of $\text{NH}_4\text{-N}$ content under non-sterilized condition than that at two other stages.

iii) Soil types: Soil types had no significant differential influence on $\text{NH}_4\text{-N}$ content during the 30th day of crop growth. However, significant differences were noticed during later stages. In either case in the red soil, accumulation of $\text{NH}_4\text{-N}$ was high, when compared to the black soil. The mean value for the main effect observed were 25.7 and 22.2 ppm during 30th day, 42.9 and 50.5 ppm during 60th day; and 7.1 and 10.2 ppm for 90th day for the black and the red soil respectively. It is appropriate to mention here that there was enhanced accumulation of $\text{NH}_4\text{-N}$ with progress in growth in both the soil types at 60 days. With further progress in growth, the status of $\text{NH}_4\text{-N}$ showed a pronounced decrease.

iv) P levels: The status of $\text{NH}_4\text{-N}$ was found to be significantly influenced by the P levels. At all stages of crop growth, the addition of P was associated with significantly reduced accumulation of $\text{NH}_4\text{-N}$ in the soil.

v) N levels: The status of $\text{NH}_4\text{-N}$ concentration was found to be not appreciably influenced by N levels as

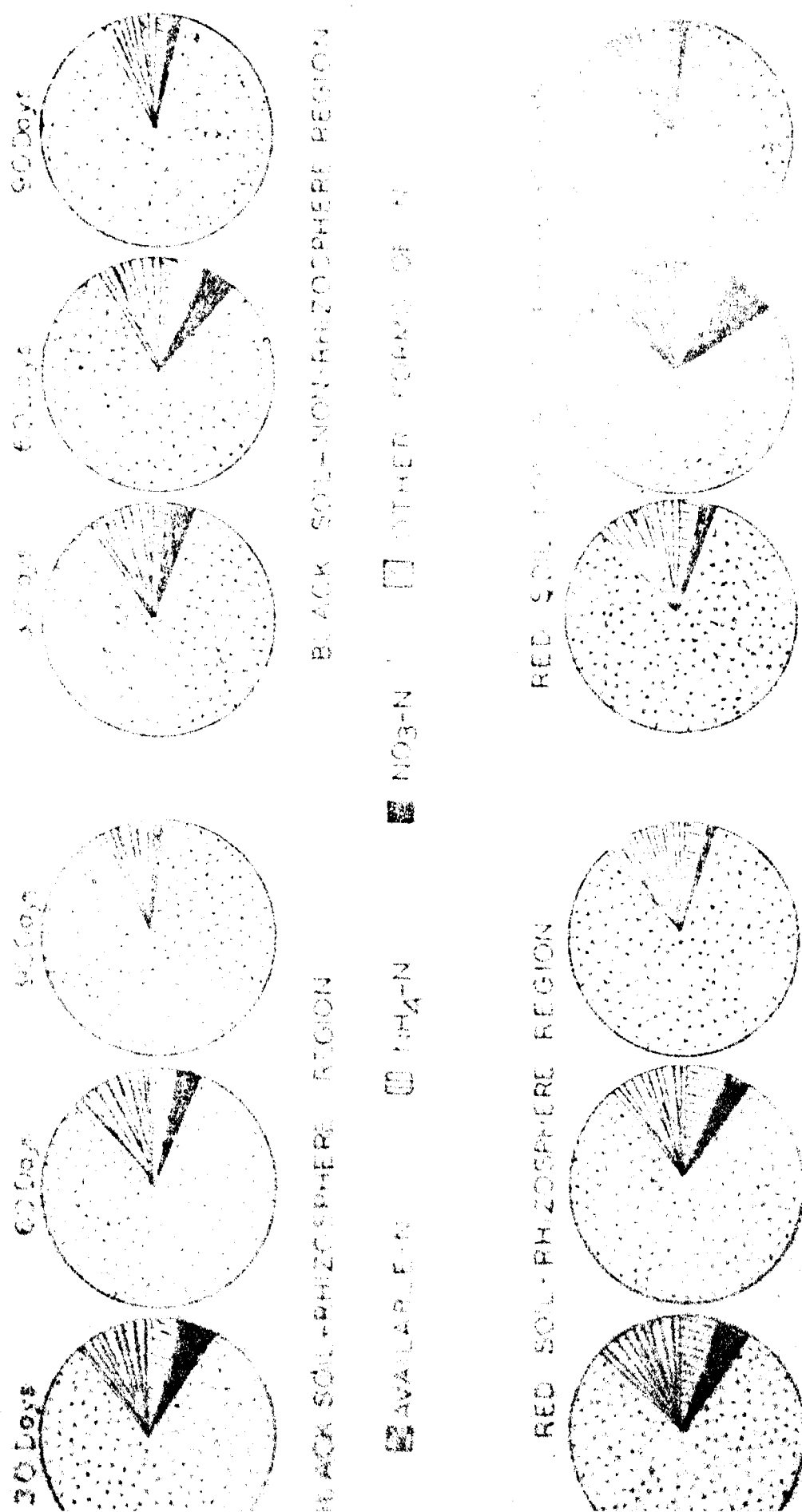


FIG. 6 DIFFERENT FORMS OF N AS INFLUENCED BY RHIZOSPHERE AND SOIL TYPES AT DIFFERENT STAGES OF CROP GROWTH

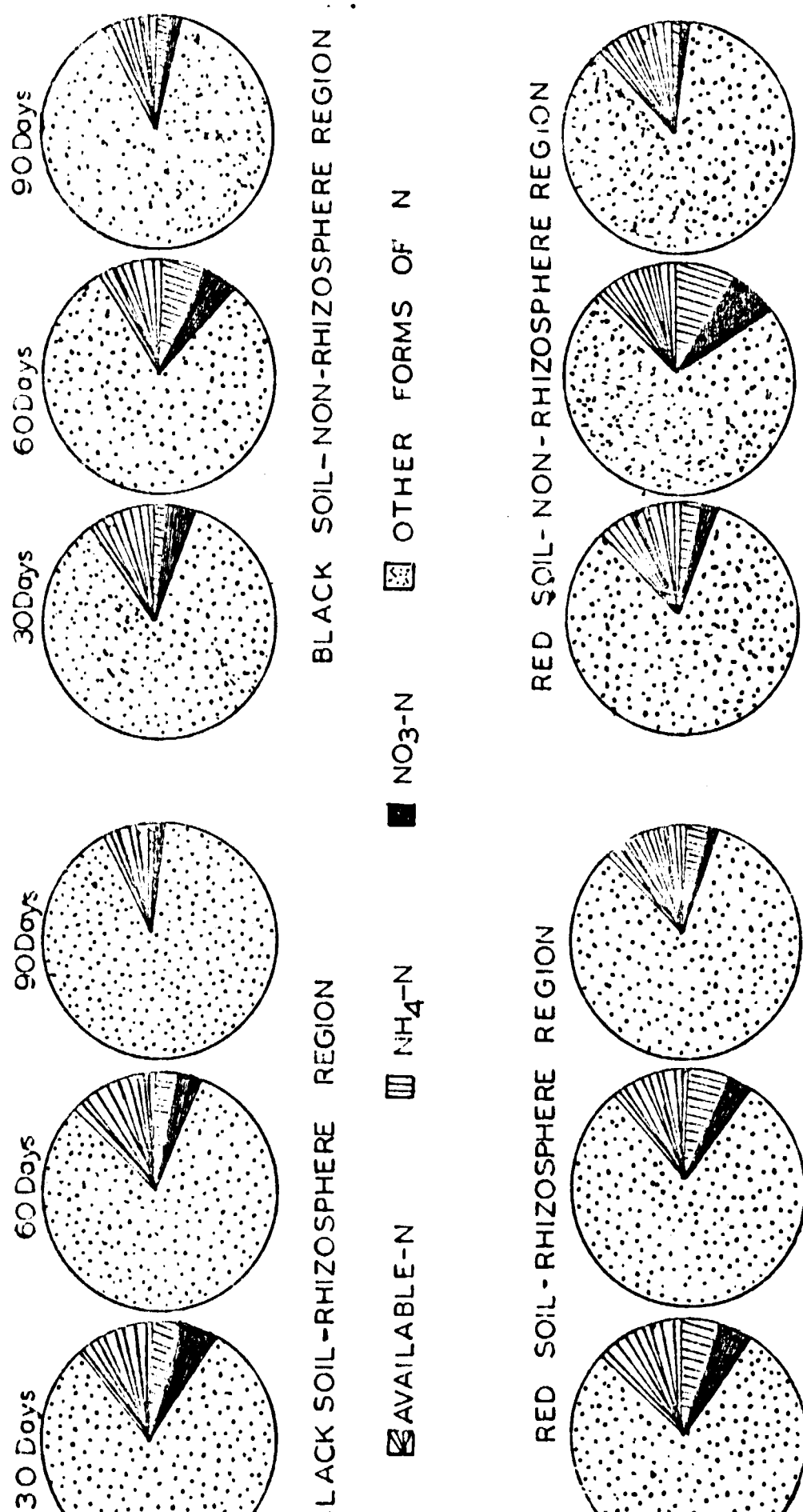


FIG.6 DIFFERENT FORMS OF N AS INFLUENCED BY RHIZOSPHERE AND SOIL TYPES AT DIFFERENT STAGES OF CROP GROWTH

evidenced by the mean values ranging from 23.8 to 24.1 ppm at 30th day; 44.7 to 50.3 ppm at 60th day and 7.7 to 9.3 ppm at 90th day. However, under all levels of N, there was enhanced accumulation of $\text{NH}_4\text{-N}$ at 60th day as compared to other stages.

Interaction effects

At 30th day, the interaction effects viz., St x Rh, St x N, Rh x P and S x N showed statistical significance. The important inferences drawn are: (i) in the rhizosphere soil under sterilized condition of the soil more $\text{NH}_4\text{-N}$ content was exhibited than that under non-sterilized condition and this effect was found to be reversed in the non-rhizosphere soil; (ii) N_{100} level registered increased values of $\text{NH}_4\text{-N}$ content whereas N_{50} and N_0 levels were on par; under sterilized condition, N_0 level recorded higher values of $\text{NH}_4\text{-N}$ content than N_{50} and N_{100} levels in both the soil types; (iii) at N_0 level, $\text{NH}_4\text{-N}$ contents under sterilized and non-sterilized conditions were on par while at N_{50} at N_{100} levels under non-sterilized condition of the soil higher amount of $\text{NH}_4\text{-N}$ content was recorded than that under sterilized condition; (iv) in the presence of P application, the rhizosphere soil had greater accumulation of $\text{NH}_4\text{-N}$ content than the non-rhizosphere soil and (v) $\text{NH}_4\text{-N}$ content increased with the levels of N in the black soil though all the levels were on par; and at N_{50} and N_{100} levels, the black soil registered higher amount of $\text{NH}_4\text{-N}$ content than the red soil.

At 60th day stage, the interactions viz., S x P and S x N showed statistical significance. The S x N interaction showed the same trend as that observed at 30th day; at P_0 level, the red soil recorded higher NH_4 -N content than at P_{50} level.

At 90th day, the interactions viz., St x P, Rh x S, Rh x P, S x P and P x N revealed statistical significance. The salient inferences drawn are: (i) at P_0 level more NH_4 -N content got accumulated under non-sterilized condition than at P_{50} level; (ii) in the absence of added P, the rhizosphere soil contained more NH_4 -N than non-rhizosphere soil and this effect vanished with added P; (iii) the differential accumulation of NH_4 -N content was confined to no P application; and (iv) the NH_4 -N content was not influenced due to N application at P_0 level whereas at P_{50} level, N_{50} and N_{100} levels resulted in higher NH_4 -N content than N_0 level; at N_0 level, P_0 level resulted in higher NH_4 -N content than at P_{50} level whereas the other two N levels did not increase the NH_4 -N content.

4.5.1.2. Nitrate -N (NO_3 -N) (Table 11)

Individual effects

i) Rhizosphere: The mean value for the main effect ranged from 2.9 to 47.3 ppm. The amount of NO_3 -N accumulation

in the rhizosphere soil was considerably more at 30 and 60 days stage but such effect was not obtained at 90 days stage.

ii) Sterilization: The mean value for this main effect ranged from 2.7 to 47.5 ppm. The sterilized condition accounted for significantly low $\text{NO}_3\text{-N}$ accumulation during the earlier stages of crop growth, but near about the harvest, such a difference was not observed. This implied that the effect of sterilization was only temporary and very soon the soil behaved as that of normal soil. In other words, the soil provided a medium very conducive for microbial growth and any attempt to sterilize could cause only a temporary cessation and the microflora build up occurred soon. This was reflected in $\text{NO}_3\text{-N}$ accumulation and in the present study irrespective of sterilization on par concentrations of $\text{NO}_3\text{-N}$ were noticed at harvest stage.

iii) Soil types: The $\text{NO}_3\text{-N}$ content was significantly higher in the black soil at 60 days stage, but this trend got reversed at 90 days stage. The mean value observed were 2.2 to 47.3 ppm. The $\text{NO}_3\text{-N}$ content got enhanced markedly at 60 days stage, but at 90th day, it was reduced to very low values of 2 to 3 ppm.

iv) P levels: During the initial stages of crop growth, the application of P significantly depressed the $\text{NO}_3\text{-N}$ content but at advanced growth stages i.e., at 60 and 90 days stages, the presence of P was more conducive for $\text{NO}_3\text{-N}$ accumulation.

TABLE 11. EFFECT OF TREATMENTS ON $\text{NO}_3\text{-N}$ IN RHIZOSPHERE AND NON-RHIZOSPHERE REGIONS OF SORGHUM IN BLACK AND RED SOILS (ppm)

Treatments (1)	30 days (2)	60 days (3)	90 days (4)
Rh	41.8	47.3	2.9
NRh	25.1	26.9	3.1
St	29.6	26.7	2.7
NSt	37.3	47.5	3.3
S_1	42.2	42.4	2.2
S_2	24.7	47.3	3.7
P_0	39.9	41.9	2.7
P_{50}	27.0	32.3	3.3
SE	1.4	1.0	0.2
CD	4.0	2.8	0.7
N_0	34.7	36.9	2.7
N_{50}	32.1	38.5	4.0
N_{100}	33.5	35.8	2.3
SE	1.7	1.2	0.3
CD	4.9	3.4	0.8
Rh x St	54.1	33.1	2.4
Rh x NSt	29.6	20.7	3.3
NRh x St	5.1	61.8	2.9
NRh x NSt	45.0	32.8	3.3
Rh x S_1	49.4	31.8	2.1
Rh x S_2	34.3	22.0	3.6
NRh x S_1	35.1	53.1	2.3
NRh x S_2	15.0	41.4	3.9
Rh x P_0	50.2	31.3	2.4
Rh x P_{50}	33.5	22.5	3.3
NRh x P_0	29.6	52.4	3.0
NRh x P_{50}	20.6	42.1	3.2
St x S_1	33.3	48.6	1.6
St x S_2	25.9	46.3	3.7
NSt x S_1	51.1	36.3	2.8
NSt x S_2	23.4	17.1	3.8

Contd.,

(1)	(2)	(3)	(4)
St x P ₀	36.2	51.4	2.2
St x P ₅₀	23.0	43.5	3.1
NSt x P ₀	43.6	32.3	3.2
NSt x P ₅₀	31.0	21.2	3.5
S ₁ x P ₀	46.9	51.4	2.1
S ₁ x P ₅₀	37.6	43.5	2.3
S ₂ x P ₀	32.9	32.3	3.2
S ₂ x P ₅₀	16.5	21.2	4.2
SE	2.0	1.0	0.3
CD	5.6	2.8	0.9
Rh x N ₀	49.8	28.5	2.6
Rh x N ₅₀	33.2	24.8	3.8
Rh x N ₁₀₀	42.4	27.4	2.2
NRh x N ₀	19.6	45.3	2.7
NRh x N ₅₀	31.0	52.2	4.2
NRh x N ₁₀₀	24.6	44.3	2.4
St x N ₀	36.8	44.5	2.7
St x N ₅₀	20.4	50.2	2.8
St x N ₁₀₀	31.5	47.7	2.5
NSt x N ₀	32.6	29.4	2.6
NSt x N ₅₀	43.9	26.8	5.3
NSt x N ₁₀₀	35.4	24.0	2.1
S ₁ x N ₀	37.2	36.9	1.9
S ₁ x N ₅₀	45.7	45.7	2.7
S ₁ x N ₁₀₀	43.8	44.7	2.0
S ₂ x N ₀	32.2	36.9	2.4
S ₂ x N ₅₀	18.6	31.2	5.3
S ₂ x N ₁₀₀	23.1	27.0	2.5
N ₀ x P ₀	46.2	42.2	2.1
N ₀ x P ₅₀	23.2	31.5	3.2
N ₅₀ x P ₀	35.0	44.2	3.6
N ₅₀ x P ₅₀	29.3	32.8	4.4
N ₁₀₀ x P ₀	38.4	39.1	2.3
N ₁₀₀ x P ₅₀	28.5	32.5	2.2
SE	2.4	1.7	0.4
CD	6.9	4.8	1.12

v) N levels: The N levels brought about an appreciable difference in the $\text{NO}_3\text{-N}$ content for any given stage of crop growth. However it may be noted that the amount of $\text{NO}_3\text{-N}$ content of 34.7 ppm at 30 days got reduced to 2.7 ppm at 90th day indicating the unstable nature and greater losses associated with nitrate form of nitrogen.

Interaction effects

At 30th day, the interactions viz., St x S, St x N, St x Rh, S x N and P x N showed statistical significance. The important inferences emanating from the above interactions are: (i) sterilized condition made no difference in the red soil; (ii) in the absence of any added N, again the sterilized condition showed no differential influence; (iii) the sterilized condition caused enhanced $\text{NO}_3\text{-N}$ accumulation in the rhizosphere soil; (iv) in the absence of any added N, P addition diminished the $\text{NO}_3\text{-N}$ content; and (v) in the absence of any added N, both the soils recorded on par concentration of $\text{NO}_3\text{-N}$.

At 60th day, the various interaction viz., St x Rh, St x S, St x N, Rh x N and S x N revealed statistical significance. The salient points from the above interactions are: (i) irrespective of sterilized condition, the rhizosphere soil contained more $\text{NO}_3\text{-N}$ content than the non-

rhizosphere soil; (ii) under sterilized condition greater accumulation of $\text{NO}_3\text{-N}$ content was favoured in both the soil types; (iii) whether N was added or not, the sterilized condition caused greater accumulation; (iv) for any level of N, the rhizosphere soil carried higher amounts of $\text{NO}_3\text{-N}$ content; and (v) in the absence of any added N, the red soil was associated with more $\text{NO}_3\text{-N}$ and the effect was found to be reversed with the addition of N.

At 90th day, S x N interaction alone revealed statistical significance. At N_0 and N_{50} levels, more $\text{NO}_3\text{-N}$ accumulated in the red soil and the difference got nullified at N_{100} level between the two soil types.

4.5.2. Effect on P transformation (Fig. 7)

4.5.2.1. Saloid-bound P (Table 12)

Individual effects

i) Rhizosphere: The mean values for this main effect ranged from 3.13 to 4.84 ppm for rhizosphere soil and from 2.59 to 9.65 ppm for non-rhizosphere region. The non rhizosphere soil relatively contained more saloid-bound P than the rhizosphere soil the trend was reversed at 90th day.

TABLE 12. EFFECT OF TREATMENTS ON SALOID-BOUND P IN RHIZOSPHERE AND NON-RHIZOSPHERE REGIONS OF SORGHUM IN BLACK AND RED SOILS (ppm)

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Treatments (1)	30 days (2)	60 days (3)	90 days (4)
Rh	4.84	4.34	3.13
NRh	9.65	4.06	2.59
St	7.95	4.58	2.60
NSt	6.54	3.82	3.12
S ₁	5.20	3.17	2.19
S ₂	9.28	5.23	3.53
P ₀	6.80	3.61	2.83
P ₅₀	7.69	4.79	2.89
SE	0.34	0.04	0.017
CD	0.97	0.11	0.049
N ₀	7.93	3.98	2.68
N ₅₀	7.22	4.42	2.88
N ₁₀₀	6.58	4.20	3.01
SE	0.42	0.048	0.021
CD	1.19	0.14	0.060
Rh x St	4.98	4.72	2.63
Rh x NSt	4.69	3.96	3.62
NRh x St	10.92	3.67	2.56
NRh x NSt	8.38	4.45	2.62
Rh x S ₁	3.94	3.29	2.47
Rh x S ₂	5.74	5.39	3.79
NRh x S ₁	6.47	3.04	1.91
NRh x S ₂	12.83	5.08	3.27
Rh x P ₀	4.27	3.77	3.09
Rh x P ₅₀	5.40	4.91	3.17
NRh x P ₀	9.33	3.45	2.58
NRh x P ₅₀	9.97	4.66	2.60
St x S ₁	3.82	2.41	1.92
St x S ₂	12.08	5.25	3.27
NSt x S ₁	6.59	3.92	2.45
NSt x S ₂	6.49	5.25	3.79

(1)	(2)	(3)	(4)
St x P ₀	6.08	2.64	2.52
St x P ₅₀	9.82	4.99	2.67
NSt x P ₀	7.51	4.58	3.14
NSt x P ₅₀	5.56	4.58	3.10
S ₁ x P ₀	4.63	2.47	1.76
S ₁ x P ₅₀	5.78	3.86	2.62
S ₂ x P ₀	8.97	4.75	3.91
S ₂ x P ₅₀	9.60	5.72	3.15
SE	0.48	0.056	0.024
CD	0.37	0.14	0.069
Rh x N ₀	5.43	4.16	2.91
Rh x N ₅₀	4.49	4.60	3.17
Rh x N ₁₀₀	4.59	4.27	3.31
NRh x N ₀	10.43	3.80	2.45
NRh x N ₅₀	9.94	4.25	2.60
NRh x N ₁₀₀	8.57	4.12	2.71
St x N ₀	8.51	3.59	2.39
St x N ₅₀	8.45	4.22	2.64
St x N ₁₀₀	6.89	3.64	2.76
NSt x N ₀	7.35	4.37	2.98
NSt x N ₅₀	5.98	4.62	3.13
NSt x N ₁₀₀	6.28	4.76	3.26
S ₁ x N ₀	5.42	3.09	2.02
S ₁ x N ₅₀	5.41	3.32	2.25
S ₁ x N ₁₀₀	4.78	3.09	2.30
S ₂ x N ₀	10.44	4.88	3.35
S ₂ x N ₅₀	9.03	5.52	3.52
S ₂ x N ₁₀₀	8.39	5.30	3.72
N ₀ x P ₀	7.00	3.23	2.66
N ₀ x P ₅₀	8.86	4.73	2.71
N ₅₀ x P ₀	6.47	3.90	2.88
N ₅₀ x P ₅₀	7.97	4.95	2.89
N ₁₀₀ x P ₀	6.92	3.71	2.96
N ₁₀₀ x P ₅₀	6.24	4.68	3.06
SE	0.59	0.074	0.03
CD	1.68	0.19	0.08

ii) Sterilization: The mean value for the main effect ranged from 2.60 to 7.95 ppm. The sterilization process tended to enhance saloid-bound P. At 90th day, the non-sterilized condition showed higher amounts of saloid-bound P.

iii) Soil types: The amount of saloid-bound P ranged from 2.19 to 9.28 ppm and during all the three stages, the red soil was associated with significantly higher amounts of saloid-bound P.

iv) P levels: The mean value for this main effect ranged from 2.83 ppm to 7.69 ppm. Phosphrous application enhanced the saloid-P contnt in the soil at 60 days of crop growth period.

v) N levels: During the initial stages, much of the phosphorus remained in solution as evidenced by the control recording more saloid-bound P over those which received P application. But this effect was reversed during the subsequent stages owing to better opportunities for the reactions involving P. At 90th day, increasing N addition was associated with increased saloid-bound P.

Interaction effects

At 30th day, the interactions St x Rh, St x S and St x P were found to be statistically significant. The

important inferences deduced are: (i) the sterilization effect in increasing the saloid-bound P was confined to the non-rhizosphere soil; (ii) the sterilized condition enhanced the saloid-bound P in the red soil while the reverse was true in the black soil; and (iii) the effect of sterilization was more pronounced in the presence of added P.

At 60th day, St x S, St x P, S x P, S x N and P x N interactions were associated with statistical significance indicating the following important inferences: (i) the effect of sterilization in diminishing the saloid-bound P was confined to black soil; (ii) under non-sterilized condition both the P levels recorded on par content of saloid-bound P; (iii) whether it be red soil or black soil, the addition of P enhanced the saloid-bound P; (iv) in both the soil types, N₅₀ level was associated with enhanced saloid-bound P over other N levels; and (v) for any given level of N, added P favoured greater accumulation of saloid-bound P.

At 90th day, the interactions viz., St x Rh, St x P, S x P and S x N were associated with statistical significance. These interactions revealed the following inferences: (i) both under sterilized and non-sterilized conditions of the soil, the rhizosphere soil carried more saloid-bound P; (ii) the addition of P in enhancing the saloid-bound P was confined to the sterilized condition;

(iii) the tendency of P addition to enhance the saloid-bound P was more pronounced in the black soil and the effect was reversed in the red soil; and (iv) for any given level of N, the red soil was associated with more saloid-bound P over the black soil.

4.5.2.2. Aluminium phosphate (Al-P); (Table 13)

Individual effects

i) Rhizosphere: The mean value of Al-P for this effect ranged from 3.50 to 4.63 ppm. At all the three stages of crop growth, the rhizosphere soil accounted for more Al-P than non-rhizosphere soil.

ii) Sterilization: The mean value of Al-P for this main effect fell within the range of 3.40 to 4.49 ppm and at all the three stages of crop growth, the sterilized condition favoured more Al-P content than the normal soil.

iii) Soil types: The mean value of Al-P for this main effect remained within the range of 3.15 to 4.93 ppm. During all the three stages, the black soil was associated with greater amounts of Al-P than the red soil.

iv) P levels: The mean value showed a range of 3.49 to 4.31 ppm. Though the added P had no effect at 30 days of crop growth, at 90 days of crop growth P application increased the Al-P content in the soil. At 60 days, P_{50} and P_{100} levels were on par.

TABLE 13. EFFECT OF TREATMENTS ON Al-P IN RHIZOSPHERE AND NON-RHIZOSPHERE REGIONS OF SORGHUM IN BLACK AND RED SOILS (ppm)

Treatments (1)	30 days (2)	60 days (3)	90 days (4)
Rh	4.63	4.38	3.67
NRh	3.90	4.14	3.50
St	4.49	4.31	3.76
NSt	4.03	4.21	3.40
S ₁	4.85	4.93	4.01
S ₂	3.67	3.59	3.15
P ₀	4.31	4.24	3.49
P ₅₀	4.21	4.28	3.68
SE	0.06	0.04	0.02
CD	0.17	0.11	0.05
N ₀	4.67	4.31	3.70
N ₅₀	4.22	4.17	3.47
N ₁₀₀	3.89	4.30	3.57
SE	0.07	0.05	0.02
CD	0.20	0.14	0.06
Rh x St	4.69	4.45	3.84
Rh x NSt	4.57	4.30	3.50
NRh x St	4.30	4.16	3.69
NRh x NSt	3.49	4.12	3.30
Rh x S ₁	5.23	5.06	4.08
Rh x S ₂	4.02	3.69	3.25
NRh x S ₁	4.48	4.80	3.94
NRh x S ₂	3.31	3.48	3.06
Rh x P ₀	4.62	4.38	3.58
Rh x P ₅₀	4.63	4.38	3.76
NRh x P ₀	4.00	4.10	3.40
NRh x P ₅₀	3.79	4.18	3.60
St x S ₁	5.13	4.92	3.99
St x S ₂	3.85	3.69	3.54
NSt x S ₁	4.57	4.94	4.04
NSt x S ₂	3.49	3.48	2.77

Contd.,

(1)	(2)	(3)	(4)
St x P ₀	4.47	4.25	3.79
St x P ₅₀	4.52	4.36	3.74
NSt x P ₀	4.15	4.22	3.19
NSt x P ₅₀	3.91	4.21	3.61
S ₁ x P ₀	5.11	4.96	3.88
S ₁ x P ₅₀	4.60	4.90	4.14
S ₂ x P ₀	3.51	3.52	3.09
S ₂ x P ₅₀	3.82	3.66	3.22
SE	0.08	0.04	0.03
CD	0.23	0.11	0.07
Rh x N ₀	5.04	4.40	3.76
Rh x N ₅₀	4.61	4.32	3.58
Rh x N ₁₀₀	4.23	4.42	3.66
NRh x N ₀	4.31	4.21	3.64
NRh x N ₅₀	3.82	4.03	3.37
NRh x N ₁₀₀	3.55	4.17	3.49
St x N ₀	4.92	4.64	4.15
St x N ₅₀	4.30	4.18	3.65
St x N ₁₀₀	4.25	4.09	3.49
NSt x N ₀	4.43	3.97	3.25
NSt x N ₅₀	4.13	4.17	3.30
NSt x N ₁₀₀	3.53	4.50	3.65
S ₁ x N ₀	5.82	5.29	4.33
S ₁ x N ₅₀	4.64	4.65	3.76
S ₁ x N ₁₀₀	4.10	4.85	3.94
S ₂ x N ₀	3.53	3.32	3.07
S ₂ x N ₅₀	3.79	3.70	3.18
S ₂ x N ₁₀₀	3.68	3.74	3.21
N ₀ x P ₀	4.74	4.43	3.53
N ₀ x P ₅₀	4.61	4.18	3.88
N ₅₀ x P ₀	4.14	4.08	3.41
N ₅₀ x P ₅₀	4.30	4.27	3.53
N ₁₀₀ x P ₀	4.06	4.20	3.52
N ₁₀₀ x P ₅₀	3.72	4.39	3.63
SE	0.10	0.07	0.03
CD	0.29	0.19	0.09

v) N levels: The mean value ranged from 3.47 to 4.67 ppm and nitrogen additions tended to diminish the Al-P content at 30 and 90 days of crop growth stage while at 60 days N_0 and N_{100} levels and N_{100} and N_{50} levels were on par.

Interaction effects

At 30th day, St x Rh, St x N, and S x N interactions indicated statistical significance. The salient points deduced are: (i) the sterilized condition enhanced Al-P only in the non-rhizosphere soil; (ii) the effect of sterilization in enhancing Al-P was observed under all levels of N; and (iii) the effect of N in diminishing the Al-P content was confined to the black soil.

At 60th day, several interactions such as St x S, S x N and P x N were associated with statistical significance. The salient points of inferences are: (i) under sterilized condition enhancement of Al-P was confined to the red soil; (ii) at all levels of N, the red soil registered more Al-P than the black soil; (iii) in the absence of any added N, addition of P favoured enhanced accumulation of Al-P fraction but this effect got vanished on the application of N.

At 90th day again, several interactions were significant and the following important inferences were drawn:

(i) while the sterilized condition made no difference in respect of the black soil, it caused a significant enhancement in the red soil; (ii) the influence of P addition in enhancing Al-P content occurred only under non-sterilized condition; (iii) the effect of sterilization enhanced Al-P content only under N_0 and N_{50} levels (iv) the influence of P addition on Al-P occurred irrespective of soil types; (v) under all levels of N, the black soil contained more Al-P content than the red soil; and (vi) the P addition enhanced Al-P content under all levels of N.

4.5.2.3. Iron phosphate (Fe-P) (Table 14)

Individual effects

i) Rhizosphere: The mean value of Fe-P ranged from 32.3 to 43.5 ppm. The concentration of Fe-P during the earlier stages in rhizosphere and non-rhizosphere soils were on par but at 90th day, the accumulation of Fe-P in the rhizosphere soil was significantly higher than in the non-rhizosphere soil.

ii) Sterilization: The mean value of Fe-P was found to range from 30.0 to 46.7 ppm. The process of sterilization enhanced the Fe-P content and this effect continued to remain during the subsequent stages as well.

iii) Soil types: The mean value of Fe-P ranged from 29.2 to 51.1 ppm for this main effect and the red soil contained more Fe-P during all the three stages of crop growth.

iv) P levels: The mean value for this main effect ranged from 31.6 to 43.7 ppm. The addition of P reflected in enhancement of Fe-P content in the soil during 60 and 90 days of crop growth but at 30th day, such a significant difference was not observed.

v) N levels: The mean value fell within the range of 28.6 to 44.3 ppm. N_{100} level decreased the Fe-P content at 30 and 60 days of crop growth but at 90th day N_{100} and N_0 levels were on par.

Interaction effects

At 30th day, the interactions viz., St x S, St x P, St x N, S x P, S x N and P x N were associated with significant effects. The important inferences drawn from the above interaction effects are; (i) while the sterilized condition could account for enhanced Fe-P content in the red soil, the reverse was the case in the black soil; (ii) the addition of P in enhancing Fe-P was confined to the sterilized condition; (iii) At all levels of N, the

TABLE 14. EFFECT OF TREATMENTS ON Fe-P IN RHIZOSPHERE AND NON-RHIZOSPHERE REGIONS OF GORGNUM IN BLACK AND RED SOILS (ppm)

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Treatments (1)	30 days (2)	60 days (3)	90 days (4)
Rh	43.5	40.7	34.2
NRh	42.4	39.5	32.3
St	46.7	43.9	30.0
NSt	39.2	36.3	36.5
S ₁	34.8	32.6	29.2
S ₂	51.1	47.6	37.2
P ₀	42.1	38.7	31.6
P ₅₀	43.7	41.5	34.8
SE	0.7	0.6	0.4
CD	2.0	1.8	1.3
N ₀	44.1	40.5	35.1
N ₅₀	44.3	41.6	28.6
N ₁₀₀	40.3	38.1	35.9
SE	0.8	0.8	0.5
CD	2.4	2.2	1.5
Rh x St	47.2	44.6	37.0
Rh x NSt	39.7	36.7	31.4
NRh x St	46.2	43.1	36.0
NRh x NSt	38.6	35.9	28.6
Rh x S ₁	35.4	33.1	30.2
Rh x S ₂	51.6	48.2	38.1
NRh x S ₁	34.2	32.0	28.2
NRh x S ₂	50.6	47.1	36.3
Rh x P ₀	42.7	39.6	32.5
Rh x P ₅₀	44.2	41.7	35.8
NRh x P ₀	41.6	37.8	30.8
NRh x P ₅₀	43.2	41.3	33.8
St x S ₁	32.8	30.3	34.4
St x S ₂	60.6	57.4	38.5
NSt x S ₁	36.8	34.8	28.9
NSt x S ₂	41.6	37.8	31.1

Contd.,

(1)	(2)	(3)	(4)
St x P ₀	44.5	41.8	34.4
St x P ₅₀	48.9	45.9	38.5
NSt x P ₀	39.8	35.6	28.9
NSt x P ₅₀	38.5	37.1	31.1
S ₁ x P ₀	37.6	34.7	29.2
S ₁ x P ₅₀	31.9	30.4	29.2
S ₂ x P ₀	46.6	42.7	34.1
S ₂ x P ₅₀	55.5	52.6	40.4
SE	0.97	0.9	0.6
CD	2.8	2.5	1.8
Rh x N ₀	44.9	41.4	36.2
Rh x N ₅₀	45.1	42.4	29.4
Rh x N ₁₀₀	40.4	38.2	36.9
NRh x N ₀	43.4	39.6	34.0
NRh x N ₅₀	43.6	40.9	27.9
NRh x N ₁₀₀	40.3	38.1	34.9
St x N ₀	44.2	41.3	36.4
St x N ₅₀	49.4	46.7	33.4
St x N ₁₀₀	46.4	43.5	39.6
NSt x N ₀	44.0	39.7	33.8
NSt x N ₅₀	39.2	36.6	23.8
NSt x N ₁₀₀	34.3	32.7	32.2
S ₁ x N ₀	42.6	39.9	33.8
S ₁ x N ₅₀	34.2	32.2	22.9
S ₁ x N ₁₀₀	27.5	25.6	30.9
S ₂ x N ₀	45.7	41.2	36.4
S ₂ x N ₅₀	54.4	51.1	34.4
S ₂ x N ₁₀₀	53.1	50.6	40.9
N ₀ x P ₀	45.0	40.1	32.5
N ₀ x P ₅₀	43.3	40.9	37.7
N ₅₀ x P ₀	38.5	35.4	27.2
N ₅₀ x P ₅₀	50.2	47.9	30.0
N ₁₀₀ x P ₀	42.9	40.7	35.2
N ₁₀₀ x P ₅₀	37.7	35.6	36.6
SE	1.2	1.1	0.8
CD	3.4	3.1	2.2

sterilized condition favoured greater accumulation of Fe-P content than the non-sterilized condition; (iv) at both the P levels and at all levels of N, the red soil had more Fe-P than the black soil; and (v) in the absence of N addition, P application produced no appreciable effect on Fe-P content in the soil; but at N₅₀ level P₅₀ level had a significant effect; however at N₁₀₀ level, absence of P recorded more Fe-P content than P application.

At 60th day, the interactions viz., St x S, St x N, S x P, S x N and P x N revealed statistical significance. The important inferences drawn are: (i) the sterilized condition increased Fe-P content in the red soil and decreased the same in the black soil; (ii) under sterilized condition enhancement of Fe-P content occurred at all levels of N; (iii) at P₅₀ level and at N₅₀ and N₁₀₀ levels more Fe-P content was observed in the red soil than in the black soil and (iv) N and P combined addition was found to be less conducive for Fe-P accumulation.

At 90th day, the interactions viz., St x S, St x N, S x P, S x N and P x N were significant. The important inferences drawn are: (i) the sterilized condition brought about significant difference in Fe-P content in the red soil; (ii) under all levels of N the sterilized condition was better than non-sterilized condition; (iii) the effect of P

addition in enhancing Fe-P content was observed only in the red soil; (iv) at all levels of N, the red soil recorded more Fe-P content than the black soil; and v) irrespective of N level, P addition favoured accumulation of Fe-P content in the soil.

4.5.2.4. Calcium phosphate (Ca-P) (Table 15)

Individual effects

i) Rhizosphere: The mean value for the main effect fell within the range of 4.16 to 6.39 ppm at all stages of crop growth. The rhizosphere soil contained significantly higher amount of Ca-P than the non-rhizosphere soil.

ii) Sterilization: The mean value for this main effect ranged from 3.87 to 6.90 ppm. At all the three stages of crop growth, the sterilized condition brought about a significant depression on Ca-P content in the soil.

iii) Soil types: The mean value remained within the range of 2.93 to 7.56 ppm. During all the three stages, the black soil was associated with greater amount of Ca-P content than the red soil.

iv) P levels: The mean values ranged from 3.77 to 6.37 ppm. P application enhanced the Ca-P content at all the three stages of crop growth.

TABLE 15. EFFECT OF TREATMENTS ON Ca-P IN RHIZOSPHERE AND NON-RHIZOSPHERE REGIONS OF SORGHUM IN BLACK AND RED SOILS (ppm)

Treatments (1)	30 days (2)	60 days (3)	90 days (4)
Rh	6.39	5.24	4.38
NRh	5.46	5.00	4.16
St	4.94	4.40	3.87
NSt	6.90	5.81	4.68
S ₁	7.56	6.58	5.61
S ₂	4.28	3.63	2.93
P ₀	5.47	4.73	3.77
P ₅₀	6.37	5.48	4.77
SE	0.06	0.04	0.04
CD	0.16	0.11	0.11
N ₀	6.15	5.15	4.43
N ₅₀	5.49	4.95	4.14
N ₁₀₀	6.13	5.22	4.25
SE	0.07	0.05	0.05
CD	0.20	0.15	0.14
Rh x St	5.24	4.53	4.00
Rh x NSt	7.54	5.95	4.78
NRh x St	4.65	4.27	3.75
NRh x NSt	6.27	5.67	4.57
Rh x S ₁	7.93	6.75	5.73
Rh x S ₂	4.85	3.72	3.03
NRh x S ₁	7.20	6.40	5.49
NRh x S ₂	3.71	3.54	2.84
Rh x P ₀	5.90	4.83	3.91
Rh x P ₅₀	6.88	5.64	4.85
NRh x P ₀	5.05	4.63	3.63
NRh x P ₅₀	5.87	5.32	4.69
St x S ₁	7.04	6.22	5.52
St x S ₂	2.84	2.57	2.21
NSt x S ₁	8.09	6.93	5.70
NSt x S ₂	5.72	4.69	3.65

Contd.,

(1)	(2)	(3)	(4)
St x P ₀	4.09	3.66	2.98
St x P ₅₀	5.79	5.14	4.76
NSt x P ₀	6.85	5.81	4.57
NSt x P ₅₀	6.95	5.82	4.78
S ₁ x P ₀	6.32	5.69	4.57
S ₁ x P ₅₀	8.81	7.47	6.65
S ₂ x P ₀	4.62	3.78	2.97
S ₂ x P ₅₀	3.94	3.49	2.89
SE	0.08	0.06	0.06
CD	0.16	0.17	0.16
Rh x N ₀	6.58	5.28	4.54
Rh x N ₅₀	5.95	5.02	4.30
Rh x N ₁₀₀	6.63	5.41	4.30
NRh x N ₀	5.72	5.01	4.32
NRh x N ₅₀	5.02	4.89	3.98
NRh x N ₁₀₀	5.63	5.02	4.19
St x N ₀	5.09	4.63	4.18
St x N ₅₀	5.11	4.71	4.98
St x N ₁₀₀	4.62	3.86	3.35
NSt x N ₀	7.20	5.67	4.68
NSt x N ₅₀	5.86	5.20	4.21
NSt x N ₁₀₀	7.65	6.57	5.15
S ₁ x N ₀	7.50	6.51	5.38
S ₁ x N ₅₀	7.21	6.51	5.49
S ₁ x N ₁₀₀	7.98	6.72	5.96
S ₂ x N ₀	4.79	3.79	3.47
S ₂ x N ₅₀	3.76	3.40	2.80
S ₂ x N ₁₀₀	4.28	3.71	2.53
N ₀ x P ₀	5.82	4.73	3.85
N ₀ x P ₅₀	6.47	5.57	5.00
N ₅₀ x P ₀	5.06	4.67	3.85
N ₅₀ x P ₅₀	5.92	5.23	4.42
N ₁₀₀ x P ₀	5.54	4.79	3.61
N ₁₀₀ x P ₅₀	6.73	5.64	4.88
SE	0.10	0.07	0.07
CD	0.28	0.21	0.20

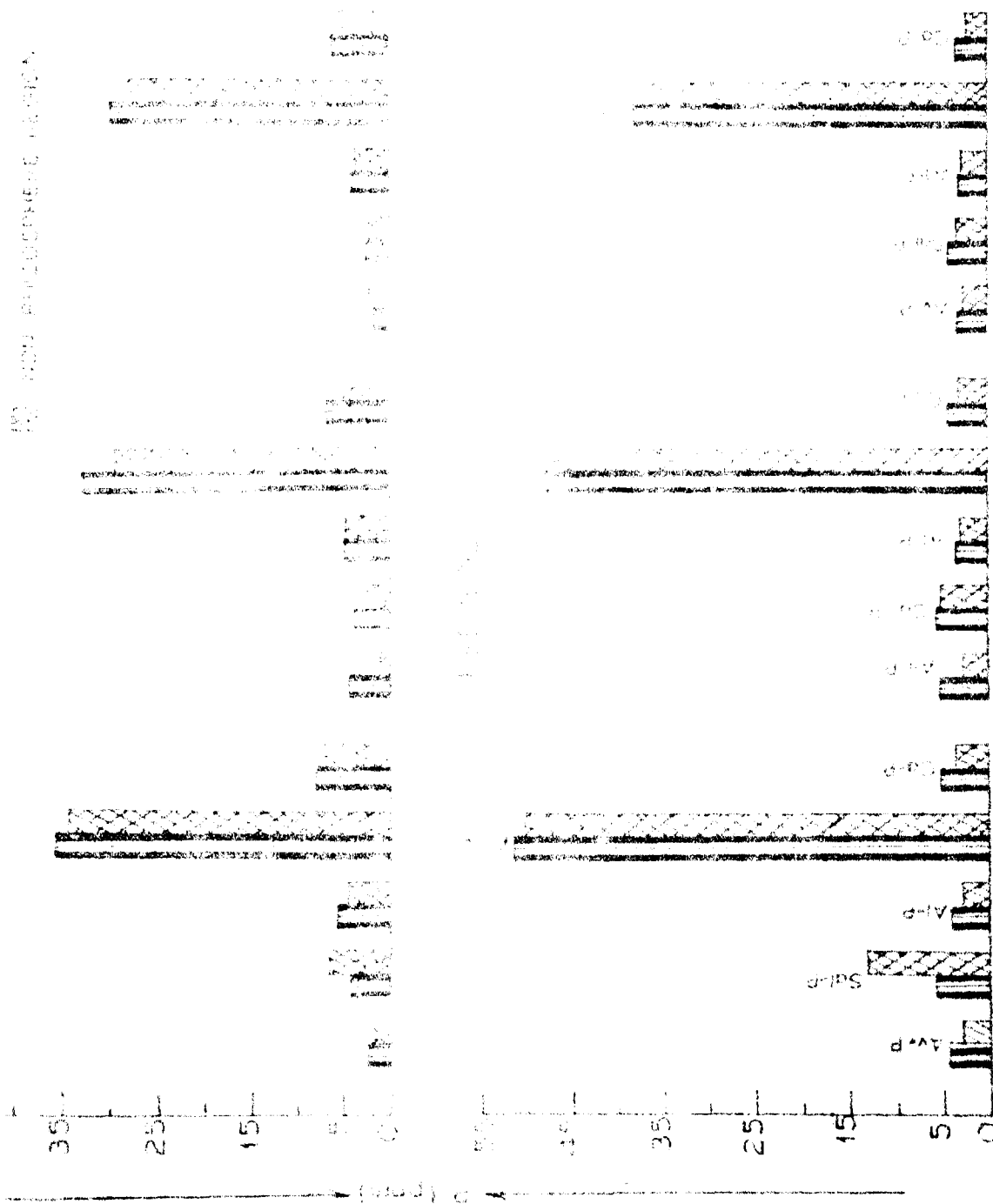


FIG. 7 DIFFERENT FORMS OF P AS INFLUENCED BY RHIZOSPHERE AND SOIL TYPES AT DIFFERENT STAGES OF CROP GROWTH

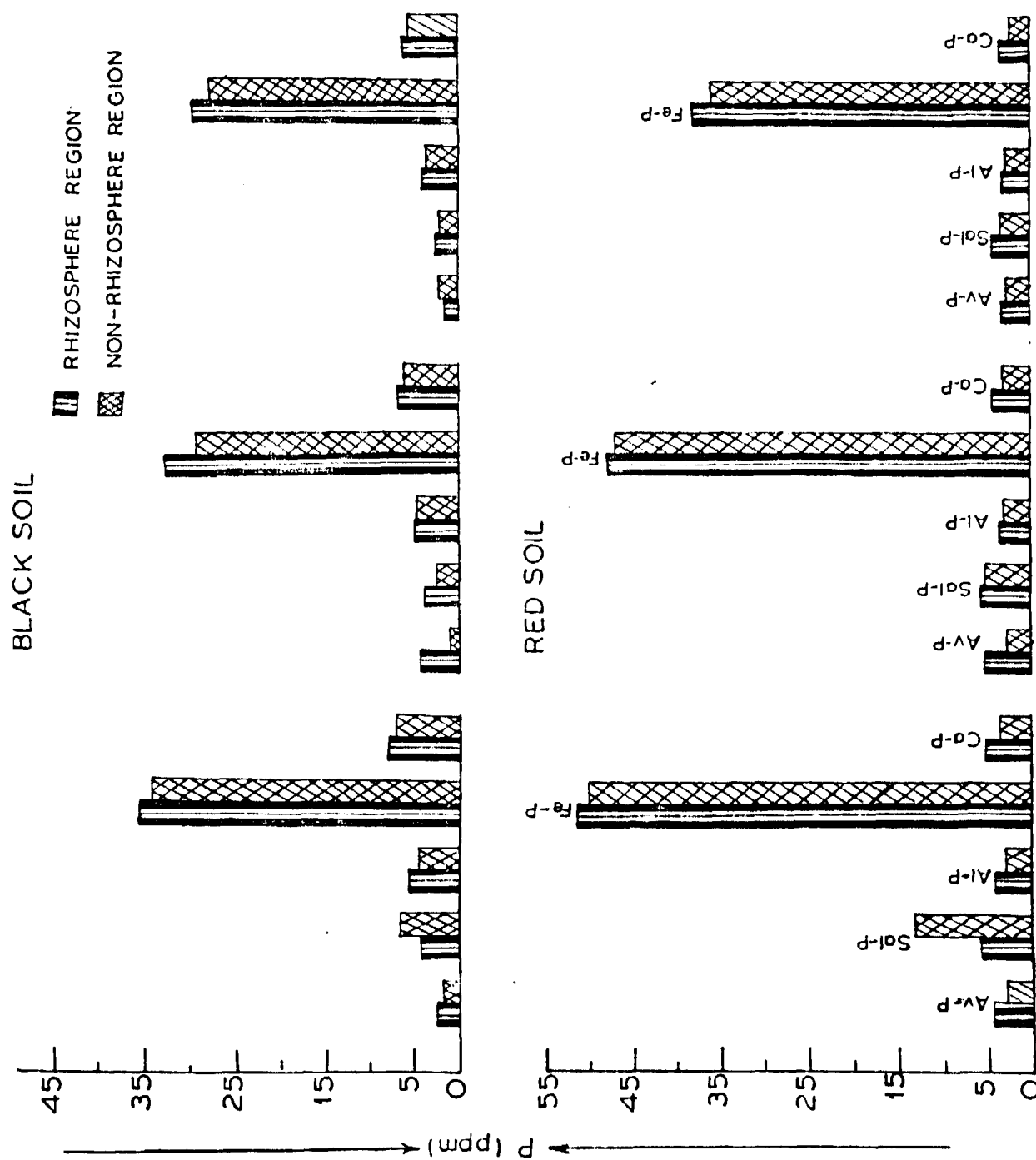


FIG.7 DIFFERENT FORMS OF P AS INFLUENCED BY RHIZOSPHERE AND SOIL TYPES AT DIFFERENT STAGES OF CROP GROWTH

v) N levels: The mean value ranged from 4.14 to 6.15 ppm. At all the three stages of crop growth N_{50} level significantly caused depression of Ca-P content in the soil at 30 and 60 days of crop growth while at 90 days N_{100} and N_{50} levels were on par.

Interaction effects

At 30th day, the interactions viz., St x Rh, St x S, St x P, St x N, R x S, S x P, S x N and P x N showed statistical significance. The salient inferences deduced are: (i) the sterilized condition caused depression in Ca-P content both in rhizosphere and non-rhizosphere soils; (ii) only under sterilized condition, P fertilization had positive effect on Ca-P content; and (iii) with no P application, N addition at 50 and 100 kg level resulted in the reduction of Ca-P content in the soil.

At 60th day, the interactions viz., St x S, St x P, St x N, S x P and S x N attained statistical significance. The important inferences deduced are: (i) addition of P enhanced Ca-P content only under sterilized condition; and (ii) addition of P enhanced the Ca-P content only in the black soil.

At 90th day, the interactions viz., St x S, St x P, St x N, S x P, S x N and P x N showed statistical significance. The salient inferences deduced are: (i) without addition of P, the sterilized condition caused a marked decrease in Ca-P content, but at added levels of P, the difference was meagre; and (ii) as regards the effect of N fertilization on Ca-P content in two types of soils, the black soil had positive effect while the red soil had opposite effect on Ca-P content.

4.5.3. Effect on K transformation (Fig. 8)

4.5.3.1. Water soluble-K (Table 16)

Individual effects

i) Rhizosphere: The mean value for the main effect ranged from 20.1 to 67.6 ppm. The rhizosphere soil contained higher concentration of water soluble-K than the non-rhizosphere soil at all the three stages of crop growth.

ii) Sterilization: The mean value of water soluble K content remained within the range of 27.3 to 62.7 ppm. Under sterilized condition of the soil the water soluble-K content was increased upto 30 days of crop growth, but at 90 days stage, the trend got reversed. At 60th day of crop growth, the effect of sterilization was on par with the non-sterilized condition.

TABLE 16. EFFECT OF TREATMENTS ON WATER SOLUBLE - K IN RHIZOSPHERE AND NON-RHIZOSPHERE REGIONS OF SORGHUM IN BLACK AND RED SOILS (ppm)

Treatments (1)	30 days (2)	60 days (3)	90 days (4)
Rh	67.6	48.1	49.2
NRh	44.3	26.4	20.1
St	62.7	38.2	27.3
NSt	49.2	36.4	42.0
S ₁	50.4	30.2	29.2
S ₂	61.5	44.3	40.1
P ₀	58.7	37.3	35.1
P ₅₀	53.2	37.2	34.2
SE	1.7	1.2	2.7
CD	4.8	3.4	7.5
N ₀	56.7	39.0	34.3
N ₅₀	51.0	39.7	36.3
N ₁₀₀	60.2	33.0	33.3
SE	2.1	1.5	3.2
CD	5.8	4.2	9.2
Rh x St	66.6	50.8	36.1
Rh x NSt	66.6	45.3	62.3
NRh x St	56.8	25.5	18.5
NRh x NSt	31.8	27.4	21.8
Rh x S ₁	63.2	38.0	41.6
Rh x S ₂	72.0	58.2	56.8
NRh x S ₁	37.7	22.5	16.8
NRh x S ₂	51.0	30.4	23.5
Rh x P ₀	68.6	47.3	50.4
Rh x P ₅₀	66.5	48.9	48.0
NRh x P ₀	48.8	27.3	19.9
NRh x P ₅₀	39.8	25.6	20.4
St x S ₁	49.9	29.3	21.7
St x S ₂	75.5	47.0	32.9
NSt x S ₁	51.0	31.2	36.7
NSt x S ₂	47.5	41.5	47.3

Contd.,

(1)	(2)	(3)	(4)
St x P ₀	61.4	33.9	26.0
St x P ₅₀	64.0	42.5	28.5
NSt x P ₀	56.1	40.7	44.3
NSt x P ₅₀	42.3	32.0	39.8
S ₁ x P ₀	49.8	34.2	30.7
S ₁ x P ₅₀	51.1	26.3	27.8
S ₂ x P ₀	67.7	40.4	39.6
S ₂ x P ₅₀	55.3	48.2	40.6
SE	2.4	1.7	3.7
CD	6.7	4.8	10.7
Rh x N ₀	69.4	46.1	47.4
Rh x N ₅₀	61.3	52.6	51.4
Rh x N ₁₀₀	72.0	45.5	48.8
NRh x N ₀	43.9	31.9	21.3
NRh x N ₅₀	40.8	26.8	21.2
NRh x N ₁₀₀	48.3	20.6	17.9
St x N ₀	62.6	37.7	26.0
St x N ₅₀	56.4	45.6	31.8
St x N ₁₀₀	69.1	31.2	24.1
NSt x N ₀	50.8	40.4	42.7
NSt x N ₅₀	45.7	33.8	40.9
NSt x N ₁₀₀	51.2	34.9	42.5
S ₁ x N ₀	45.1	31.9	27.8
S ₁ x N ₅₀	48.2	29.1	30.1
S ₁ x N ₁₀₀	58.0	29.6	29.8
S ₂ x N ₀	68.3	46.1	40.9
S ₂ x N ₅₀	53.9	50.3	42.5
S ₂ x N ₁₀₀	62.3	36.4	36.9
N ₀ x P ₀	62.0	40.1	34.4
N ₀ x P ₅₀	51.4	37.9	34.3
N ₅₀ x P ₀	55.1	38.1	38.3
N ₅₀ x P ₅₀	46.9	41.4	34.4
N ₁₀₀ x P ₀	59.1	33.7	32.8
N ₁₀₀ x P ₅₀	61.3	32.4	33.9
SE	2.9	2.1	4.6
CD	8.2	5.9	13.1

iii) Soil types: The mean water soluble K content ranged from 29.2 to 61.5 ppm. During all the three stages of crop growth, the red soil was associated with greater amount of water soluble-K content than the black soil.

iv) P levels: The mean value for the main effect ranged from 36.2 ppm to 58.7 ppm. Application of P at 50 kg level reduced water soluble-K content at 30 days of crop growth while at 60 and 90 days of crop growth, P_0 and P_{50} levels were on par.

v) N levels: The mean value for the main effect ranged from 33.0 to 60.2 ppm. N application either at 50 or 100 kg level showed no beneficial effect in enhancing water soluble-K content at all the three stages of crop growth.

Interaction effects

At 30th day, the interactions viz., St x Rh, St x S, St x P, S x P and S x N were found to be significant. The salient points deduced are: (i) increased water soluble-K content was observed in the non-rhizosphere soil under sterilized condition; (ii) only under sterilized condition, the red soil had more water soluble-K content; (iii) P addition had no effect under sterilized condition; (iv) P application exhibited no difference in accumulating water soluble-K content but with no P application, the red soil recorded more water soluble-K content than the black soil.

At 60th day, the interactions viz., St x Rh, St x S, St x P, St x N, Rh x S, Rh x N, S x P and S x N showed statistical significance. The important conclusions drawn are: (i) under sterilized condition of the soil positive influence on water soluble-K content was recorded in the rhizosphere soil; (ii) in the red soil also, P addition tended to increase the water soluble-K content in the soil; (iii) the reduction of water soluble-K content due to N addition was confined to the non-rhizosphere region; and (iv) in the red soil positive effect was observed due to P application and negative effect in the black soil.

At 90th day, the interaction St x Rh showed significance. The conclusion drawn is that under sterilized condition of the soil marked decrease in water soluble-K content occurred in the rhizosphere soil.

4.5.3.2. $N.N.NH_4OAc$ extractable-K or exchangeable-K content (Table 17)

Individual effects

i) Rhizosphere: The mean value for this effect ranged from 206 to 432 ppm. At all the three stages of crop growth, the rhizosphere soil showed higher amount of exchangeable-K content than the non-rhizosphere soil.

ii) Sterilization: The mean value for this main effect ranged from 245 to 340 ppm. Under sterilized condition of the soil exchangeable-K content was increased at 60 and 90 days of crop growth, while at 30 days reverse was the case.

iii) Soil types: The mean value remained within the range of 163 to 434 ppm. The red soil showed higher amount of exchangeable-K than the black soil at 30 days of crop growth, while at later stages, the trend was reversed.

iv) P levels: The mean value for this main effect ranged from 264 to 326 ppm. P application decreased the exchangeable-K content at 90 days of crop growth while at 30 and 60 days of crop growth P_0 and P_{50} levels were on par.

v) N levels: The mean value for this main effect ranged from 247 to 327 ppm. Application of N at two levels did not increase the exchangeable-K content at all the three stages of crop growth.

Interaction effects

At 30th day, the interactions viz., St x Rh, St x S, St x P, Rh x S and S x N showed statistical significance. The salient points of inferences drawn are: (i) the sterilized

TABLE 17. EFFECT OF TREATMENTS ON EXCHANGEABLE-K IN RHIZOSPHERE
AND NON-RHIZOSPHERE REGIONS OF SORGHUM IN BLACK AND RED
SOILS (ppm)

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Treatments (1)	30 days (2)	60 days (3)	90 days (4)
Rh	432	350	297
NRh	206	223	235
St	299	298	287
NSt	340	276	245
S ₁	434	394	370
S ₂	204	180	163
P ₀	313	291	269
P ₅₀	326	282	264
SE	6.0	6.0	5.4
CD	17.0	17.0	15.3
N ₀	314	297	268
N ₅₀	316	278	247
N ₁₀₀	327	286	284
SE	7.3	7.3	6.6
CD	21.0	21.0	18.8
Rh x St	397	369	311
Rh x NSt	467	332	283
NRh x St	201	226	263
NRh x NSt	211	220	207
Rh x S ₁	593	459	398
Rh x S ₂	271	241	197
NRh x S ₁	276	328	343
NRh x S ₂	137	119	128
Rh x P ₀	420	367	310
Rh x P ₅₀	444	334	285
NRh x P ₀	206	216	228
NRh x P ₅₀	207	231	243
St x S ₁	403	406	391
St x S ₂	195	189	183
NSt x S ₁	466	381	349
NSt x S ₂	213	171	142

Contd.,

(1)	(2)	(3)	(4)
St x P ₀	281	298	289
St x P ₅₀	316	297	285
NSSt x P ₀	344	284	248
NSSt x P ₅₀	335	268	242
S ₁ x P ₀	425	416	386
S ₁ x P ₅₀	443	371	354
S ₂ x P ₀	200	166	151
S ₂ x P ₅₀	208	194	174
SE	8.4	8.4	7.6
CD	24.0	24.0	21.7
Rh x N ₀	432	371	308
Rh x N ₅₀	422	333	274
Rh x N ₁₀₀	442	347	311
NRh x N ₀	196	223	227
NRh x N ₅₀	211	223	221
NRh x N ₁₀₀	212	225	258
St x N ₀	286	318	285
St x N ₅₀	302	278	258
St x N ₁₀₀	308	296	319
NSSt x N ₀	342	275	250
NSSt x N ₅₀	331	277	237
NSSt x N ₁₀₀	346	275	250
S ₁ x N ₀	390	409	361
S ₁ x N ₅₀	440	363	338
S ₁ x N ₁₀₀	473	408	412
S ₂ x N ₀	238	185	174
S ₂ x N ₅₀	193	192	157
S ₂ x N ₁₀₀	182	163	157
N ₀ x P ₀	311	314	284
N ₀ x P ₅₀	317	280	251
N ₅₀ x P ₀	316	260	242
N ₅₀ x P ₅₀	317	296	253
N ₁₀₀ x P ₀	311	300	281
N ₁₀₀ x P ₅₀	343	271	288
SE	10.3	10.3	9.3
CD	29.4	29.4	26.5

condition caused reduction in exchangeable K content in the rhizosphere soil and also in the black soil; (ii) P application recorded higher exchangeable-K content in the soil under sterilized condition than under non-sterilized condition; and (iii) N fertilization at 50 and 100 kg level increased the exchangeable-K content in the black soil.

At 60th day, the interactions viz., Rh x P, S x P, S x N and P x N showed statistical significance. The important inferences drawn are: (i) P fertilization reduced the exchangeable-K in both the rhizosphere and non-rhizosphere soils; but the reduction was conspicuous in the rhizosphere soil; (ii) significantly lower exchangeable K content was associated with P fertilization in the black soil than that in the red soil; and (iii) higher exchangeable K content in the red soil than that in the black soil was observed due to P fertilization.

At 90th day, the interactions viz., St x N, Rh x P, S x P, S x N and P x N showed statistical significance. The salient inferences drawn are: (i) P fertilization reduced the exchangeable-K content in the rhizosphere soil; (ii) P fertilization reduced the exchangeable-K content in the black soil; (iii) N fertilization at higher level had positive effect in the black soil; (iv) though P application caused reduction in exchangeable-K content in the absence of N addition, it showed positive effect for N addition at the two

levels; and (v) an inconsistent trend for N fertilization was observed since the sterilized condition increased exchangeable K content in the soil at N_0 and N_{100} levels markedly, but it was meagre at N_{50} level.

4.5.3.3. HNO_3 extractable-K (Table 18)

Individual effects

i) Rhizosphere: The mean value for this main effect fell within the range of 217 to 415 ppm. The rhizosphere soil registered higher value of HNO_3 extractable-K content at all the three stages of crop period than the non-rhizosphere soil.

ii) Sterilization: The mean value for this main effect remained within the range of 262 to 370 ppm. The process of sterilization decreased the HNO_3 extractable-K content at 30 and 90 days, but showed a reverse effect at 60 days of crop growth.

iii) Soil types: The mean value for this main effect ranged from 242 to 377 ppm. At all the three stages, the black soil registered higher amounts of HNO_3 extractable-K content than the red soil.

TABLE 18. EFFECT OF TREATMENTS ON HNO_3 EXTRACTABLE-K IN RHIZOSPHERE AND NON-RHIZOSPHERE REGIONS OF SORGHUM IN BLACK AND RED SOILS (ppm)

Treatments (1)	30 days (2)	60 days (3)	90 days (4)
Rh	415	317	296
NRh	258	232	217
St	370	286	252
NSt	302	263	262
S ₁	377	302	271
S ₂	296	247	242
P ₀	336	283	256
P ₅₀	337	266	257
SE	4.7	4.7	4.7
CD	13.3	13.3	13.3
N ₀	349	285	259
N ₅₀	319	265	245
N ₁₀₀	341	274	266
SE	5.7	5.7	5.7
CD	16.3	16.3	16.3
Rh x St	368	336	239
Rh x NSt	461	298	310
NRh x St	237	236	221
NRh x NSt	279	228	213
Rh x S ₁	474	353	308
Rh x S ₂	355	281	283
NRh x S ₁	279	251	234
NRh x S ₂	236	214	200
Rh x P ₀	409	323	291
Rh x P ₅₀	253	311	300
NRh x P ₀	262	243	220
NRh x P ₅₀	253	222	214
St x S ₁	330	316	264
St x S ₂	275	257	239
NSt x S ₁	424	288	278
NSt x S ₂	316	278	245

Contd.,

(1)	(2)	(3)	(4)
St x P ₀	267	288	253
St x P ₅₀	338	284	250
NSt x P ₀	404	278	258
NSt x P ₅₀	336	249	265
S ₁ x P ₀	366	324	287
S ₁ x P ₅₀	388	280	255
S ₂ x P ₀	306	242	225
S ₂ x P ₅₀	285	253	259
SE	6.6	6.6	6.6
CD	18.8	18.8	18.8
Rh x N ₀	423	323	288
Rh x N ₅₀	383	306	278
Rh x N ₁₀₀	439	322	322
NRh x N ₀	276	247	230
NRh x N ₅₀	255	225	211
NRh x N ₁₀₀	243	226	211
St x N ₀	318	308	257
St x N ₅₀	285	275	238
St x N ₁₀₀	305	276	260
NSt x N ₀	381	262	261
NSt x N ₅₀	353	255	251
NSt x N ₁₀₀	377	273	273
S ₁ x N ₀	382	327	279
S ₁ x N ₅₀	365	270	253
S ₁ x N ₁₀₀	384	308	282
S ₂ x N ₀	316	243	239
S ₂ x N ₅₀	272	260	236
S ₂ x N ₁₀₀	298	240	251
N ₀ x P ₀	357	305	273
N ₀ x P ₅₀	341	264	245
N ₅₀ x P ₀	321	252	236
N ₅₀ x P ₅₀	316	278	253
N ₁₀₀ x P ₀	329	291	259
N ₁₀₀ x P ₅₀	352	257	274
SE	8.0	8.0	8.0
CD	23.0	23.0	23.0

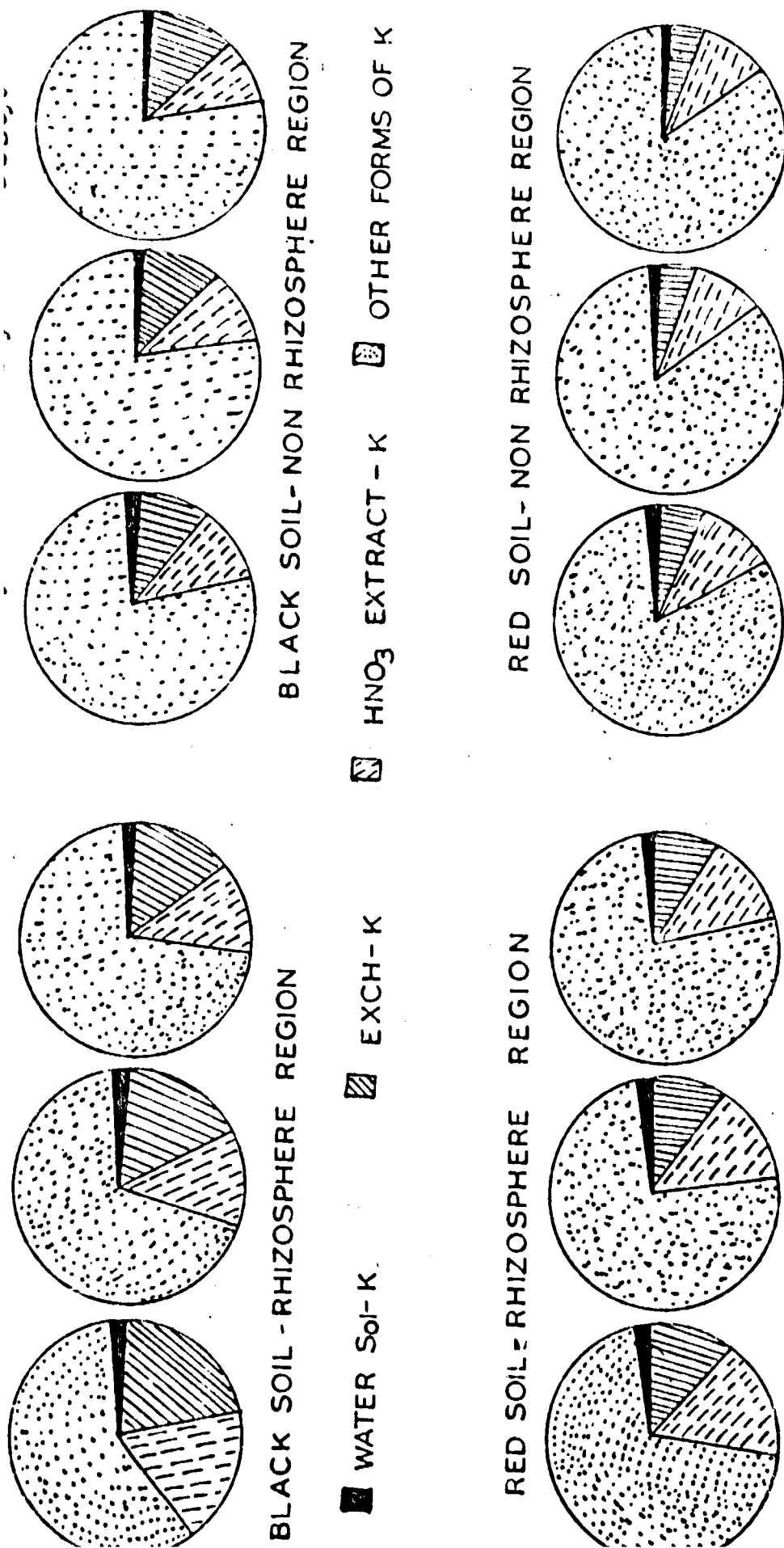


FIG.8 DIFFERENT FORMS OF K AS INFLUENCED BY RHIZOSPHERE AND SOIL TYPES AT DIFFERENT STAGES OF CROP GROWTH

iv) P levels: The mean value for this main effect ranged from 256 to 337 ppm. P application at 30 and 90 days had no effect on HNO_3 extractable-K content, while at 60 days stage, it recorded lowest value of HNO_3 extractable-K content.

v) N levels: The mean value for this main effect ranged from 245 to 349 ppm. Application of N at 50 kg level decreased the HNO_3 extractable-K content at all the three stages of crop growth generally.

Interaction effects

At 30th day, the interactions viz., St x Rh, St x S, St x P, Rh x S, Rh x N and S x P showed statistical significance. The important inferences drawn are: (i) In the P fertilization, the HNO_3 extractable-K content differed in both, sterilized and non-sterilized conditions since HNO_3 extractable-K was significantly higher due to P addition under sterilized condition, while under non-sterilized condition P addition caused marked decrease; (ii) N addition at 100 kg level caused marked reduction of HNO_3 extractable-K in non-rhizosphere region; and (iii) P fertilization on HNO_3 extractable-K content had positive and negative effects in black and red soils respectively.

At 60th day, the interactions viz., St x Rh, St x N, Rh x S, S x P, S x N and P x N showed statistical significance. The inferences drawn are: (i) under sterilized condition, N fertilization caused reduction in HNO_3 extractable-K content and (ii) P fertilization decreased HNO_3 extractable -K content in the black soil.

At 90th day, the interactions viz., St x Rh, Rh x N, S x P and P x N showed statistical significance. The inferences drawn are: (i) the sterilized condition increased the HNO_3 extractable-K content in the non-rhizosphere soil and decreased the same in the rhizosphere soil and also N application at 100 kg level increased the HNO_3 extractable-K content in the rhizosphere soil; (ii) P application interacted differently with soils, since the lowest value was associated with P addition in the black soil and the reverse was the case for the red soil; and (iii) the synergistic effect of P x N was observed for HNO_3 extractable-K content as revealed by the trend of mean values for P x N interaction.

4.6. Effect on nutrient flow rate or flux or uptake rate in the plant

4.6.1. Effect on N, P and K flow rate in the plant (Table 19)

(Fig. 9)

4.6.1.1. Effect on N flow rate

Individual effects

i) Sterilization: The differential trend in N flow rate for both the conditions of the soil was not marked.

ii) Soil types: The N flow rate was significantly high in the black soil ($146.4 \mu \text{ moles/cm/day} \times 10^{-4}$) than the red soil ($87.0 \mu \text{ moles/cm/day} \times 10^{-4}$).

iii) P levels: Difference in N flow rate due to P application was not significant.

iv) N levels: The N application at 100 kg level recorded significantly higher value for N flow rate ($136.3 \mu \text{ moles/cm/day} \times 10^{-4}$) but it was on par with N_0 level. Nitrogen flow rate at N_{50} level was recorded as $92.0 \mu \text{ moles/cm/day} \times 10^{-4}$.

v) Stages: Nitrogen flow rate at 30 days stage was found to be high registering $296.8 \mu \text{ moles/cm/day} \times 10^{-4}$. The rate was high at the early growth phase, more or less 8 to 16 times more than that at 90 and 60 days stages respectively.

Interaction effects

The interactions viz., Stages x St, S x Stages, S x P, S x N, Stages x P and Stages x N attained statistical

significance. The main inferences drawn are: (i) on an overall basis under sterilized condition of the soil N flow rate at 30 days stage of crop growth was enhanced; (ii) N flow rate was more in the black soil than that in the red soil at 30 days stage, while the difference in flow rate was marginal between two soil types at later stages of crop growth, but was marked at 30 days stage; (iii) P application caused reduction in N flow rate in the black soil but showed marginal increase in the red soil; (iv) N_{100} level recorded higher N flow rate in the red soil than that in the black soil; while N_{50} level was on par with N_0 level; and (v) the negative effect of P application on N flow rate was observed at 30 days vegetative stage, while at later stages the differences were only numerical.

4.6.1.2. Effect on P flow rate

Individual effects

i) Sterilization: Differential trend in P flow rate for both the conditions of the soil was insignificant.

ii) Soil types: Similar to that of N flow rate, P flow rate was observed to be higher in the black soil ($33.2 \mu \text{ moles/cm/day} \times 10^{-4}$) than that in the red soil ($16.8 \mu \text{ moles/cm/day} \times 10^{-4}$).

iii) P levels: P application significantly reduced P flow rate from 31.0 to 19.0 μ moles/cm/day $\times 10^{-4}$.

iv) N levels: N application had no significant effect on P flow rate.

v) Stages: P flow rate at 30 days stage was found to be remarkably high registering 67.30 μ moles/cm/day $\times 10^{-4}$.

Interaction effects

The interactions viz., St $\times$ P, S $\times$ Stages, S $\times$ P, S $\times$ N, Stages $\times$ P, Stages $\times$ N and P $\times$ N attained statistical significance. The salient inferences are: (i) under normal condition of the soil higher P flow rate was recorded than that under sterilized condition; (ii) at 30 days stage P flow rate was more in the black soil than that in the red soil but with advancement of crop growth, this trend was not observed; (iii) P application recorded significantly lower P flow rate in the black soil while it recorded marginal difference in the red soil; (iv) N application which was able to cause a stepwise reduction in P flow rate in the black soil showed a reverse trend in the red soil; (v) the negative effect of P application on P flow rate was observed only at 30 days stage, while at later stages the effect of P application was on par with no P application; and (vi) the combined application of N_{100} P_{50} showed a complimentary effect.

4.6.1.3. Effect on K flow rate

Individual effects

i) Sterilization: Differential trend in K flow rate for both the conditions of the soil was insignificant though under normal condition of the soil a numerically higher value of K flow rate was recorded than that under sterilized condition of the soil.

ii) Soil types: Similar to that of N flow rate, K flow rate was found to be higher in the black soil ($82.7 \mu \text{ moles/cm/day} \times 10^{-4}$) than that in the red soil ($54.0 \mu \text{ moles/cm/day} \times 10^{-4}$).

iii) P levels: P application significantly reduced K flow rate from 77.6 to $59.1 \mu \text{ moles/cm/day} \times 10^{-4}$.

iv) N levels: N application had no significant effect on K flow rate.

v) Stages: K flow rate at 30 days stage was significantly higher registering $82.7 \mu \text{ moles/cm/day} \times 10^{-4}$ than that at 60 and 90 days stages.

Interaction effects

The interactions viz., St x S, St x Stages, S x Stages, S x P, Stages x P and P x N attained statistical significance.

TABLE 19. EFFECT OF TREATMENTS ON N, P AND K UPTAKE RATE IN SORGHUM PLANT IN
BLACK AND RED SOILS (μ moles/cm/day $\times 10^{-4}$)

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Treatments	N uptake rate	P uptake rate	K uptake rate
St	129.1	22.8	69.5
NSt	104.3	27.3	67.2
S ₁	146.4	33.2	82.7
S ₂	87.0	16.8	54.0
P ₀	131.5	31.0	77.6
P ₅₀	102.5	19.0	59.1
SE	10.2	1.6	4.8
CD	28.7	4.5	13.6
N ₀	122.0	27.2	74.9
N ₁	92.0	22.2	58.2
N ₂	136.3	25.6	72.0
St ₁	296.8	67.3	165.8
St ₂	17.8	1.4	12.0
St ₃	35.5	6.3	27.3
SE	12.5	2.0	5.9
CD	35.2	5.5	16.7
St $\times$ S ₁	157.9	30.5	73.5
St $\times$ S ₂	100.2	15.0	65.5
NSt $\times$ S ₁	135.0	36.0	92.0
NSt $\times$ S ₂	73.7	18.6	42.6
St $\times$ P ₀	139.6	26.5	76.4
St $\times$ P ₅₀	118.5	19.1	62.6
NSt $\times$ P ₀	123.4	35.6	78.9
NSt $\times$ P ₅₀	85.2	18.9	55.6
S ₁ $\times$ P ₀	185.0	44.8	109.4
S ₁ $\times$ P ₅₀	108.0	21.6	56.0
S ₂ $\times$ P ₀	78.1	17.3	45.9
S ₂ $\times$ P ₅₀	95.9	16.4	62.2
SE	14.4	2.3	6.9
CD	40.6	6.4	19.2
St $\times$ St ₁	361.6	65.1	187.8
St $\times$ St ₂	10.8	1.3	8.3
St $\times$ St ₃	15.0	1.9	12.4
NSt $\times$ St ₁	232.0	69.5	143.7
NSt $\times$ St ₂	24.8	1.6	15.7
NSt $\times$ St ₃	56.1	10.6	42.3
St $\times$ N ₀	142.5	27.5	74.7
St $\times$ N ₅₀	101.4	18.6	54.6
St $\times$ N ₁₀₀	143.3	22.2	79.2
NSt $\times$ N ₀	101.4	26.9	75.2
NSt $\times$ N ₅₀	82.3	25.9	61.9
NSt $\times$ N ₁₀₀	129.2	28.9	64.6

Contd.,

(1)	(2)	(3)	(4)
$S_1 \times St_1$	377.5	9.3	207.0
$S_1 \times St_2$	20.0	1.1	11.8
$S_1 \times St_3$	41.9	6.2	29.4
$S_2 \times St_1$	216.1	42.3	124.6
$S_2 \times St_2$	15.6	1.8	12.2
$S_2 \times St_3$	35.5	6.4	25.3
$S_1 \times N_0$	173.8	41.7	106.7
$S_1 \times N_{50}$	122.8	32.1	76.3
$S_1 \times N_{100}$	142.7	25.8	65.0
$S_2 \times N_0$	70.1	12.7	43.2
$S_2 \times N_{50}$	61.0	12.3	40.1
$S_2 \times N_{100}$	129.8	25.4	78.8
$N_0 \times P_0$	158.8	42.0	96.1
$N_0 \times P_{50}$	85.1	12.4	53.8
$N_1 \times P_0$	101.8	26.6	57.9
$N_1 \times P_{50}$	82.0	17.9	58.6
$N_2 \times P_0$	134.0	24.5	79.0
$N_2 \times P_{50}$	138.5	26.7	64.9
$St_1 \times P_0$	352.3	87.5	203.0
$St_1 \times P_{50}$	241.3	47.2	128.6
$St_2 \times P_0$	18.1	1.4	10.2
$St_2 \times P_{50}$	17.4	1.4	13.8
$St_3 \times P_0$	24.1	4.2	19.8
$St_3 \times P_{50}$	47.0	8.4	34.9
SE	17.7	2.8	8.4
CD	49.7	7.8	23.6
$St_1 \times N_0$	299.8	73.5	173.0
$St_1 \times N_{50}$	232.8	57.4	143.0
$St_1 \times N_{100}$	358.4	71.0	181.5
$St_2 \times N_0$	18.8	1.5	11.5
$St_2 \times N_{50}$	14.2	1.5	12.6
$St_2 \times N_{100}$	18.4	1.3	11.0
$St_3 \times N_0$	47.3	6.5	40.4
$St_3 \times N_{50}$	27.2	7.8	18.3
$St_3 \times N_{100}$	32.0	4.5	23.4
SE	21.6	3.4	10.3
CD	60.9	9.6	28.9

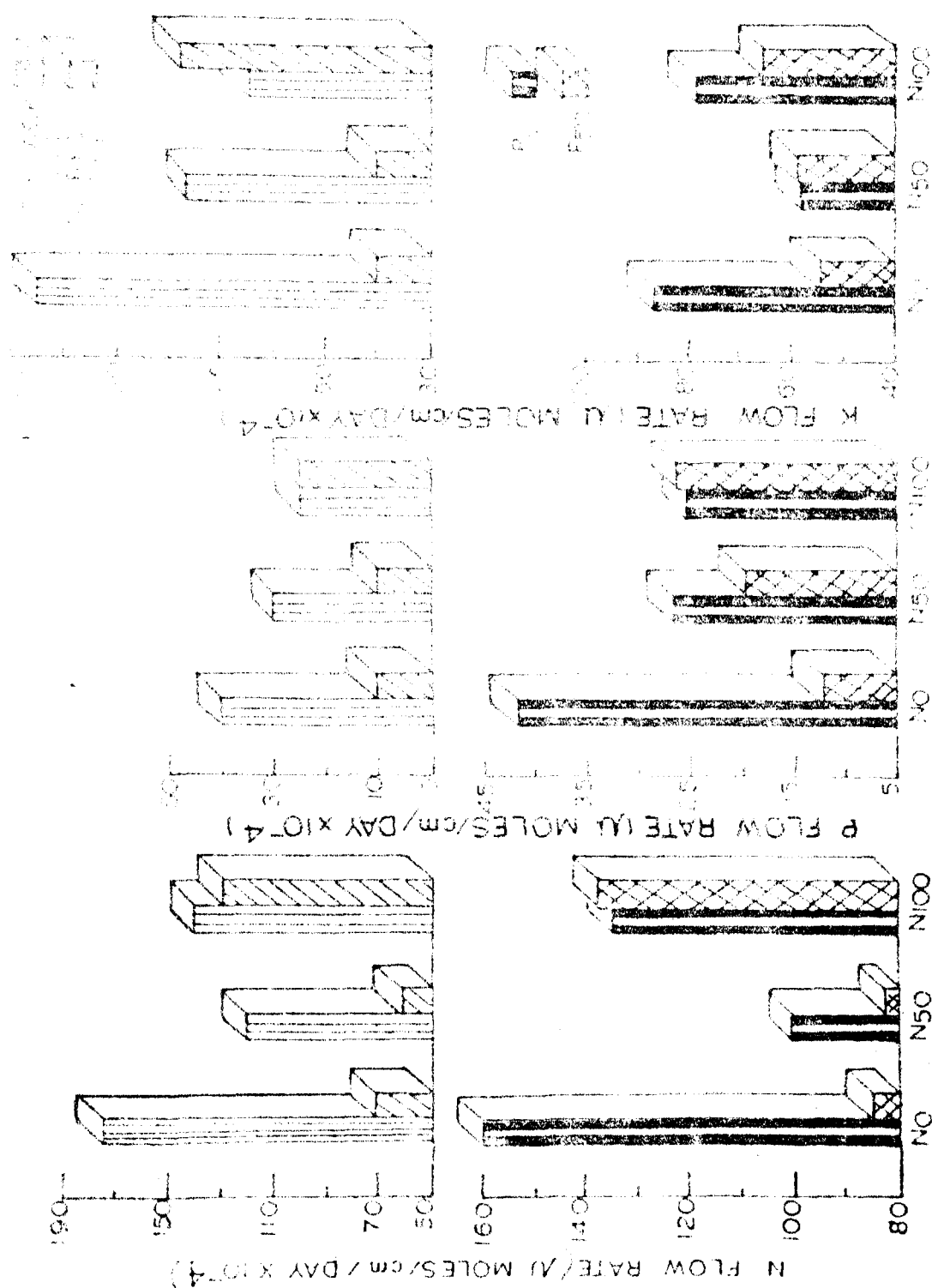


FIG. 9 FLOW RATE OF MAJOR NUTRIENTS AS INFLUENCED BY SOIL TYPES AND N AND P APPLICATION

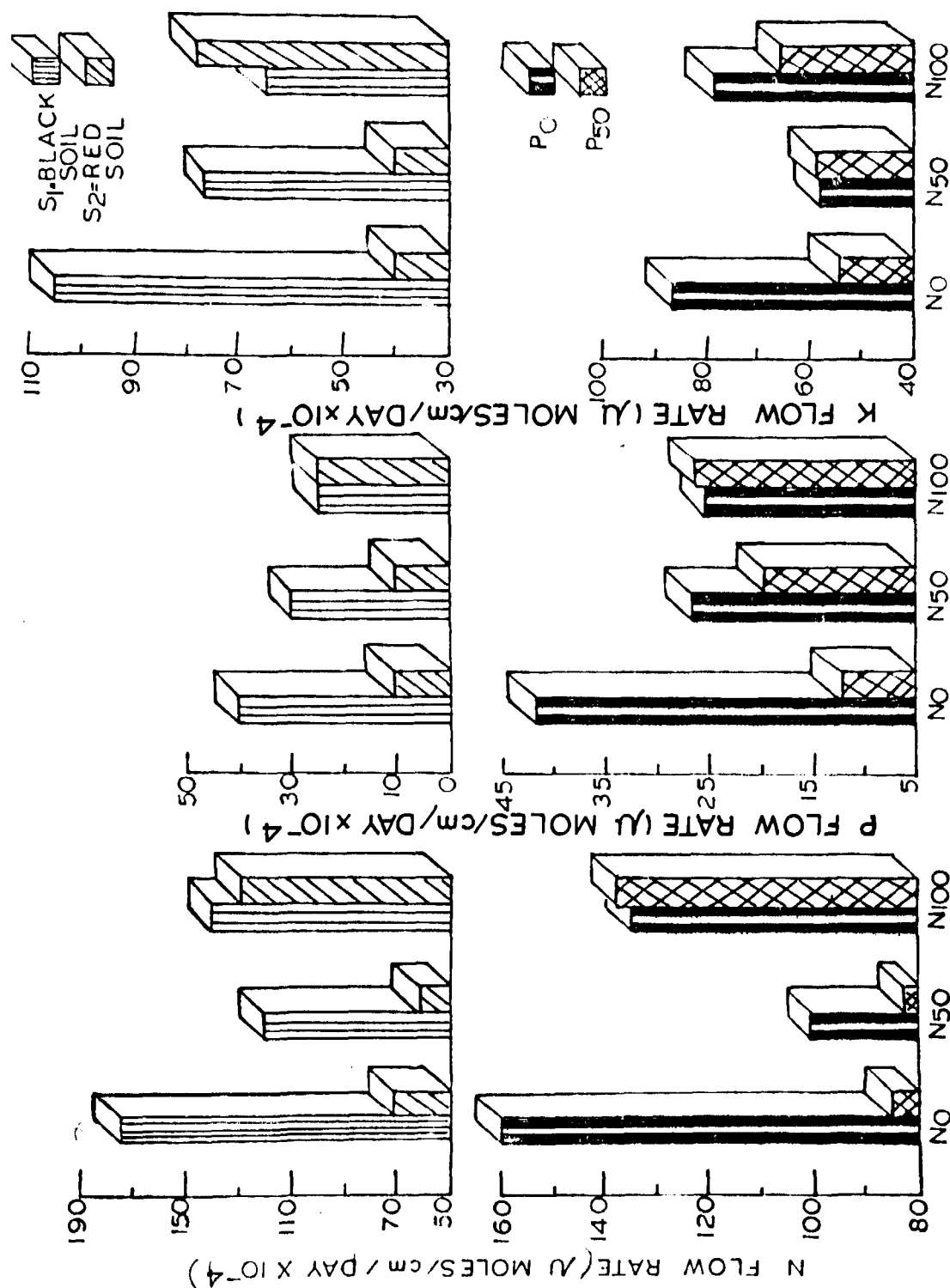


FIG. 9 FLOW RATE OF MAJOR NUTRIENTS AS INFLUENCED BY SOIL TYPES AND N AND P APPLICATION

The important inferences drawn are: (i) at 30 days stage under sterilized condition of the soil, higher K flow rate was recorded than that under normal condition of the soil but at later stages under both the conditions of the soil, the effect was similar; (ii) K flow rate was high in the black soil at P_0 level and also at 30 days stage; (iii) N_{100} level had synergistic effect on K flow rate in the red soil; (iv) P application reduced K flow rate only at 30 days stage but registered numerically higher value than no P application at 60 and 90 days stages; and (v) P application reduced K flow rate significantly in the absence of N while in the presence of N it had no effect.

4.6.2. Effect on micronutrient flow rate in the plant

(Table 20) (Fig. 10)

4.6.2.1. Effect on Fe flow rate

Individual effects

i) Sterilization: Under sterilized condition of the soil Fe flow rate was significantly reduced from 645.0 to 434.6 μ moles/cm/day $\times 10^{-6}$.

ii) Soil types: The Fe flow rate was conspicuously higher in the black soil registering 686.5 μ moles/cm/day $\times 10^{-6}$ than that in the red soil (393.0 μ moles/cm/day $\times 10^{-6}$).

iii) P levels: The P application significantly reduced Fe flow rate from 610.0 to 469.4 μ moles/cm/day $\times 10^{-6}$.

iv) N levels: The N application showed an inconsistent trend in Fe flow rate.

v) Stages: The Fe flow rate at 30 days stage was found to be significantly high registering 1334.0 μ moles/cm/day $\times 10^{-6}$.

Interaction effects

The interactions viz., St x S, St x Stages, St x P, St x N, S x Stages, Stages x P and Stages x N attained statistical significance. The important inferences drawn are: (i) under sterilized condition of the soil, Fe mobility at 30 days stage was reduced as compared to that under normal conditions of the soil and the same trend was absent at 60 and 90 days stage as well as at added levels of N and P; (ii) at 30 days stage Fe flow rate was more in the black soil than that in the red soil while this difference was not observed at later stages of crop growth; (iii) P application which caused a reduction in Fe flow rate at 30 days stage, showed an increasing trend at 60 and 90 days stages; and (iv) N₅₀ level was found to be beneficial for Fe mobility at 30 days stage and the trend got reversed at later stage.

4.6.2.2. Effect on Mn flow rate

Individual effects

i) Sterilization: Under sterilized condition of the soil Mn flow rate was enhanced from 50.3 to 94.6 μ moles/cm/day $\times 10^{-6}$.

ii) Soil types: Similar to Fe flow rate, Mn flow rate was remarkably high in the black soil registering 108.0 μ moles/cm/day $\times 10^{-6}$.

iii) P levels: P application significantly reduced Mn flow rate from 102.6 to 42.2 μ moles/cm/day $\times 10^{-6}$.

iv) N levels: N application showed an inconsistent trend on Mn mobility.

v) Stages: Mn flow rate was remarkably high at 30 days stage registering 189.0 μ moles/cm/day $\times 10^{-6}$.

Interaction effects

The interactions viz., St $\times$ Stages, St $\times$ P, S $\times$ Stages, S $\times$ P, S $\times$ N, Stages $\times$ P and P $\times$ N attained statistical significance. The inferences drawn are : (i) under sterilized condition of the soil higher Mn flow rate was registered at 30 days stage than that under normal

condition of the soil, but with advancement of crop growth this trend was not observed; (ii) P application reduced Mn flow rate under sterilized condition while under normal condition of the soil, P application marginally reduced Mn flow rate; (iii) Mn flow rate was more in the black soil as that of main effect only at 30 days stage, while at 60 and 90 days stage, the same was on par with that in the red soil; (iv) application of N at two levels reduced Mn flow rate in the black soil; (v) the negative effect of P application on Mn flow rate was observed only at 30 days stage while at later stages such effect was not existing; and (vi) N application was detrimental on Mn flow rate only in the absence of P application.

4.6.2.3. Effect on Cu flow rate

Individual effects

i) Sterilization: Under normal condition of the soil, Cu flow rate exhibited only a marginal increase over that under sterilized condition of the soil.

ii) Soil types: Cu flow rate was significantly high in the black soil registering $10.7 \mu \text{ moles/cm/day} \times 10^{-6}$.

iii) P levels: P application significantly reduced Cu flow rate from 10.0 to $6.6 \mu \text{ moles/cm/day} \times 10^{-6}$.

iv) N levels: N_{100} level significantly increased Cu flow rate from 6.7 to 11.1 μ moles/cm/day $\times 10^{-6}$.

v) Stages: Cu flow rate was remarkably high at 30 days stage registering 15.2 μ moles/cm/day $\times 10^{-6}$.

Interaction effects

The interactions viz., St $\times$ Stages, St $\times$ P, S $\times$ Stages, S $\times$ P, S $\times$ N, Stages $\times$ P, St $\times$ N and P $\times$ N attained statistical significance. The important inferences drawn are: (i) on an overall basis, under sterilized condition of the soil Cu flow rate was significantly increased at 30 days stage only, while at P_{50} level it showed a negative trend; (ii) Cu flow rate was more in the black soil than in the red soil at 30 days stage and in the black soil P application reduced Cu flow rate, while N application at 100 kg level had a positive effect on Cu flow rate; (iii) P application reduced Cu flow rate, while N_{50} or N_{100} level had a positive effect on Cu flow rate at 30 days stage; and (iv) P application at N_{100} level caused a significant reduction in Cu flow rate.

4.6.2.4. Effect on Zn flow rate

Individual effects

i) Sterilization: Under sterilized conditions of the soil, a marginal increase in Zn flow rate over that under normal condition of the soil was observed.

TABLE 20. EFFECT OF TREATMENTS ON Fe, Mn, Cu AND Zn UPTAKE RATE
IN SORGHUM PLANT IN BLACK AND RED SOILS (μ moles/cm/day $\times 10^{-6}$)

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Treatments (1)	Fe uptake rate (2)	Mn uptake rate (3)	Cu uptake rate (4)	Zn uptake rate (5)
St	434.6	94.6	8.1	40.7
NSt	645.0	50.3	8.5	39.4
S ₁	686.5	108.0	10.7	46.9
S ₂	393.0	37.0	5.8	33.2
P ₀	610.0	102.6	10.0	42.8
P ₅₀	469.4	42.2	6.6	37.3
SE	37.4	11.1	0.8	3.0
CD	105.1	31.1	2.3	8.4
N ₀	593.4	98.6	7.0	38.8
N ₅₀	442.1	58.6	6.7	36.4
N ₁₀₀	583.8	60.0	11.1	45.0
St ₁	1334.0	189.0	15.2	93.7
St ₂	158.0	11.5	3.7	7.7
St ₃	127.2	10.7	6.0	18.7
SE	45.8	13.5	1.0	3.7
CD	128.7	38.0	2.9	10.3
St x S ₁	483.4	143.6	11.0	43.0
St x S ₂	385.8	45.6	5.2	38.5
NSt x S ₁	889.6	72.3	10.5	50.8
NSt x S ₂	400.2	28.2	6.5	28.0
St x P ₀	437.3	146.0	11.5	44.3
St x P ₅₀	432.0	43.3	4.7	37.2
NSt x P ₀	783.0	59.4	8.5	41.4
NSt x P ₅₀	507.0	41.1	8.5	37.3
S ₁ x P ₀	792.0	165.3	14.3	57.3
S ₁ x P ₅₀	581.0	50.5	7.2	36.5
S ₂ x P ₀	428.3	40.0	5.6	28.4
S ₂ x P ₅₀	357.7	34.0	6.1	38.0
SE	52.9	15.6	1.2	4.3
CD	148.6	43.9	3.2	11.9
St x St ₁	998.7	254.7	17.8	109.8
St x St ₂	243.5	16.2	3.5	6.6
St x St ₃	61.6	12.8	3.0	6.5
NSt x St ₁	1669.4	123.2	12.5	78.4
NSt x St ₂	72.5	6.9	3.8	8.9
NSt x St ₃	192.8	20.6	9.1	30.9

(1)	(2)	(3)	(4)	(5)
St x N ₀	597.7	143.5	6.6	39.4
St x N ₅₀	329.4	76.5	5.2	37.6
St x N ₁₀₀	376.7	63.7	12.6	45.3
NSt x N ₀	589.1	53.6	7.5	38.1
NSt x N ₅₀	554.7	40.8	8.3	35.2
NSt x N ₁₀₀	990.8	56.3	9.7	44.7
S ₁ x St ₁	1689.4	289.7	21.0	111.7
S ₁ x St ₂	234.0	16.5	4.4	7.0
S ₁ x St ₃	136.1	17.6	6.8	22.2
S ₂ x St ₁	978.7	88.3	9.3	75.8
S ₂ x St ₂	82.1	6.6	3.0	8.6
S ₂ x St ₃	118.2	15.8	5.2	15.2
S ₁ x N ₀	828.2	163.9	7.9	50.7
S ₁ x N ₅₀	564.7	85.4	8.6	45.0
S ₁ x N ₁₀₀	666.5	74.5	15.8	45.1
S ₂ x N ₀	358.6	33.3	6.2	25.8
S ₂ x N ₅₀	319.4	31.9	4.8	27.8
S ₂ x N ₁₀₀	501.0	45.6	6.5	45.0
St ₁ x P ₀	1668.1	275.8	20.8	106.0
St ₁ x P ₅₀	1000.0	102.2	9.5	81.4
St ₂ x P ₀	58.1	9.9	4.1	6.6
St ₂ x P ₅₀	257.9	13.2	3.3	9.0
St ₃ x P ₀	104.2	22.3	4.9	16.0
St ₃ x P ₅₀	150.2	11.2	7.1	21.4
N ₀ x P ₀	713.4	160.7	8.0	48.3
N ₀ x P ₅₀	473.4	36.4	6.0	29.2
N ₁ x P ₀	431.2	75.9	5.9	40.7
N ₁ x P ₅₀	452.9	41.4	7.5	32.1
N ₂ x P ₀	685.7	71.3	15.9	39.5
N ₂ x P ₅₀	481.8	48.7	6.4	50.5
SE	64.8	19.2	1.4	5.2
CD	182.0	53.8	4.0	14.6
St ₁ x N ₀	1289.6	259.4	9.6	86.6
St ₁ x N ₅₀	1132.9	153.5	11.9	83.1
St ₁ x N ₁₀₀	1579.6	154.0	24.0	111.5
St ₂ x N ₀	323.6	13.4	4.9	6.1
St ₂ x N ₅₀	91.4	15.8	3.3	11.1
St ₂ x N ₁₀₀	59.1	5.3	2.8	6.0
St ₃ x N ₀	167.0	22.8	6.5	23.6
St ₃ x N ₅₀	101.8	6.6	4.8	15.0
St ₃ x N ₁₀₀	112.6	20.8	6.6	17.5
SE	79.4	23.5	1.8	6.4
CD	223.0	65.9	4.9	18.0

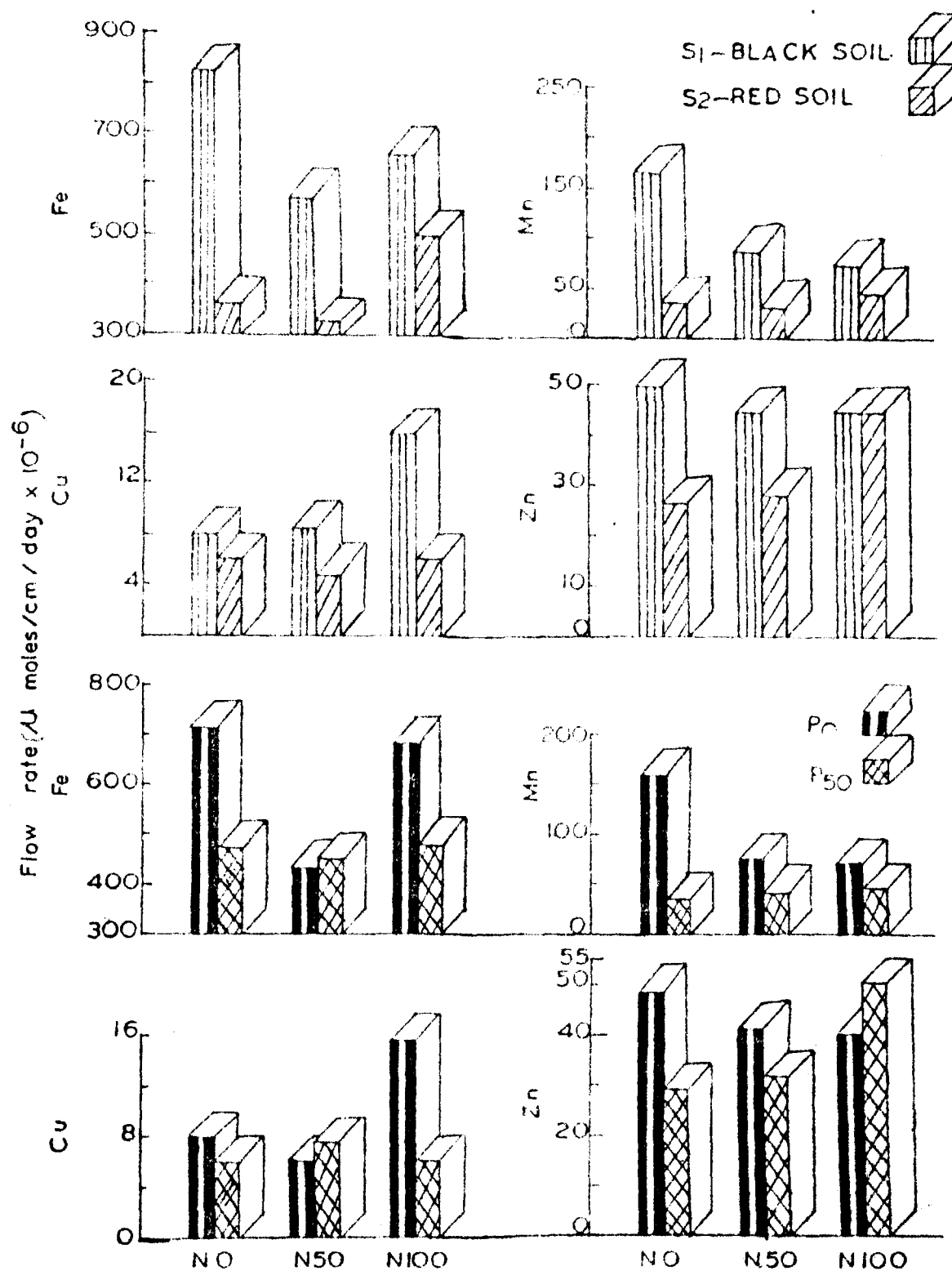


FIG. 10 FLOW RATE OF MICRONUTRIENTS AS INFLUENCED BY SOIL TYPES AND N AND P APPLICATION

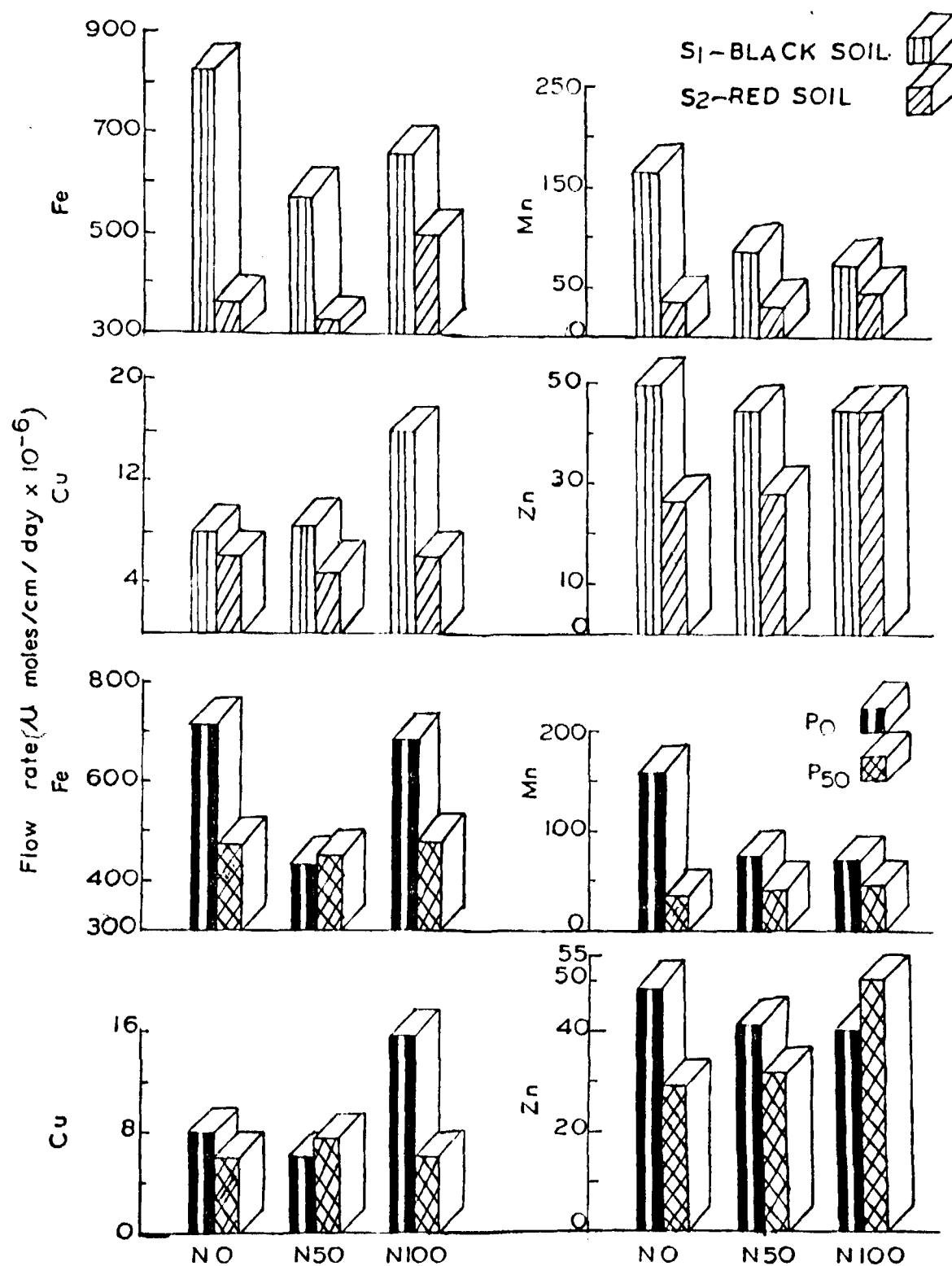


FIG. 10 FLOW RATE OF MICRONUTRIENTS AS INFLUENCED BY SOIL TYPES AND N AND P APPLICATION

ii) Soil types: The Zn flow rate was significantly higher in the black soil registering $46.9 \mu \text{ moles/cm/day} \times 10^{-6}$ than that in the red soil which registered $33.2 \mu \text{ moles/cm/day} \times 10^{-6}$.

iii) P levels: The P application showed no significant effect on Zn flow rate.

iv) N levels: The N application showed no significant effect on Zn flow rate.

v) Stages: The Zn flow rate was significantly high at 30 days stage registering $93.7 \mu \text{ moles/cm/day} \times 10^{-6}$ and got reduced with advancement of crop growth.

Interaction effects

The interactions viz., St x S, St x Stages, S x Stages, S x P, Stages x P, Stages x N and P x N attained statistical significance. The important inferences drawn are: (i) under sterilized condition of the soil at 30 days stage Zn flow rate was increased while at 90 days stage, a reverse trend was observed; (ii) the black soil recorded higher value of Zn flow rate than the red soil at 30 days stage crop growth while at later stages the difference for the soils was meagre; (iii) P application which caused a significant

reduction in Zn flow rate in the black soil, exhibited a positive effect in the red soil; (iv) P application reduced Zn flow rate at 30 days stage while at later stages P application showed marginal increase of Zn flow rate over no P application; and (v) the effect of N_{100} level was complimentary for Zn flow rate at 30 days stage; the combined application of $N_{100} P_{50}$ increased Zn flow rate.

4.7. Effect on nutrient content in plant parts

4.7.1. Effect on N, P and K content in root of sorghum plant

4.7.1.1. Effect on N content (Table 21)

Individual effects

i) Sterilization: The mean value for this mean effect ranged from 0.34 to 0.56 per cent. At 60th day, root N content was significantly increased but at 30 and 90 days of crop growth, there was no marked difference between sterilized and non-sterilized conditions.

ii) Soil types: The mean value for this main effect ranged from 0.29 per cent to 0.60 per cent. At all the three stages of crop growth, the black soil recorded significantly higher root N content than the red soil.

iii) P levels: The mean value for this main effect ranged from 0.31 to 0.48 per cent. P_{50} level significantly

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Treatments (1)	30 days (2)	60 days (3)	90 days (4)
St	0.42	0.56	0.45
NSI	0.36	0.34	0.43
S ₁	0.43	0.60	0.56
S ₂	0.36	0.29	0.33
P ₀	0.47	0.48	0.46
P ₅₀	0.31	0.42	0.43
SE	0.022	0.006	0.027
CD	0.065	0.018	0.078
N ₀	0.42	0.50	0.53
N ₅₀	0.36	0.40	0.41
N ₁₀₀	0.40	0.45	0.48
SE	0.027	0.007	0.033
CD	0.029	0.022	0.035
St x S ₁	0.45	0.89	0.73
St x S ₂	0.40	0.22	0.17
NSI x S ₁	0.42	0.12	0.19
NSI x S ₂	0.31	0.36	0.48
St x P ₀	0.45	0.63	0.47
St x P ₅₀	0.40	0.48	0.43
NSI x P ₀	0.50	0.33	0.45
NSI x P ₅₀	0.23	0.35	0.42
S ₁ x P ₀	0.49	0.72	0.50
S ₁ x P ₅₀	0.37	0.48	0.62
S ₂ x P ₀	0.45	0.24	0.42
S ₂ x P ₅₀	0.26	0.35	0.23
SE	0.031	0.008	0.038
CD	0.092	0.025	0.110
St x N ₀	0.45	0.74	0.65
St x N ₅₀	0.39	0.53	0.36
St x N ₁₀₀	0.43	0.40	0.35
NSI x N ₀	0.39	0.25	0.41
NSI x N ₅₀	0.33	0.27	0.27
NSI x N ₁₀₀	0.36	0.50	0.62
S ₁ x N ₀	0.49	0.73	0.90
S ₁ x N ₅₀	0.39	0.57	0.42
S ₁ x N ₁₀₀	0.41	0.50	0.36
S ₂ x N ₀	0.35	0.26	0.17
S ₂ x N ₅₀	0.33	0.23	0.21
S ₂ x N ₁₀₀	0.39	0.40	0.60
N ₀ x P ₀	0.57	0.42	0.35
N ₀ x P ₅₀	0.57	0.57	0.72
N ₅₀ x P ₀	0.43	0.55	0.36
N ₅₀ x P ₅₀	0.40	0.24	0.27
N ₁₀₀ x P ₀	0.43	0.47	0.67
N ₁₀₀ x P ₅₀	0.47	0.43	0.29

reduced the root N content at 30 and 60 days but no significant difference was observed due to P application at 90 days stage.

iv) N levels: The mean value for this main effect ranged from 0.31 per cent to 0.53 per cent. There was no significant increase in N content due to added levels of N application at 30 and 90 days. At 60 days stage N_{50} level significantly reduced the root N content, while no N application increased the root N content.

Interaction effects

At 30th day, the interactions revealed that P application had decreased the N content at N_0 and N_{50} levels.

At 60th day, the interactions viz., $S \times N$, $St \times S$ and $St \times N$ were significant. The salient inferences drawn are: (i) P application increased the N content only in the red soil; (ii) it had a positive effect on root N content only at N_0 level; (iii) P application reduced the N content under sterilized condition; and (iv) though on overall basis sterilized conditions increased the N content of root in the red soil, it failed to do so in the black soil and at N_{100} level.

At 90th day, the interactions, S x N, S x P, S x St, N x P and N x St showed significance. The important conclusions drawn are: (i) N application had positive effect in the red soil, particularly at N₁₀₀ level; (ii) P₅₀ level increased the N content at N₀ level, it recorded significantly lower value at N₅₀ level; (iii) P₅₀ level increased the root N content in the black soil, while it was more at P₀ level than at P₅₀ level in the red soil; (iv) root N content was more in the black soil than in the red soil under sterilized condition; and (v) sterilized condition decreased the root N content at N₁₀₀ level.

4.7.1.2. Effect on P content (Table 22)

Individual effects

i) Sterilization: The mean value for this main effect ranged from 0.14 to 0.51 per cent. Under sterilized condition the root P content was significantly decreased at 30 and 90 days of crop growth, but no significant difference was observed at 60th day between sterilized and normal soil.

ii) Soil types: The mean value for this main effect ranged from 0.23 to 0.69 per cent. The black soil recorded significantly higher value of P content in the root than the red soil at 30 and 60 days crop growth, but the trend got reversed at 90 days stage.

TABLE 22. EFFECT OF TREATMENTS ON P CONTENT IN ROOT OF SORGHUM IN BLACK AND RED SOILS(%)

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Treatment (1)	30 days (2)	60 days (3)	90 days (4)
St	0.51	0.27	0.14
NSt	0.61	0.25	0.48
S ₁	0.69	0.30	0.23
S ₂	0.43	0.23	0.40
P ₀	0.75	0.30	0.27
P ₅₀	0.37	0.23	0.35
SE	0.01	0.01	0.04
CD	0.04	0.02	0.01
N ₀	0.58	0.24	0.23
N ₅₀	0.54	0.27	0.40
N ₁₀₀	0.56	0.26	0.31
SE	0.02	0.01	0.01
CD	0.05	0.02	0.02
St x S ₁	0.63	0.36	0.14
St x S ₂	0.39	0.19	0.15
NSt x S ₁	0.75	0.23	0.32
NSt x S ₂	0.46	0.28	0.64
St x P ₀	0.64	0.33	0.13
St x P ₅₀	0.39	0.23	0.16
NSt x P ₀	0.86	0.28	0.42
NSt x P ₅₀	0.36	0.23	0.54
S ₁ x P ₀	0.95	0.36	0.20
S ₁ x P ₅₀	0.43	0.24	0.26
S ₂ x P ₀	0.54	0.25	0.35
S ₂ x P ₅₀	0.31	0.21	0.44
SE	0.02	0.01	0.01
CD	0.05	0.02	0.02
St x N ₀	0.50	0.23	0.12
St x N ₅₀	0.53	0.32	0.15
St x N ₁₀₀	0.52	0.29	0.16
NSt x N ₀	0.67	0.25	0.35
NSt x N ₅₀	0.55	0.28	0.64
NSt x N ₁₀₀	0.59	0.23	0.45
S ₁ x N ₀	0.74	0.24	0.21
S ₁ x N ₅₀	0.72	0.35	0.25
S ₁ x N ₁₀₀	0.63	0.30	0.22
S ₂ x N ₀	0.43	0.25	0.26
S ₂ x N ₅₀	0.36	0.24	0.54
S ₂ x N ₁₀₀	0.49	0.22	0.39
N ₀ x P ₀	0.97	0.22	0.32
N ₀ x P ₅₀	0.21	0.26	0.15
N ₅₀ x P ₀	0.65	0.38	0.22
N ₅₀ x P ₅₀	0.43	0.22	0.57
N ₁₀₀ x P ₀	0.62	0.31	0.28
N ₁₀₀ x P ₅₀	0.49	0.21	0.33
SE	0.02	0.01	0.01
CD	0.05	0.02	0.02

iii) P levels: The mean value for this main effect ranged from 0.27 to 0.75 per cent. P application significantly decreased the root P content at 30 and 60 days stage, but at 90 days stage P_{50} level significantly increased the root P content.

iv) N levels: The mean value for this main effect ranged from 0.23 to 0.58 per cent. No significant increase in root P content was observed at 30 and 60 days stage, but at 90 days stage N_{50} level increased the P content as compared to N_0 level.

Interaction effects

At 30th day, the interactions viz., S x N, S x P, N x P, N x St and P x St were significant. The important inferences drawn are: (i) P content in root was decreased due to N application at higher level in the black soil and also at P_0 level while N and P application had synergistic effect on P content; (ii) under non-sterilized condition of the soil N application at two levels decreased the root P content; and (iii) P content in root was decreased due to sterilized condition at P_0 level, while the differences were not marked at P_{50} level.

At 60th day, the interactions viz., S x N, S x P, S x St, N x P, N x St and P x St were significant. The salient points of inferences drawn are: (i) root P content was higher under sterilized condition in the black soil than that in the red soil; (ii) P content was decreased by the combined N and P application, while it increased the P content at N_0 level; (iii) P content was significantly decreased under sterilized condition at N_0 level, while it had synergistic effect at N_{50} and N_{100} levels; and (iv) P content was more under sterilized condition at P_0 level, while with the addition of P the differences were meagre under both sterilized and non-sterilized conditions.

At 90th day, the interactions viz., S x N, S x P, S x St, N x P, N x St and P x St were significant. The important inferences drawn are: (i) root P content was higher in the red soil under non-sterilized condition than in the black soil; and (ii) root P content was increased by the combined effect of N and P.

4.7.1.3. Effect on K content (Table 23)

Individual effects

i) Sterilization: The mean value for this main effect ranged from 0.31 to 1.21 per cent. Under sterilized condition of the soil root K content was significantly increased at 30 days stage, but the trend got reversed at 60 and 90 days stage.

TABLE 23. EFFECT OF TREATMENTS ON K CONTENT IN ROOT OF SORGHUM IN BLACK AND RED SOILS(%)

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Treatments	30 days	60 days	90 days
St	1.21	0.42	0.31
Nst	0.76	0.45	0.46
S ₁	1.03	0.52	0.39
S ₂	0.95	0.35	0.38
P ₀	1.35	0.47	0.33
P ₅₀	0.62	0.40	0.44
SE	0.03	0.01	0.003
CD	0.10	0.03	0.010
N ₀	0.97	0.35	0.40
N ₅₀	1.00	0.53	0.33
N ₁₀₀	0.99	0.42	0.43
SE	0.04	0.01	0.004
CD	0.12	0.04	0.012
St x S ₁	1.28	0.55	0.34
St x S ₂	1.15	0.29	0.28
Nst x S ₁	0.77	0.49	0.44
Nst x S ₂	0.74	0.40	0.48
St x P ₀	1.49	0.44	0.27
St x P ₅₀	0.94	0.41	0.36
Nst x P ₀	1.21	0.50	0.40
Nst x P ₅₀	0.31	0.39	0.51
S ₁ x P ₀	1.35	0.62	0.27
S ₁ x P ₅₀	0.70	0.42	0.51
S ₂ x P ₀	1.35	0.31	0.40
S ₂ x P ₅₀	0.55	0.38	0.37
SE	0.05	0.01	0.01
CD	0.14	0.04	0.02
St x N ₀	1.06	0.30	0.35
St x N ₅₀	1.09	0.57	0.24
St x N ₁₀₀	1.49	0.41	0.35
Nst x N ₀	0.88	0.41	0.45
Nst x N ₅₀	0.92	0.50	0.42
Nst x N ₁₀₀	0.48	0.43	0.51
S ₁ x N ₀	1.31	0.49	0.63
S ₁ x N ₅₀	1.14	0.60	0.29
S ₁ x N ₁₀₀	0.63	0.47	0.25
S ₂ x N ₀	0.63	0.21	0.18
S ₂ x N ₅₀	0.87	0.47	0.36
S ₂ x N ₁₀₀	1.34	0.36	0.60
N ₀ x P ₀	1.38	0.44	0.26
N ₀ x P ₅₀	0.56	0.26	0.55
N ₅₀ x P ₀	1.26	0.58	0.25
N ₅₀ x P ₅₀	0.74	0.49	0.40
N ₁₀₀ x P ₀	1.41	0.38	0.50
N ₁₀₀ x P ₅₀	0.57	0.45	0.36
SE	0.06	0.02	0.01
	- - -	0.05	0.02

ii) Soil types: The mean value for this main effect ranged from 0.35 to 1.03 per cent of root K content. The black soil recorded significantly higher root K content than the red soil at all the three stages of crop growth.

iii) P levels: The mean value for this main effect ranged from 0.33 to 1.35 per cent of K content in root. Though there was no effect for P application at 30 and 60 days stage, beneficial effect of P application was observed only at 90 days stage.

iv) N levels: The mean value for this main effect ranged from 0.35 to 1.00 per cent of root K content. Though N application did not increase the K content at 30 days stage, N₅₀ and N₁₀₀ levels significantly increased the K content at 60 and 90 days stages respectively.

Interaction effects

At 30th day, the root K content was increased due to N₁₀₀ level, in the red soil and also at sterilized condition as revealed by the interactions of N x St and S x N respectively.

At 60th day, the interactions viz., S x P, S x N, S x St, N x P, N x St and P x St were significant. The salient inferences drawn are: (i) P₅₀ level increased the

root K content in the red soil while negative effect was observed in the black soil; (ii) though under sterilized condition increased root K content in the black soil was recorded, the lowest value was associated with the red soil under sterilized condition; (iii) at N_{100} levels P_{50} application increased root K content; and (iv) P application under non-sterilized condition decreased root K content.

At 90th day, the interactions viz., S x N, S x St, S x P, N x P, N x St and P x St were significant. The salient inferences drawn include: (i) similar to that of main effect, root K content was increased by the P application in the black soil, while it was opposite in the red soil; (ii) under sterilized condition, root K content was higher in the black soil than that in the red soil; and (iii) though root K content was increased due to P application at N_0 and N_{50} levels, but it was not so at N_{100} level.

4.7.2. Effect on micronutrients content in root of sorghum plant

4.7.2.1. Effect on Fe content (Table 24)

Individual effects

i) Sterilization: The mean value for the main effect ranged from 380 to 693 ppm. Under sterilized condition of the soil the root Fe content was enhanced at 30 and 60 days stages, but reverse trend was observed at 90 days stage.

TABLE 24. EFFECT OF TREATMENTS ON Fe CONTENT IN ROOT OF SORGHUM IN BLACK AND RED SOILS (ppm)

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Treatments	30 days	60 days	90 days
St	693	442	380
NSt	538	342	419
S ₁	633	426	397
S ₂	598	358	402
P ₀	753	429	431
P ₅₀	478	355	368
SE	3.0	1.0	1.0
CD	9.0	3.0	3.0
N ₀	590	362	382
N ₅₀	620	452	457
N ₁₀₀	636	361	360
SE	4.0	1.0	1.0
CD	11.0	3.0	3.0
St x S ₁	657	499	437
St x S ₂	728	385	323
NSt x S ₁	608	353	356
NSt x S ₂	468	331	482
St x P ₀	807	477	430
St x P ₅₀	578	406	331
NSt x P ₀	699	380	432
NSt x P ₅₀	378	304	406
S ₁ x P ₀	740	446	377
S ₁ x P ₅₀	525	406	416
S ₂ x P ₀	766	412	484
S ₂ x P ₅₀	430	304	321
SE	4.0	1.0	1.0
CD	13.0	3.0	4.0
St x N ₀	670	403	356
St x N ₅₀	652	512	412
St x N ₁₀₀	755	409	373
NSt x N ₀	510	322	308
NSt x N ₅₀	589	392	408
NSt x N ₁₀₀	517	313	347
S ₁ x N ₀	532	378	382
S ₁ x N ₅₀	682	480	411
S ₁ x N ₁₀₀	684	420	397
S ₂ x N ₀	648	347	381
S ₂ x N ₅₀	559	424	504
S ₂ x N ₁₀₀	588	303	323
N ₀ x P ₀	698	386	418
N ₀ x P ₅₀	481	339	486
N ₅₀ x P ₀	802	547	388
N ₅₀ x P ₅₀	439	358	345
N ₁₀₀ x P ₀	758	354	429
N ₁₀₀ x P ₅₀	514	369	331
SE	4.0	1.0	2.0

ii) Soil types: The mean value for this main effect ranged from 358 to 633 ppm. Root Fe content was more in the black soil than that in the red soil at 30 and 60 days growth stages but at 90th day the reverse trend was observed.

iii) P levels: The mean value for this main effect remained within the range of 355 to 753 ppm. The P application tended to depress Fe accumulation in root at all the three stages studied, thereby exhibiting the antagonistic role of P on Fe.

iv) N levels: The mean value for this main effect fell within the range of 360 to 636 ppm. Though N_{100} level significantly enhanced the Fe content in root at 30 days stage but N_{50} level significantly increased the same at 60 and 90 days growth stages.

Interaction effects

At 30th day, the interactions, $S \times P$, $S \times St$ and $N \times St$ assumed relatively important significance. The salient inferences drawn include: (i) the Fe accumulation in root of sorghum crop growth in the red soil was more under P_0 level than that in the black soil, but P_{50} level accumulated more Fe in root in the black soil than in the red soil; (ii) non-sterilized condition favoured for greater accumulation of Fe in root in the black soil and the sterilized condition

favoured in the red soil; and (iii) N_{100} level under sterilized condition and N_{50} level under non-sterilized condition increased Fe accumulation in root.

At 60th day, the interactions viz., S x P, S x St and N x P showed important significance. The salient inferences drawn are: (i) irrespective of P application, the root of sorghum crop growth in the black soil showed higher concentration of Fe than that of the red soil; (ii) under both the sterilized and unsterilized conditions, the black soil favoured the Fe accumulation than the red soil; and (iii) N_{100} P_{50} combined application accounted for increased root Fe content.

At 90th day, the interactions viz., S x P, S x St and N x St showed statistical significance. The salient inferences drawn include: (i) P application enhanced the Fe accumulation in the root of sorghum crop grown in the black soil; (ii) under non-sterilized condition greater accumulation of Fe was favoured in root in the red soil than that under sterilized condition; and (iii) N_{100} level under sterilized condition enhanced the Fe accumulation in root.

4.7.2.2. Effect on Mn content (Table 25)

Individual effects

i) Sterilization: The mean values for the main effect fell within the range of 26.1 to 65.5 ppm. Under

sterilized condition, significantly higher root Mn content was recorded at 30 and 60 days stage than under non-sterilized condition, but reverse trend was observed at 90 days stage.

ii) Soil types: The mean value for the main effect ranged from 26.3 to 60.5 ppm. The root Mn content was found to be higher in the black soil than that in the red soil at 30 days stage and reverse trend was observed at 90 days stage. No such difference was observed at 60 days stage.

iii) P levels: The mean value for the main effect ranged from 28.0 to 75.0 ppm. The P application decreased root Mn content at all the three stages, thereby exhibiting antagonistic effect of P on Mn nutrition.

iv) N levels: The mean value for the main effect remained within the range of 23.5 to 64.1 ppm. Though N_{50} and N_{100} levels did not enhance root Mn content at 30th day, N application at both the levels caused a greater accumulation of Mn in root than N_0 level at 60 days stage. At 90 days stage N_{50} level increased root Mn content.

Interaction effects

The interactions viz., S x N and N x P showed important significance at 30th day. The salient inferences

TABLE 25. EFFECT OF TREATMENTS ON Mn CONTENT IN ROOT OF SORGHUM IN BLACK AND RED SOILS (ppm)

Treatments	30 days	60 days	90 days
St	65.5	32.8	26.1
NSt	49.9	26.4	37.2
S ₁	60.5	30.2	26.3
S ₂	54.9	29.0	36.9
P ₀	75.0	31.2	32.1
P ₅₀	40.5	28.0	31.1
SE	0.8	0.8	0.11
CD	2.2	2.2	0.33
N ₀	64.1	23.5	26.3
N ₅₀	53.3	32.9	36.8
N ₁₀₀	55.8	32.5	31.8
SE	0.9	0.9	0.14
CD	2.7	2.8	0.41
St x S ₁	68.6	33.9	26.3
St x S ₂	62.5	31.8	25.8
NSt x S ₁	52.5	26.5	26.4
NSt x S ₂	47.3	26.3	48.0
St x P ₀	81.1	32.4	26.9
St x P ₅₀	50.0	33.2	25.3
NSt x P ₀	68.9	30.1	33.4
NSt x P ₅₀	30.9	22.7	37.0
S ₁ x P ₀	73.9	32.6	25.0
S ₁ x P ₅₀	47.2	27.7	27.7
S ₂ x P ₀	76.1	30.0	39.3
S ₂ x P ₅₀	33.8	28.2	34.5
SE	1.10	1.10	0.2
CD	3.20	3.20	0.6
St x N ₀	68.9	27.0	21.7
St x N ₅₀	60.1	32.0	25.8
St x N ₁₀₀	67.6	39.5	30.7
NSt x N ₀	59.3	20.0	30.9
NSt x N ₅₀	46.5	33.7	47.8
NSt x N ₁₀₀	44.0	25.4	32.9
S ₁ x N ₀	66.8	20.5	22.2
S ₁ x N ₅₀	61.0	35.3	29.2
S ₁ x N ₁₀₀	53.9	34.7	24.6
S ₂ x N ₀	61.4	26.4	30.4
S ₂ x N ₅₀	45.6	30.6	44.4
S ₂ x N ₁₀₀	57.8	30.3	36.0
N ₀ x P ₀	86.1	22.9	29.7
N ₀ x P ₅₀	42.0	24.0	22.9
N ₅₀ x P ₀	67.6	36.3	37.1
N ₅₀ x P ₅₀	39.0	29.5	36.4
N ₁₀₀ x P ₀	71.3	34.6	29.6
N ₁₀₀ x P ₅₀	40.4	30.4	34.0

drawn are; (i) the black soil accumulated more of Mn in root than the red soil at N_0 and N_{50} levels, but at N_{100} level the trend was reversed; and (ii) at N_0P_0 level root Mn content was increased but at P_{50} level all N levels remained on par.

At 60th day, the notable interaction effects are $N \times P$ and $P \times St$. The important inferences drawn are: (i) in the absence of P addition N addition at two levels favoured greater Mn accumulation in root than N_0 level; (ii) sterilization or otherwise made no difference in the Mn content in root at P_0 level, but at P_{50} level Mn concentration in root was increased under sterilized condition.

At 90th day, the interactions viz., $S \times P$, $S \times St$, and $P \times St$ showed important significance. The salient inferences drawn are: (i) a synergistic role of P in the red soil and an antagonistic role of P in the black soil were observed; (ii) non-sterilized condition of the red soil and sterilized condition of the black soil caused favourable effect in the matter of Mn accumulation in root; and (iii) the antagonistic effect of P in diminishing the Mn concentration in root was pronounced only under sterilized condition.

4.7.2.3. Effect on Cu content (Table 26)

Individual effects

i) Sterilization: The mean value for this main effect ranged from 2.57 to 5.16 ppm. Under sterilized condition a significant increase in Cu content in the root was brought about at 30 days stage and the difference between sterilized and non-sterilized conditions vanished at 60 days stage. However at 90 days stage, non-sterilized condition favoured more accumulation of Cu content in root than the sterilized condition.

ii) Soil types: The mean value for this main effect ranged from 3.23 to 4.65 ppm. Root Cu content was higher in the black soil than the red soil at 60 days stage and the trend was reversed at 90 days stage. No such difference was observed at 30 days stage.

iii) P levels: The mean value for the main effect ranged from 3.09 to 5.07 ppm. P application significantly reduced root Cu content at 30 and 60 days stage, but reverse was the trend at 90 days stage.

iv) N levels: The mean value for the main effect ranged from 3.07 to 4.84 ppm. The N_{50} level significantly enhanced root Cu content at 30 and 60 days stage, but at 90 days stage N_{100} level significantly increased root Cu content.

TABLE 26. EFFECT OF TREATMENTS ON Cu CONTENT IN ROOT OF SORGHUM IN BLACK AND RED SOILS (ppm)

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Treatments	30 days	60 days	90 days
St	5.16	3.72	2.57
NSt	4.08	3.79	4.44
S ₁	4.59	4.17	3.23
S ₂	4.65	3.33	3.78
P ₀	5.07	4.22	3.09
P ₅₀	4.17	3.30	3.92
SE	0.052	0.028	0.015
CD	0.151	0.082	0.045
N ₀	4.56	3.87	3.74
N ₅₀	4.84	4.33	2.98
N ₁₀₀	4.45	3.07	3.81
SE	0.063	0.034	0.019
CD	0.184	0.101	0.055
St x S ₁	5.90	5.07	2.84
St x S ₂	4.42	2.37	2.31
NSt x S ₁	3.28	3.27	3.62
NSt x S ₂	4.88	4.31	5.26
St x P ₀	5.86	3.77	2.31
St x P ₅₀	4.46	3.67	2.83
NSt x P ₀	4.28	4.66	3.88
NSt x P ₅₀	3.87	2.92	5.01
S ₁ x P ₀	4.11	4.52	2.82
S ₁ x P ₅₀	5.07	3.82	3.64
S ₂ x P ₀	6.04	3.91	3.37
S ₂ x P ₅₀	3.26	2.77	4.20
SE	0.073	0.039	0.022
CD	0.213	0.116	0.064
St x N ₀	5.33	3.91	3.00
St x N ₅₀	5.83	4.14	2.30
St x N ₁₀₀	4.33	3.11	2.42
NSt x N ₀	3.79	3.83	4.49
NSt x N ₅₀	3.86	4.51	3.66
NSt x N ₁₀₀	4.58	3.03	5.18
S ₁ x N ₀	3.74	3.63	4.11
S ₁ x N ₅₀	5.79	2.92	3.00
S ₁ x N ₁₀₀	4.24	3.47	2.58
S ₂ x N ₀	5.38	4.12	3.38
S ₂ x N ₅₀	3.90	5.73	2.95
S ₂ x N ₁₀₀	4.67	2.66	5.03
N ₀ x P ₀	5.50	3.73	3.39
N ₀ x P ₅₀	3.63	4.02	4.10
N ₅₀ x P ₀	4.79	6.12	1.79
N ₅₀ x P ₅₀	4.89	2.53	4.17
N ₁₀₀ x P ₀	4.93	2.80	4.11
N ₁₀₀ x P ₅₀	3.98	3.34	3.49
SE	0.089	0.049	0.027
CD	0.261	0.142	0.078

At 30th day, the interactions viz., S x P, S x St, N x P, N x St, S x N and P x St showed statistical significance. The salient inferences deduced are: (i) P had a synergistic effect in the black soil and an antagonistic effect in the red soil in the matter of accumulation of Cu in root; (ii) under sterilized condition root Cu concentration was enhanced in the black soil and diminished in the red soil; (iii) the antagonistic effect of P in depressing the root Cu content was observed at N₀ level and this effect was nullified at N₅₀ level and at N₁₀₀ level, no P application showed beneficial effect; and (iv) at N₀ and N₅₀ levels sterilized condition accounted for higher root Cu concentration and this effect was not observed at higher level of N.

At 60th day, the interactions viz., S x N, S x P, S x St, N x P, N x St and P x St showed statistical significance. The salient inferences deduced are: (i) under non-sterilized condition the red soil accumulated more Cu content in root than the black soil and the reverse was the case under sterilized condition; and (ii) the antagonistic effect of P in diminishing root Cu content was confined under non-sterilized condition.

At 90th day, the interactions viz., S x N; S x St N x P, N x St and P x St showed statistical significance. The salient inferences drawn include: (i) at N₀ and N₅₀ levels the black soil was found to be more favourable for Cu accumulation in root than the red soil while at N₁₀₀ level the red soil accumulated enhanced Cu concentration in root; (ii) under non-sterilized condition, the red soil caused greater accumulation of Cu in root than the black soil while under sterilized condition the black soil enhanced the Cu concentration in root; and (iii) P application showed a synergistic influence at N₀ and N₅₀ levels and an antagonistic effect at N₁₀₀ level.

4.7.2.4. Effect on Zn content (Table 27)

Individual effects

i) Sterilization: The mean value for the main effect ranged from 30.3 to 81.6 ppm. Under sterilized condition root Zn content was significantly increased at 30 and 60 days stage, but the trend was reversed at 90 days stage.

ii) Soil types: The mean value for the main effect ranged from 30.9 to 70.0 ppm. The black soil significantly enhanced root Zn content at 30 and 60 days stage, while reverse was the trend at 90 days stage.

TABLE 27. EFFECT OF TREATMENTS ON Zn CONTENT IN ROOT OF
SORGHUM IN BLACK AND RED SOILS (ppm)

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Treatments	30 days	60 days	90 days
St	81.6	40.4	30.3
NSt	52.2	31.7	5.22
S ₁	70.0	41.2	38.0
S ₂	64.0	30.9	44.5
P ₀	66.3	39.9	38.9
P ₅₀	67.5	32.3	43.6
SE	0.7	0.2	0.2
CD	2.2	0.7	0.5
N ₀	72.3	33.6	44.5
N ₅₀	68.8	41.3	42.9
N ₁₀₀	59.5	33.3	36.4
SE	0.9	0.3	0.2
CD	2.7	0.8	0.6
St x S ₁	82.8	48.9	31.8
St x S ₂	80.4	31.8	28.7
NSt x S ₁	57.0	33.4	44.2
NSt x S ₂	47.3	30.1	60.3
St x P ₀	76.7	43.6	29.0
St x P ₅₀	86.5	37.1	31.6
NSt x P ₀	55.9	36.0	48.8
NSt x P ₅₀	48.4	27.4	55.6
S ₁ x P ₀	62.2	44.8	29.0
S ₁ x P ₅₀	77.6	37.6	47.0
S ₂ x P ₀	70.4	34.8	48.8
S ₂ x P ₅₀	57.3	27.0	40.2
SE	1.1	0.3	0.2
CD	3.1	0.9	0.7
St x N ₀	91.5	38.0	33.5
St x N ₅₀	81.3	45.1	31.3
St x N ₁₀₀	72.0	37.9	26.1
NSt x N ₀	53.1	29.1	55.5
NSt x N ₅₀	56.4	37.4	54.5
NSt x N ₁₀₀	47.0	28.7	46.7
S ₁ x N ₀	77.5	35.0	47.3
S ₁ x N ₅₀	76.3	46.7	35.8
S ₁ x N ₁₀₀	55.9	41.8	30.9
S ₂ x N ₀	67.1	32.1	41.7
S ₂ x N ₅₀	61.4	35.9	50.0
S ₂ x N ₁₀₀	63.1	24.8	41.8
N ₀ x P ₀	72.1	33.7	44.3
N ₀ x P ₅₀	72.5	33.5	44.7
N ₅₀ x P ₀	76.3	55.0	38.6
N ₅₀ x P ₅₀	61.4	27.6	47.2
N ₁₀₀ x P ₀	50.5	30.8	33.8
N ₁₀₀ x P ₅₀	68.5	35.8	38.9

iii) P levels: The mean value for the main effect ranged from 32.3 to 67.5 ppm. The P application increased root Zn content at 30 and 90 days stage, but this effect was not observed at 60 days stage.

iv) N levels: The mean value for the main effect ranged from 33.3 to 72.3 ppm. N₅₀ level significantly enhanced root Zn content at 60 days stage, but the beneficial effect of N application was not observed at 30 and 90 days of crop growth.

Interaction effects

At 30th day, the interactions viz., S x N, S x P, S x St, N x P, N x St and P x St showed statistical significance. The salient inferences drawn are: (i) the black soil favoured more accumulation of Zn content in the root due to P addition than the red soil; (ii) under non-sterilized condition the black soil favoured more accumulation of zinc content in the root than the red soil and this effect was nullified under sterilized condition; (iii) in the absence of N addition application of P brought about no differential effect on root Zn content; (iv) at N₅₀ level antagonistic effect and at N₁₀₀ level synergistic effect had operated; and (v) P addition under sterilized condition enhanced root Zn content.

At 60th day, the interactions viz., S x N, S x St, N x P and P x St were significant. It was observed that in the absence of N addition P application brought about no differential effect on root Zn content.

At 90th day, the interactions viz., S x N, S x P, S x St, N x P, N x St and P x St showed statistical significance. The salient points of inferences drawn are: (i) enhanced root Zn content was observed in the red soil in the absence of P addition and more Zn content was observed in the black soil at added P level; (ii) sterilized condition favoured higher root Zn content in the black soil while non-sterilized condition proved more conducive for the red soil than the black soil; and (iii) the synergistic effect of P became pronounced at N₅₀ and N₁₀₀ levels.

4.7.3. Effect on N, P and K content in shoot of sorghum plant

4.7.3.1. Effect on N content (Table 28)

Individual effects

i) Sterilization: The mean value for this main effect ranged from 0.52 to 1.41 per cent. Under sterilized condition shoot N content was enhanced at 30 and 60 days stages but the trend was reversed at 90 days stage.

ii) Soil types: The mean value for this main effect ranged from 0.50 to 1.16 per cent. The black soil registered

significantly higher shoot N content at 30 and 60 days stages but reverse was the case at 90 days stage.

iii) P levels: The mean value for this main effect fell within the range of 0.52 to 1.23 per cent. Though P application did not increase N content in shoot at 30 days stage, it produced marginal increase at 60 days stage and spectacular increase at 90 days stage.

iv) N levels: The mean value for this main effect ranged from 0.50 to 1.33 per cent. N_{100} level enhanced shoot N content at 30 and 90 days stage, but there was no differential effect due to N application at two levels at 60 days stage.

Interaction effects

At 30th day, the interactions viz., $S \times N$, $S \times St$, $N \times P$, $N \times St$ and $P \times St$ showed statistical significance. The salient inferences drawn include: (i) N accumulation in the shoot of sorghum crop grown in the black soil was greater at N_{100} level than that in the red soil, whereas in the red soil the effect due to N application at both the levels was not observed; (ii) there was greater accumulation of N in shoot in both the soils under sterilized condition; (iii) accumulation of N was greater at $N_{100} P_0$ level than the other level of combinations; (iv) irrespective of sterilization

TABLE 28. EFFECT OF TREATMENTS ON N CONTENT IN SHOOT OF SORGHUM IN BLACK AND RED SOILS(%)

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Treatments	30 days	60 days	90 days
St	1.41	1.37	0.52
NSt	0.94	1.09	0.56
S ₁	1.30	1.30	0.50
S ₂	1.60	1.16	0.58
P ₀	1.23	1.22	0.52
P ₅₀	1.13	1.24	0.57
SE	0.01	0.01	0.002
CD	0.03	0.04	0.005
N ₀	1.26	1.25	0.52
N ₅₀	0.94	1.21	0.50
N ₁₀₀	1.33	1.23	0.61
SE	0.01	0.02	0.002
CD	0.04	0.05	0.007
St x S ₁	1.58	1.37	0.44
St x S ₂	1.25	1.37	0.60
NSt x S ₁	1.01	1.24	0.56
NSt x S ₂	0.87	0.95	0.57
St x P ₀	1.41	1.30	0.52
St x P ₅₀	1.42	1.44	0.52
NSt x P ₀	1.04	1.14	0.51
NSt x P ₅₀	0.84	1.05	0.62
S ₁ x P ₀	1.35	1.27	0.45
S ₁ x P ₅₀	1.24	1.33	0.55
S ₂ x P ₀	1.10	1.17	0.58
S ₂ x P ₅₀	1.01	1.15	0.59
SE	0.02	0.02	0.003
CD	0.05	0.06	0.008
St x N ₀	1.53	1.36	0.46
St x N ₅₀	1.09	1.39	0.46
St x N ₁₀₀	1.63	1.35	0.66
NSt x N ₀	1.00	1.15	0.59
NSt x N ₅₀	0.78	1.03	0.53
NSt x N ₁₀₀	1.04	1.10	0.57
S ₁ x N ₀	1.31	1.34	0.41
S ₁ x N ₅₀	1.14	1.24	0.53
S ₁ x N ₁₀₀	1.45	1.32	0.57
S ₂ x N ₀	1.22	1.17	0.63
S ₂ x N ₅₀	0.74	1.18	0.46
S ₂ x N ₁₀₀	1.21	1.13	0.66
N ₀ x P ₀	1.31	1.26	0.38
N ₀ x P ₅₀	1.22	1.25	0.67
N ₅₀ x P ₀	0.93	1.21	0.42
N ₅₀ x P ₅₀	0.95	1.21	0.57
N ₁₀₀ x P ₀	1.45	1.19	0.75
N ₁₀₀ x P ₅₀	1.22	1.26	0.48
...	0.02	0.02	0.003

N_{100} level proved to be much better in accumulation of N in shoot than N_0 and N_{50} levels; and (v) accumulation of N was greater in shoot under sterilized condition irrespective of P application.

At 60th day, the interactions viz., S x N, S x St, N x St and P x St showed statistical significance. The salient inferences drawn are: (i) irrespective of the levels of N tried, accumulation of N in shoot was greater in the black soil than that in the red soil; (ii) under sterilized condition as observed at 30th day, there was enhanced shoot N content in both the soils as well as at all levels of N and P tried.

At 90th day, the interactions viz., S x P, S x N, S x St, N x P, N x St and P x St assumed statistical significance. The salient inferences drawn are: (i) accumulation of N in shoot was enhanced at N_{100} level and P_{50} level in both the soils; (ii) irrespective of P application and sterilized condition there was enhanced accumulation of N in shoot of the test crop grown in the red soil; (iii) at P_0 level N_{100} level registered enhanced accumulation of N in shoot while the trend was reversed at P_{50} level; and (iv) accumulation of N in shoot was increased under sterilized condition at N_{100} level and P_0 level, while under non-sterilized condition at N_0 level and P_{50} level the same was increased.

4.7.3.2. Effect on P content (Table 29)

Individual effects

i) Sterilization: The mean value for this main effect fell within the range of 0.09 to 0.15 per cent. Under sterilized condition shoot P content was enhanced at 30 days stage, but the trend was reversed at 60 and 90 days stage.

ii) Soil types: The mean value for this main effect ranged from 0.09 to 0.14 per cent. The black soil registered significantly higher content of P in shoot than the red soil at all the three stages of crop growth.

iii) P levels: The mean value for this main effect fell within the range of 0.08 to 0.14 per cent. The P application enhanced shoot P content at 60 days stage, but such effect was not observed at 30 and 90 days stage.

iv) N levels: The mean value for this main effect fell within the range of 0.06 to 0.13 per cent. N_{100} level significantly increased shoot P content at 30 and 60 days of crop growth, but at 90 days stage either N_{50} or N_{100} level did not increase shoot P content.

Interaction effects

At 30th day, the interactions viz., $S \times N$, $S \times P$, $S \times St$, $N \times P$, $N \times St$ and $P \times St$ showed statistical

TABLE 29. EFFECT OF TREATMENTS ON P CONTENT IN SHOOT OF SORGHUM IN BLACK AND RED SOILS (%)

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Treatments	30 days	60 days	90 days
St	0.15	0.09	0.11
NSt	0.09	0.10	0.12
S ₁	0.14	0.10	0.14
S ₂	0.10	0.09	0.09
P ₀	0.14	0.08	0.14
P ₅₀	0.10	0.11	0.08
SE	0.0005	0.002	0.003
CD	0.001	0.005	0.009
N ₀	0.10	0.10	0.19
N ₅₀	0.12	0.08	0.09
N ₁₀₀	0.13	0.11	0.06
SE	0.0006	0.002	0.004
CD	0.002	0.006	0.011
St x S ₁	0.18	0.07	0.11
St x S ₂	0.12	0.10	0.11
NSt x S ₁	1.02	0.13	0.17
NSt x S ₂	0.07	0.08	0.07
St x P ₀	0.20	0.08	0.11
St x P ₅₀	0.10	0.10	0.11
NSt x P ₀	0.08	0.08	0.18
NSt x P ₅₀	0.10	0.12	0.06
S ₁ x P ₀	0.14	0.07	0.17
S ₁ x P ₅₀	0.14	0.12	0.10
S ₂ x P ₀	0.13	0.08	0.12
S ₂ x P ₅₀	0.06	0.10	0.07
SE	0.0007	0.002	0.004
CD	0.002	0.007	0.012
St x N ₀	0.09	0.08	0.15
St x N ₅₀	0.19	0.09	0.11
St x N ₁₀₀	0.17	0.09	0.06
NSt x N ₀	0.11	0.11	0.22
NSt x N ₅₀	0.05	0.07	0.07
NSt x N ₁₀₀	0.10	0.13	0.06
S ₁ x N ₀	0.10	0.09	0.22
S ₁ x N ₅₀	0.14	0.07	0.15
S ₁ x N ₁₀₀	0.18	0.13	0.03
S ₂ x N ₀	0.10	0.11	0.15
S ₂ x N ₅₀	0.09	0.08	0.04
S ₂ x N ₁₀₀	0.09	0.08	0.09
N ₀ x P ₀	0.12	0.06	0.30
N ₀ x P ₅₀	0.08	0.13	0.08
N ₅₀ x P ₀	0.17	0.10	0.06
N ₅₀ x P ₅₀	0.07	0.06	0.13
N ₁₀₀ x P ₀	0.12	0.08	0.08
N ₁₀₀ x P ₅₀	0.15	0.14	0.04
SE	0.0007	0.003	0.005

significance. The salient inferences drawn are: (i) irrespective of the levels of N and P tried and sterilized condition, there was greater accumulation of P in shoot of test crop grown in the black soil; (ii) the combined application of $N_{100} P_{50}$ level enhanced shoot P content; (iii) under sterilized condition at N_{50} and N_{100} levels shoot P content was increased, while at N_0 level the trend was reversed; (iv) under non-sterilized condition P application increased shoot P content, while under sterilized condition no P treatment increased shoot P content.

At 60th day, the interactions viz., S x N, S x P, S x St, N x P, N x St and P x St showed significance. The salient inferences drawn are: (i) the black soil at N_{100} level and the red soil at N_0 level enhanced shoot P content, while P_{50} level enhanced the same in both the soils; (ii) the black soil under non-sterilized condition and the red soil under sterilized condition enhanced shoot P content; (iii) $N_{100}P_{50}$ level and $N_{50}P_0$ level proved to be better in accumulating P content in shoot compared to other combined applications; (iv) N_{100} level under non-sterilized condition, while under sterilized condition N_{100} and N_{50} levels being on par increased shoot P content; and (v) irrespective of sterilized condition P_{50} level enhanced shoot P content.

At 90th day, the interactions viz., S x N, S x St, N x P, N x St and P x St were significant. The important

inferences drawn are: (i) N_0 level showed enhanced shoot P content in both the soils; (ii) as was observed at 60th day, the black soil under non-sterilized condition and the red soil under sterilized condition enhanced shoot P content; (iii) with N_{50} and N_{100} applications there was reduction in the accumulation of shoot P content irrespective of sterilized condition; and (iv) under sterilized condition P application was needed for increasing shoot P content.

4.7.3.3 Effect on K content (Table 30)

Interaction effects

i) Sterilization: The mean value for this main effect fell within the range of 1.44 to 2.09 per cent. Under normal condition of the soil, shoot K content was significantly higher than under sterilized condition at 30 and 60 days stage while the trend was reversed at 90 days of crop growth stage.

ii) Soil types: The mean value for this main effect ranged from 1.51 to 1.90 per cent. The black soil significantly increased shoot K content at 30 days stage and a reverse trend was observed at 90 days stage. There was no difference on K content among the two soils at 60 days stage.

iii) P levels: The mean value for this main effect ranged from 1.49 to 1.88 per cent. Though P application did

TABLE 30. EFFECT OF TREATMENTS ON K CONTENT IN SHOOT OF SORGHUM IN BLACK AND RED SOILS(2)

Treatments	30 days	60 days	90 days
St	1.45	1.59	1.70
NSt	1.71	2.09	1.44
S ₁	1.65	1.90	1.53
S ₂	1.51	1.79	1.62
P ₀	1.66	1.81	1.49
P ₅₀	1.50	1.88	1.65
SE	0.014	0.031	0.01
CD	0.041	0.089	0.03
N ₀	1.54	1.87	1.56
N ₅₀	1.51	1.84	1.51
N ₁₀₀	1.68	1.83	1.65
SE	0.017	0.037	0.012
CD	0.050	0.109	0.035
St x S ₁	1.48	1.41	1.49
St x S ₂	1.42	1.78	1.90
NSt x S ₁	1.81	2.40	1.56
NSt x S ₂	1.60	1.89	1.33
St x P ₀	1.50	1.59	1.55
St x P ₅₀	1.40	1.60	1.84
NSt x P ₀	1.81	2.04	1.42
NSt x P ₅₀	1.60	2.16	1.47
S ₁ x P ₀	1.77	1.90	1.36
S ₁ x P ₅₀	1.53	1.90	1.69
S ₂ x P ₀	1.55	1.72	1.62
S ₂ x P ₅₀	1.47	1.85	1.61
SE	0.02	0.04	0.01
CD	0.06	0.13	0.04
St x N ₀	1.34	1.56	1.52
St x N ₅₀	1.31	1.61	1.65
St x N ₁₀₀	1.71	1.61	1.93
NSt x N ₀	1.75	2.18	1.60
NSt x N ₅₀	1.71	2.06	1.36
NSt x N ₁₀₀	1.66	2.06	1.37
S ₁ x N ₀	1.54	1.84	1.46
S ₁ x N ₅₀	1.69	2.12	1.61
S ₁ x N ₁₀₀	1.71	1.75	1.51
S ₂ x N ₀	1.55	1.90	1.66
S ₂ x N ₅₀	1.33	1.55	1.40
S ₂ x N ₁₀₀	1.65	1.92	1.79
N ₀ x P ₀	1.38	1.67	1.46
N ₀ x P ₅₀	1.71	2.07	1.66
N ₅₀ x P ₀	1.45	1.72	1.32
N ₅₀ x P ₅₀	1.57	1.95	1.70
N ₁₀₀ x P ₀	2.14	2.05	1.69
N ₁₀₀ x P ₅₀	1.23	1.62	1.60
SE	0.02	0.05	0.02

not increase shoot K content at 30 days stage, its beneficial effect was marginal at 60 days stage and was pronounced at 90 days stage.

iv) N levels: The mean value for this main effect remained within the range of 1.51 to 1.87 per cent. N_{100} level markedly increased the K content in shoot at 30 and 90 days stage, while the differential behaviour due to N application was nullified at 60 days stage.

Interaction effects

At 30th day, the interactions viz., $S \times N$, $S \times P$, $S \times St$, $N \times P$, $N \times St$ and $P \times St$ assumed statistical significance. The salient inferences drawn are: (i) N_{100} level enhanced shoot K content in both the soils; (ii) irrespective of P application and irrespective of sterilized condition, the black soil showed higher K content in shoot than the red soil; (iii) the combined application of $N_{100} P_0$ and $N_0 P_{50}$ showed higher accumulation of shoot K content than the other combined applications; and (v) under sterilized condition, N_{100} level was needed for increasing shoot K content while P application showed no beneficial effect both under sterilized and normal conditions.

At 60th day, the interactions viz., $S \times N$, $S \times St$, and $N \times P$ were statistically significant. The salient inferences

drawn are: (i) accumulation of K content in shoot was greater in the black soil than that in the red soil at N_{50} level and in the red soil at N_{100} level which was on par with N_0 level; (ii) in both the soils, the non-sterilized condition proved to be much better in increasing shoot K content than the sterilized condition; and (iii) the combined application of $N_{100} P_0$ and $N_0 P_{50}$ showed higher shoot K content than the other combined applications.

At 90th day, the interactions viz., S x N, S x P, S x St, N x P, N x St and P x St assumed statistical significance. The important inferences drawn are: (i) similar to that observed at 60th day shoot K content was greater in the black soil than the red soil at N_{50} level and in the red soil at N_{100} level; (ii) P application enhanced shoot K content in the black soil while it showed no increasing trend in the red soil; (iii) the black soil under normal condition, while the red soil under sterilized condition and the combined applications of $N_{100} P_0$ and $N_{50} P_{50}$ showed beneficial effect in enhancing shoot K content; and (iv) under sterilized condition N_{100} level was needed to enhance shoot K content and irrespective of sterilized condition P application was found to be better in accumulating K content in shoot than no P application.

4.7.4. Effect on micronutrient content in shoot of sorghum plant

4.7.4.1. Effect on Fe content (Table 31)

Individual effects

i) Sterilization: The mean value for this main effect ranged from 1056 to 3328 ppm. Under sterilized condition, shoot Fe content was not enhanced at 30 days stage but at 60 and 90 days stage the same was increased.

ii) Soil types: The mean value for this main effect ranged from 1124 to 2990 ppm. The black soil significantly enhanced shoot Fe content at all the three stages of crop growth.

iii) P levels: The mean value for this main effect ranged from 1275 to 2810 ppm. The P application had no effect on shoot Fe content at 30 and 60 days of crop growth and produced marginal increase at 90 days stage.

iv) N levels: The mean value for this main effect ranged from 1172 to 2766 ppm. The N application at the two levels did not enhance shoot Fe content at all the three stages of crop growth.

Interaction effects

At 30th day, the interactions viz., S x N, S x P, S x St, N x P, N x St and P x St assumed statistical

TABLE 31. EFFECT OF TREATMENTS ON Fe CONTENT IN SHOOT OF SORGHUM IN BLACK AND RED SOILS(ppm)

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Treatments	30 days	60 days	90 days
St	1600	3231	1504
NSt	3328	1257	1056
S ₁	2556	2990	1436
S ₂	2372	1498	1124
P ₀	2810	2380	1275
P ₅₀	2118	2158	1286
SE	4.00	13.0	27
CD	12.0	37.0	79
N ₀	2662	2766	1405
N ₅₀	2138	1672	1263
N ₁₀₀	2592	2294	1172
SE	5.0	16.0	33
CD	14.0	46.0	97
St x S ₁	988	4703	1804
St x S ₂	2213	1759	1204
NSt x S ₁	4123	1277	1068
NSt x S ₂	2532	1238	1045
St x P ₀	1777	3342	1479
St x P ₅₀	1424	3113	1529
NSt x P ₀	3843	1312	1070
NSt x P ₅₀	2812	1203	1042
S ₁ x P ₀	2686	3279	1429
S ₁ x P ₅₀	2426	2701	1443
S ₂ x P ₀	2934	1381	1120
S ₂ x P ₅₀	1810	1615	1129
SE	6.0	18.0	38.0
CD	17.0	53.0	111.2
St x N ₀	1833	4182	1847
St x N ₅₀	1439	2144	1330
St x N ₁₀₀	1530	3367	1335
NSt x N ₀	3491	1350	963
NSt x N ₅₀	2838	1201	1196
NSt x N ₁₀₀	3654	1221	1010
S ₁ x N ₀	2469	3553	1688
S ₁ x N ₅₀	2534	2155	1463
S ₁ x N ₁₀₀	2664	3262	1157
S ₂ x N ₀	2854	1979	1122
S ₂ x N ₅₀	1743	1190	1063
S ₂ x N ₁₀₀	2521	1325	1188
N ₀ x P ₀	3393	2213	1457
N ₀ x P ₅₀	1930	3319	1352
N ₅₀ x P ₀	1992	1868	1341
N ₅₀ x P ₅₀	2285	1476	1185
N ₁₀₀ x P ₀	3045	2908	1025
N ₁₀₀ x P ₅₀	2139	1679	1320
SE	7.0	22.0	47
CD	20.0	64.0	137

significance. The salient inferences drawn are: (i) the black soil at N_{100} level and the red soil at N_0 level exhibited enhanced accumulation of Fe in shoot; (ii) irrespective of P application both the soils and irrespective of the soil type normal condition of the soil exhibited enhanced Fe content in shoot; (iii) combined application of $N_{50} P_{50}$ and $N_{100} P_0$ showed higher accumulation of Fe in shoot than the other combined applications; and (iv) irrespective of N and P levels tried, the normal condition of the soil showed higher concentration of Fe in shoot than the sterilized condition.

At 60th day, the interactions viz., S x N, S x P, S x St, N x P, N x St and P x St assumed statistical significance. The salient inferences drawn are: (i) irrespective of N and P levels tried the black soil showed higher concentration of Fe in shoot than the red soil; (ii) both the soils under sterilized condition showed higher concentration of Fe in shoot than under non-sterilized condition; (iii) the combined application of $N_{100} P_0$ and $N_0 P_{50}$ showed higher accumulation of Fe in shoot than the other combined applications; and (iv) irrespective of N and P levels tried the sterilized condition showed higher concentration of Fe in shoot than the non-sterilized condition.

At 90th day, the interactions viz., S x N, S x St, N x P and N x St showed statistical significance. The

important inferences drawn are: (i) irrespective of N application, the black soil showed higher accumulation of Fe in shoot than the red soil while a marginal increase was observed in the red soil at N_{100} level; (ii) under sterilized condition there was enhanced shoot Fe content in both the soils and at all levels of N tried as compared to that under normal condition of the soil; and (iii) the combined application of N_0P_{50} on par with $N_{100}P_{50}$ and $N_{50}P_{50}$ showed higher concentration of Fe in shoot than the other combined applications.

4.7.4.2. Effect on Mn content (Table 32)

Individual effects

i) Sterilization: The mean value for this main effect ranged from 71 to 317 ppm. Under sterilized condition shoot Mn content was significantly increased at all the three stages of crop growth.

ii) Soil types: The mean value for this main effect ranged from 79 to 331 ppm. The black soil significantly enhanced shoot Mn content at all the three stages of crop growth.

iii) P levels: The mean value for this main effect ranged from 101 to 319 ppm. The P application did not enhance shoot Mn content at all the three stages of crop growth.

TABLE 32. EFFECT OF TREATMENTS ON Mn CONTENT IN SHOOT OF
SORGHUM IN BLACK AND RED SOILS (ppm)

200

Treatments	30 days	60 days	90 days
St	317	253	160
NSL	220	92	71
S ₁	331	223	152
S ₂	207	122	79
P ₀	319	179	130
P ₅₀	218	166	101
SE	1.4	1.2	0.4
CD	4.0	3.4	1.3
N ₀	289	185	129
N ₅₀	267	156	95
N ₁₀₀	250	177	122
SE	1.7	1.4	0.5
CD	5.0	4.1	1.5
St x S ₁	389	339	227
St x S ₂	245	166	94
NSL x S ₁	273	107	77
NSL x S ₂	168	78	64
St x P ₀	422	271	191
St x P ₅₀	212	234	130
NSL x P ₀	216	86	70
NSL x P ₅₀	225	98	72
S ₁ x P ₀	399	240	178
S ₁ x P ₅₀	263	206	127
S ₂ x P ₀	239	118	83
S ₂ x P ₅₀	174	127	75
SE	2.0	1.6	0.4
CD	5.7	5.0	1.3
St x N ₀	327	276	183
St x N ₅₀	333	220	126
St x N ₁₀₀	290	262	173
NSL x N ₀	252	93	76
NSL x N ₅₀	201	92	65
NSL x N ₁₀₀	209	92	72
S ₁ x N ₀	306	224	172
S ₁ x N ₅₀	342	205	121
S ₁ x N ₁₀₀	345	239	164
S ₂ x N ₀	273	146	86
S ₂ x N ₅₀	192	107	70
S ₂ x N ₁₀₀	154	114	81
N ₀ x P ₀	360	198	158
N ₀ x P ₅₀	218	172	100
N ₅₀ x P ₀	313	150	96
N ₅₀ x P ₅₀	221	162	95
N ₁₀₀ x P ₀	283	189	137
N ₁₀₀ x P ₅₀	216	165	107
SE	2.4	2.0	0.7

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iv) N levels: The mean value for this main effect ranged from 95 to 289 ppm. The N application at the two levels did not enhance shoot Mn content at all the three stages of crop growth.

Interaction effects

At 30th day, the interactions viz., S x N, S x P, S x St, N x P, N x St and P x St were significant. The salient inferences drawn are: (i) irrespective of the levels of N and P tried the black soil showed higher shoot Mn content than the red soil; (ii) under sterilized condition both the soils showed increased shoot Mn content; (iii) the combined application of $N_{50} P_{50}$ being on par with $N_0 P_{50}$ and $N_{100} P_{50}$ registered greater accumulation of Mn in shoot than the other combined applications; and (iv) at all N levels under sterilized condition and at P_0 level under sterilized condition, while at P_{50} level non-sterilized condition were found to increase the accumulation of Mn in shoot.

At 60th day, the interactions viz., S x N, S x P, S x St, N x P, N x St, and P x St were significant. The salient inferences drawn are: (i) irrespective of levels of N and P tried the black soil showed higher Mn content in shoot than the red soil; however, the black soil at N_{100} and P_0 level and the red soil at N_0 and P_{50} levels proved to be

better in increasing Mn content in shoot; (ii) sterilized condition helped to enhance Mn accumulation in shoot in both the soils and at all levels of N and P tried.

At 90th day, the interactions viz., S x N, S x P, S x St, N x P, N x St and P x St attained statistical significance. The salient inferences drawn are: (i) at all levels of N and P the black soil showed enhanced shoot Mn content; (ii) irrespective of N and P applications at all levels and irrespective of soil types sterilized condition registered increased shoot Mn content; and (iii) the combined application of N₁₀₀ P₅₀ showed higher accumulation of Mn in the shoot than the other combined applications.

4.7.4.3. Effect on Cu content (Table 33)

Individual effects

i) Sterilization: The mean value for this main effect ranged from 23.1 to 107.0 ppm. Under sterilized condition shoot Cu content at 60 and 90 days of crop growth was increased, while under normal soil condition shoot Cu content showed increasing trend at 30 days stage.

ii) Soil types: The mean value for this main effect ranged from 26.8 to 108.6 ppm. The red soil showed increased

TABLE 33. EFFECT OF TREATMENTS ON Cu CONTENT IN SHOOT OF SORGHUM IN BLACK AND RED SOILS (ppm)

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Treatments	30 days	60 days	90 days
St	23.1	98.7	107.0
NSt	31.2	83.6	79.1
S ₁	26.8	104.0	108.6
S ₂	27.6	78.3	79.5
P ₀	29.8	90.6	85.6
P ₅₀	24.6	91.7	85.5
SE	0.3	0.7	0.6
CD	0.9	2.1	1.7
N ₀	27.3	91.5	93.1
N ₅₀	28.1	79.0	93.7
N ₁₀₀	26.2	102.9	92.4
SE	0.4	0.9	0.7
CD	1.1	2.6	2.0
St x S ₁	21.4	120.3	122.0
St x S ₂	24.8	77.2	91.9
NSt x S ₁	32.2	87.8	95.2
NSt x S ₂	30.3	79.4	64.1
St x P ₀	26.9	100.2	111.8
St x P ₅₀	19.4	97.3	102.2
NSt x P ₀	32.7	81.0	89.4
NSt x P ₅₀	29.8	86.2	68.8
S ₁ x P ₀	26.2	103.3	119.7
S ₁ x P ₅₀	27.4	104.8	97.5
S ₂ x P ₀	33.4	77.9	81.5
S ₂ x P ₅₀	21.7	78.7	73.5
SE	0.4	1.0	0.8
CD	1.3	2.9	2.4
St x N ₀	22.9	98.3	111.3
St x N ₅₀	22.9	71.7	104.5
St x N ₁₀₀	23.6	126.3	105.1
NSt x N ₀	31.6	84.7	74.9
NSt x N ₅₀	33.2	86.6	83.0
NSt x N ₁₀₀	28.9	79.5	79.6
S ₁ x N ₀	20.7	104.1	107.8
S ₁ x N ₅₀	30.5	91.7	119.4
S ₁ x N ₁₀₀	29.4	116.4	98.7
S ₂ x N ₀	33.8	78.9	78.4
S ₂ x N ₅₀	25.6	66.6	68.1
S ₂ x N ₁₀₀	23.2	89.4	86.0
N ₀ x P ₀	31.6	87.8	91.2
N ₀ x P ₅₀	22.9	95.2	94.9
N ₅₀ x P ₀	30.9	74.6	114.9
N ₅₀ x P ₅₀	25.3	83.7	72.6
N ₁₀₀ x P ₀	26.9	109.5	95.7
N ₁₀₀ x P ₅₀	25.6	96.3	89.0
SE	0.5	1.2	1.0

Cu content in shoot of sorghum crop at 30 days stage while the black soil showed increasing trend at 60 and 90 days stage.

iii) P levels: The mean value for this main effect ranged from 24.6 to 100.6 ppm. Though P application did not increase shoot Cu content at 30 and 90 days stage, it produced marginal increase at 60 days stage.

iv) N levels: The mean value for this main effect ranged from 26.2 to 102.9 ppm. The N application at 100 kg level showed marked increase of shoot Cu content at 60 days stage but at 30 and 90 days it showed only marginal increase.

Interaction effects

At 30th day, the interactions viz., S x N, S x P, S x St, N x P, N x St and P x St attained statistical significance. The salient inferences drawn are: (i) the red soil registered greater accumulation of Cu in shoot at N_0 level and P_0 level than the black soil while the black soil registered greater, accumulation of Cu in shoot at N_{50} and N_{100} levels and at P_{50} level than the red soil; (ii) in both the soils, under sterilized condition shoot Cu content was not increased in both the soil types; (iii) $N_0 P_0$ level on par with $N_{50} P_0$ and $N_{100} P_{50}$ level on par with $N_{50} P_{50}$ level

increased shoot Cu content; and (iv) at all levels of N and P tried under non-sterilized condition higher accumulation of shoot Cu content was registered than under sterilized condition.

At 60th day, the interactions viz., S x St, N x P, S x P, N x St and P x St attained statistical significance. The salient inferences drawn are: (i) under sterilized condition shoot Cu content was enhanced in the black soil at N_0 and N_{100} levels and at P_0 and P_{50} levels, whereas under non-sterilized condition it was enhanced in the red soil at N_{50} level; and ii) combined application of N_0P_{50} and $N_{100}P_0$ increased shoot Cu content, however the combined application of $N_{100}P_{50}$ was on par with N_0P_{50} application.

At 90th day, the interactions viz., S x N, S x P, N x P, N x St and P x St was significant. The important inferences drawn include: (i) the black soil registered greater accumulation of Cu in shoot at N_{50} level than the red soil while the red soil at N_{100} level than the black soil; (ii) irrespective of P application the black soil registered higher accumulation of shoot Cu content than the red soil; (iii) under sterilized condition higher accumulation of Cu in shoot was registered than under non-sterilized condition at all levels of N and P; and (iv) the combined application of $N_{50}P_0$ and N_0P_{50} were found to be significantly superior than the other combined applications in accumulating Cu content in shoot.

4.7.4.4. Effect on Zn content (Table 34)

Individual effects

i) Sterilization: The mean value for this main effect ranged from 162 to 337 ppm. Under sterilized condition shoot Zn content was increased significantly at 30 days stage only.

ii) Soil types: The mean value for this main effect ranged from 163 to 278 ppm. The black soil showed higher shoot Zn content than the red soil at 30 days stage growth, while at 60 and 90 days stage the effect due to soil types was insignificant.

iii) P levels: The mean value for this main effect ranged from 175 to 269 ppm. The P application significantly enhanced Zn content in shoot at 30 days stage only.

iv) N levels: The mean value for this main effect ranged from 171 to 274 ppm. The N application at 100 kg level significantly increased shoot Zn content at 30 days stage only.

Interaction effects

At 30th day, the interactions viz., S x N, S x P, N x P and N x St were significant. The salient inferences drawn are:

TABLE 34. EFFECT OF TREATMENTS ON Zn CONTENT IN SHOOT OF SORGHUM IN BLACK AND RED SOILS (ppm)

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Treatments	30 days	60 days	90 days
St	196	234	337
NSt	162	255	187
S ₁	195	265	278
S ₂	163	225	246
P ₀	175	243	269
P ₅₀	183	246	255
SE	2.7	13.0	20.0
CD	7.9	NS	NS
N ₀	171	239	249
N ₅₀	173	246	274
N ₁₀₀	194	249	263
SE	3.3	16.0	25.0
CD	9.7	NS	NS
St x S ₁	209	241	352
St x S ₂	183	228	321
NSt x S ₁	181	288	204
NSt x S ₂	144	222	170
St x P ₀	194	230	333
St x P ₅₀	199	239	340
NSt x P ₀	156	256	204
NSt x P ₅₀	168	254	171
S ₁ x P ₀	177	259	279
S ₁ x P ₅₀	213	270	277
S ₂ x P ₀	173	227	258
S ₂ x P ₅₀	154	223	234
SE	4.0	17.0	29.0
CD	11.0	NS	NS
St x N ₀	179	222	319
St x N ₅₀	195	241	346
St x N ₁₀₀	214	240	345
NSt x N ₀	163	257	178
NSt x N ₅₀	151	251	202
NSt x N ₁₀₀	172	257	181
S ₁ x N ₀	173	248	273
S ₁ x N ₅₀	193	278	297
S ₁ x N ₁₀₀	220	267	265
S ₂ x N ₀	169	230	225
S ₂ x N ₅₀	154	214	251
S ₂ x N ₁₀₀	168	230	262
N ₀ x P ₀	167	241	247
N ₀ x P ₅₀	175	238	251
N ₅₀ x P ₀	195	253	274
N ₅₀ x P ₅₀	151	239	274
N ₁₀₀ x P ₀	164	235	285
N ₁₀₀ x P ₅₀	224	262	241
SE	5.0	23.0	35.0

(i) the black soil registered greater accumulation of shoot Zn content than the red soil at all levels of N and P; (ii) the combined applications of $N_{50} P_0$ and $N_{100} P_{50}$ were found to be significantly superior than the other combined applications in accumulating Zn content in shoot; and (iii) under sterilized condition higher accumulation of shoot Zn content was registered at all levels of N.

None of the interactions were found to be significant at 60 and 90 days stages.

4.7.5. Effect on N, P and K content in sorghum grain (Table 35)

4.7.5.1. Effect on N content

Individual effect

i) Sterilization: The grain N content recorded was as 0.93 per cent and 1.25 per cent under sterilized and non-sterilized conditions respectively.

ii) Soil types: The black soil recorded significantly higher grain N content (1.17%) than the red soil (1.01%).

iii) P levels: The P application significantly depressed grain N content.

iv) N levels: The N_{100} level registered 1.19 per cent N in grain while N_0 level recorded 0.97 per cent N.

Interaction effects

The interactions viz., S x N, S x P, N x P, N x St and P x St attained statistical significance. The salient inferences drawn are: (i) the black soil at $N_{50}P_0$ level and the red soil at $N_{100}P_0$ level increased the N content in grain; (ii) at both the levels of P, N_{100} level proved to be better in increasing grain N content than the other levels of N; (iii) at all levels of N and P under normal condition of the soil grain N content was increased; and (iv) the treatment combinations $N_{100}P_0$ level proved to be the best under both sterilized and non-sterilized conditions in increasing the grain N content.

4.7.5.2. Effect on P content

Individual effects

i) Sterilization: Grain P contents recorded were as 0.07 and 0.11 per cent under sterilized and non-sterilized conditions respectively.

ii) Soil types: The red soil recorded significantly higher P content in grain (0.11%) than the black soil (0.06%).

iii) P levels: P application significantly increased grain P content.

iv) N levels: N_{100} level registered 0.13 per cent in grain while N_0 level recorded 0.08 per cent P.

Interaction effects

The interactions viz., S x N, S x P, S x St, N x P, N x St, and P x St attained statistical significance. The salient inferences drawn are: (i) at all levels of N and at P₅₀ level, the red soil registered increased grain P content; (ii) in both the soils, the combined application of N₁₀₀P₅₀ increased grain P content; (iii) irrespective of the sterilized condition the red soil registered higher P content than the black soil in grain; (iv) at both the levels of P, N₁₀₀ level registered increased P content in grain; (v) similarly at all levels of N, P₅₀ level recorded higher grain P content; (vi) at all levels of N and P, the non-sterilized condition recorded higher content of P in grain than the sterilized condition; and (vii) irrespective of the process of sterilized condition N₁₀₀ P₅₀ level recorded higher P content in grain.

4.7.5.3. Effect on K content

Individual effects

i) Sterilization: Grain K content recorded was 0.31 per cent and 0.44 per cent under sterilized and non-sterilized condition respectively.

ii) Soil types: The red soil significantly recorded increased K content in grain (0.48%) than the black soil (0.34%).

TABLE 35. EFFECT OF TREATMENTS ON N, P AND K CONTENTS IN
SORGHUM GRAIN IN BLACK AND RED SOILS (%)

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Treatments	Grain N%	Grain P%	Grain K%
St	0.93	0.07	0.37
NSt	1.25	0.11	0.44
S ₁	1.17	0.06	0.34
S ₂	1.01	0.11	0.48
P ₀	1.22	0.06	0.47
P ₅₀	0.96	0.12	0.34
SE	0.005	0.001	0.003
CD	0.014	0.003	0.009
N ₀	0.97	0.08	0.38
N ₅₀	1.11	0.05	0.35
N ₁₀₀	1.19	0.13	0.49
SE	0.007	0.001	0.004
CD	0.02	0.004	0.010
St x S ₁	1.01	0.05	0.32
St x S ₂	0.85	0.09	0.43
NSt x S ₁	1.33	0.08	0.35
NSt x S ₂	1.17	0.14	0.53
St x P ₀	1.01	0.04	0.43
St x P ₅₀	0.85	0.10	0.32
NSt x P ₀	1.43	0.07	0.52
NSt x P ₅₀	1.07	0.14	0.37
S ₁ x P ₀	1.36	0.06	0.32
S ₁ x P ₅₀	0.98	0.07	0.35
S ₂ x P ₀	1.08	0.05	0.62
S ₂ x P ₅₀	0.94	0.17	0.34
SE	0.007	0.002	0.004
CD	0.02	0.005	0.012
St x N ₀	0.89	0.07	0.34
St x N ₅₀	0.92	0.04	0.34
St x N ₁₀₀	0.98	0.09	0.45
NSt x N ₀	1.06	0.09	0.43
NSt x N ₅₀	1.29	0.05	0.37
NSt x N ₁₀₀	1.40	0.18	0.53
S ₁ x N ₀	1.07	0.06	0.35
S ₁ x N ₅₀	1.28	0.03	0.28
S ₁ x N ₁₀₀	1.16	0.10	0.39
S ₂ x N ₀	0.88	0.10	0.42
S ₂ x N ₅₀	0.93	0.06	0.43
S ₂ x N ₁₀₀	1.22	0.17	0.59
N ₀ x P ₀	1.13	0.02	0.40
N ₀ x P ₅₀	0.82	0.14	0.36
N ₅₀ x P ₀	1.21	0.02	0.36
N ₅₀ x P ₅₀	1.01	0.07	0.34
N ₁₀₀ x P ₀	1.33	0.12	0.65
N ₁₀₀ x P ₅₀	1.05	0.15	0.33
---	0.000	0.002	0.005

iii) P levels: P application significantly decreased K content in grain.

iv) N levels: N application at N_{100} level registered 0.49 per cent K in grain while N_0 level recorded 0.38 per cent.

Interaction effects

The interactions viz., S x N, S x P, S x St, N x P, N x St and P x St showed statistical significance. The important inferences drawn include: (i) At all levels of N and at P_0 level, the red soil registered higher content of K in grain; (ii) the black soil at $N_{100} P_{50}$ level and the red soil at $N_{100} P_0$ level registered higher content of K in grain than the other levels of N and P; (iii) irrespective of the soil types under non-sterilized condition grain K content was increased; (iv) the combined applications of $N_{100} P_0$ and $N_0 P_{50}$ registered higher content of K in grain than the other combined applications; and (v) at all levels of N and P under non-sterilized condition grain K content was increased.

4.7.6. Effect on micronutrients content in sorghum grain

(Table 36)

4.7.6.1. Effect on Fe content

Individual effects

i) Sterilization: Under normal condition of the soil, Fe content in grain was recorded as 426 ppm while under

ii) Soil types: The red soil recorded significantly higher Fe content in grain (414 ppm) than the black soil (351 ppm).

iii) P levels: The P application significantly depressed Fe content in grain thereby exhibiting the P-Fe antagonistic effect.

iv) N levels: The N_{100} level recorded significantly higher Fe content in grain (420 ppm) than N_{50} level (363 ppm) and N_0 level (365 ppm).

Interaction effects

The interactions viz., S x N, S x P, S x St, N x P, N x St and P x St showed statistical significance. The salient inferences drawn are: (i) the black soil at N_0 , N_{50} and P_{50} levels recorded higher Fe content in grain than the red soil; (ii) under normal condition of the soil Fe content in grain was higher than that under sterilized condition in both the soil types and the red soil showed higher Fe content in grain than the black soil; (iii) the combined applications of $N_{100} P_0$ and $N_{50} P_{50}$ showed higher accumulation of Fe content in grain than the other combined applications; (iv) at all levels of N and P normal condition of the soil showed higher Fe content in grain than the sterilized condition.

4.7.6.2. Effect on Mn content

Individual effects

- i) Sterilization: Under normal condition of the soil, grain Mn content was recorded as 49 ppm, while under sterilized condition it was recorded as 38 ppm.
- ii) Soil types: The black soil registered significantly higher Mn content in grain (48 ppm) than the red soil (39 ppm).
- iii) P levels: The P application significantly increased Mn content in grain as compared to no P application from 40 to 46 ppm.
- iv) N levels: The N_{100} level recorded significantly higher Mn content in grain as 46 ppm on par with N_{50} level while N_0 level recorded as 39 ppm.

Interaction effects

The interactions viz., S x St, N x P and P x St assumed statistical significance. The salient inferences drawn are: (i) under normal condition of the soil, grain Mn content was higher than that under sterilized condition in both the soil types and the black soil showed higher Mn content in grain than the red soil under both the soil conditions; (ii) P application

was found to increase Mn content in grain under non-sterilized condition; and (iii) at all levels of N, P₀ level was found to increase the Mn content in grain.

4.7.6.3. Effect on Cu content

Individual effects

i) Sterilization: Under normal condition of the soil, grain Cu content was recorded as 4.89 ppm while under sterilized condition recorded as 3.01 ppm.

ii) Soil types: The red soil recorded significantly higher grain Cu content as (4.20 ppm) while the black soil recorded as 3.70 ppm.

iii) P levels: P application significantly depressed Cu content in grain from 5.64 to 2.27 ppm.

iv) N levels: N₅₀ level recorded significantly higher Cu content in grain as 4.87 ppm while N₁₀₀ level recorded as 2.98 ppm.

Interaction effects

The interaction effects viz., S x N, S x P, S x St, N x P, N x St and P x St attained statistical significance.

The salient inferences are: (i) the black soil, N_0 , N_{50} and P_0 levels recorded higher Cu content in grain than the red soil but at N_{50} level both the soils recorded higher grain Cu content than the other N levels; (ii) under normal condition grain Cu content was higher than that under sterilized condition in both the soil types and the red soil showed higher grain Cu content than the black soil under both the soil conditions; (iii) at all levels of N, P_0 level was found to increase grain Cu content; and (iv) all levels of N and P under normal condition of the soil accumulation of Cu in grain was increased.

4.7.6.4. Effect on Zn content

Individual effects

i) Sterilization: Under normal condition of the soil grain Zn content recorded was 98.3 ppm while in the sterilized condition, it was 6.31 ppm.

ii) Soil types: The red soil markedly increased the grain Zn content and recorded 100.3 ppm than the black soil (61.1 ppm).

iii) P levels: Similar to the effect of N application, P application had no significant effect in increasing grain Zn content.

iv) N levels: The N application had no significant effect in increasing Zn content in grain.

Interaction effects

The interactions viz., S x N, S x P, S x St, N x P, N x St and P x St showed statistical significance. The important inferences drawn are: (i) at all levels of N and P, the red soil registered higher content of Zn in grain than the black soil (ii) at all levels of N and P and in both the soil types, under normal condition of the soil grain Zn content was increased and the red soil recorded greater content of Zn in grain than the black soil under both the soil conditions; and (iii) at all levels of N, P_0 level was found to increase Zn content in grain.

4.7.6.5. Effect on yield of grain per plant (g) (Table 36)

Individual effects

i) Sterilization: Under sterilized condition the yield of grain was 8.5 g/plant while under normal condition of the soil it was recorded as 21.0 g/plant.

ii) Soil types: The black soil produced significantly higher grain yield (18.78 g/plant) than the red soil (10.8 g/plant).

TABLE 36. EFFECT OF TREATMENTS ON Fe, Mn, Cu and Zn CONTENTS IN GRAIN
AND YIELD OF SORGHUM GRAIN IN BLACK AND RED SOILS

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Treatments	Grain Fe (ppm)	Grain Mn (ppm)	Grain Cu (ppm)	Grain Zn (ppm)	Grain yield (g plant ⁻¹)
St	340	38	3.01	63.1	8.5
NSt	426	49	4.89	98.3	21.0
S ₁	351	48	3.70	61.1	18.7
S ₂	414	39	4.20	100.3	10.8
P ₀	448	40	5.64	91.0	12.3
P ₅₀	317	46	2.27	76.5	17.2
SE	1.00	1.0	0.04	0.40	0.3
CD	3.00	3.0	0.11	1.20	0.8
N ₀	365	39	4.01	90.1	13.7
N ₅₀	383	45	4.87	67.8	15.4
N ₁₀₀	420	46	2.98	84.4	15.1
SE	1.00	1.0	0.05	0.5	0.3
CD	4.00	3.0	0.14	1.4	1.0
St x S ₁	312	41	2.96	48.4	11.0
St x S ₂	367	35	3.09	77.8	6.0
NSt x S ₁	390	55	4.46	73.9	26.3
NSt x S ₂	461	42	5.32	122.8	15.6
St x P ₀	407	36	4.46	76.3	6.2
St x P ₅₀	272	40	1.56	50.0	10.8
NSt x P ₀	489	44	6.81	105.6	18.4
NSt x P ₅₀	362	53	2.94	91.1	23.6
S ₁ x P ₀	371	44	5.83	66.4	14.7
S ₁ x P ₅₀	331	52	1.57	55.8	22.7
S ₂ x P ₀	525	37	5.44	115.3	99.0
S ₂ x P ₅₀	303	41	2.97	85.3	11.7
SE	1.00	1.0	0.06	0.6	0.4
CD	4.00	4.0	0.16	1.6	1.1
St x N ₀	328	32	2.95	73.6	8.0
St x N ₅₀	307	40	3.88	58.0	8.8
St x N ₁₀₀	385	42	2.21	57.8	8.6
NSt x N ₀	403	46	5.07	106.5	19.3
NSt x N ₅₀	419	50	5.86	77.5	22.0
NSt x N ₁₀₀	456	50	3.74	111.0	21.5
S ₁ x N ₀	388	42	4.38	65.6	17.2
S ₁ x N ₅₀	372	49	5.15	56.4	18.9
S ₁ x N ₁₀₀	293	54	1.57	61.5	20.0
S ₂ x N ₀	343	36	3.64	114.5	10.2
S ₂ x N ₅₀	353	42	4.59	79.1	12.0
S ₂ x N ₁₀₀	547	39	4.38	107.3	10.2
N ₀ x P ₀	410	38	5.65	93.3	9.1
N ₀ x P ₅₀	321	40	2.38	86.9	18.3
N ₅₀ x P ₀	342	43	7.80	80.9	13.2
N ₅₀ x P ₅₀	384	47	1.94	54.6	17.6
N ₁₀₀ x P ₀	593	40	3.46	98.6	14.5
N ₁₀₀ x P ₅₀	247	52	2.49	70.1	15.6
SE	2.00	2.0	0.07	0.7	0.5

iii) P levels: The P_{50} level recorded significantly higher grain yield (17.2 g/plant) than P_0 level (12.3 g/plant).

iv) N levels: The N_{50} level recorded significantly higher grain yield (15.4 g/plant) on par with N_{100} level (15.1 g/plant) than N_0 level (13.7 g/plant).

Interaction effects

The interaction effects viz., S x N, S x P, S x St and N x P attained statistical significance. The important inferences drawn are: (i) at all levels of N the black soil recorded higher grain yield/plant than the red soil; in the black soil N_{100} level being on par with N_{50} level registered higher grain yield, while in the red soil the effect due to N application was not observed; (ii) in both the soil types P_{50} level was found to be significantly superior in increasing the grain yield and at both the levels of P the black soil recorded higher grain yield than the red soil; (iii) in both the soil types under sterilized condition the grain yield was not increased; (iv) irrespective of the soil condition, the black soil registered higher grain yield; and (v) at all levels of N, P_{50} levels recorded increased grain yield and at P_0 level, N_{100} level being on par with N_{50} level and at P_{50} level, N_0 level were found to increase the grain yield.

4.8. Effect on nutrient uptake by shoot

4.8.1. Effect on N, P and K uptake by shoot (Table 37)

4.8.1.1. Effect on N uptake

Individual effects

i) Sterilization: Under sterilized condition of the soil, N uptake by shoot was significantly reduced from 61.94 to 39.36 mg/plant.

ii) Soil types: The red soil recorded significantly higher uptake value of N (58.61 mg/plant) than the black soil (42.69 mg/plant).

iii) P levels: The P application exhibited no significant effect on N uptake.

iv) N levels: The N application showed no significant effect on N uptake by shoot.

v) Stages: The N uptake by shoot was remarkably high at 60 days stage (68.21 mg/plant).

Interaction effects

The interactions viz., St x S, and St x Stages attained statistical significance. The salient inferences drawn are: (i) under sterilized condition N uptake by shoot

was markedly reduced in the black soil, while in the red soil there was no variation due to soil conditions; (ii) reduction in N uptake was observed at 60 and 90 days stages under sterilized condition, while at vegetative stage N uptake by shoot was numerically higher under sterilized condition than that under normal condition of the soil.

4.8.1.2. Effect on P uptake

Neither the main effect nor interaction effect had any significant effect on P uptake by shoot.

4.8.1.3. Effect on K uptake

Individual effects

i) Sterilization: Under sterilized condition of the soil K uptake by the shoot was significantly decreased from 131.1 to 75.59 mg/plant.

ii) Soil types: The soil types showed no significant effect on K uptake by shoot.

iii) P levels: The P levels exhibited no significant effect on K uptake.

iv) N levels: The N levels showed no significant effect on K uptake.

TABLE 37. EFFECT OF TREATMENTS ON N, P AND K UPTAKE BY SHOOT OF SORGHUM
PLANT IN BLACK AND RED SOILS (mg/plant)

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Treatment (1)	K uptake (2)	P uptake (3)	K uptake (4)
St	39.36	4.58	75.59
NSt	61.94	10.86	131.11
S ₁	42.69	6.21	95.86
S ₂	58.61	9.23	110.84
P ₀	46.78	6.28	93.86
P ₅₀	54.53	9.14	112.84
SE	3.50		7.7
CD	9.90	NS	21.4
N ₀	51.95	7.85	108.0
N ₁	46.58	10.45	98.08
N ₂	53.42	6.94	103.96
St ₁	30.83	2.97	41.25
St ₂	68.21	10.32	122.13
St ₃	52.09	9.85	146.67
SE	4.30		9.4
CD	12.00	NS	26.4
St x S ₁	19.28	4.70	45.61
St x S ₂	59.44	4.45	105.56
NSt x S ₁	66.11	7.72	146.11
NSt x S ₂	57.78	14.00	116.11
St x P ₀	33.56	5.29	63.28
St x P ₅₀	45.17	3.86	87.89
NSt x P ₀	60.00	7.27	124.44
NSt x P ₅₀	63.88	14.43	137.78
S ₁ x P ₀	39.67	6.06	88.83
S ₁ x P ₅₀	45.72	6.36	102.89
S ₂ x P ₀	53.89	6.49	98.89
S ₂ x P ₅₀	63.33	11.92	122.78
SE	4.90		10.9
CD	13.90	NS	31.0
St x St ₁	35.83	2.14	35.83
St x St ₂	39.75	3.56	60.92
St x St ₃	42.50	8.03	130.00
NSt x St ₁	25.83	3.79	46.67
NSt x St ₂	96.67	17.08	183.33
NSt x St ₃	63.33	11.67	163.33
St x N ₀	36.42	6.88	71.00
St x N ₅₀	34.00	2.87	72.83
St x N ₁₀₀	47.67	3.98	82.92
NSt x N ₀	67.50	8.82	145.00
NSt x N ₅₀	59.17	18.07	123.33
NSt x N ₁₀₀	59.17	5.66	125.00

Contd..

(1)	(2)	(3)	(4)
$S_1 \times St_1$	25.00	2.78	33.33
$S_1 \times St_2$	54.75	4.08	115.08
$S_1 \times St_3$	48.33	11.78	139.17
$S_2 \times St_1$	36.67	3.16	49.17
$S_2 \times St_2$	81.67	16.56	129.17
$S_2 \times St_3$	57.50	7.92	154.17
$S_1 \times N_0$	44.75	7.04	106.83
$S_1 \times N_{50}$	39.83	7.35	92.83
$S_1 \times N_{100}$	43.50	4.23	87.92
$S_2 \times N_0$	59.17	8.65	109.17
$S_2 \times N_{50}$	53.33	13.58	103.33
$S_2 \times N_{100}$	63.33	9.64	120.00
$N_0 \times P_0$	46.25	9.51	86.67
$N_0 \times P_{50}$	57.67	6.18	129.33
$N_1 \times P_0$	37.00	4.53	82.00
$N_1 \times P_{50}$	56.17	16.40	114.17
$N_2 \times P_0$	57.08	4.79	112.92
$N_2 \times P_{50}$	49.75	4.85	95.00
$St_1 \times P_0$	25.83	3.29	35.0
$St_1 \times P_{50}$	35.83	2.64	47.5
$St_2 \times P_0$	63.64	4.46	104.92
$St_2 \times P_{50}$	72.75	16.18	139.33
$St_3 \times P_0$	50.83	11.08	141.67
$St_3 \times P_{50}$	55.00	8.61	151.67
SE	6.0		13.4
CD	17.00	NS	37.9
$St_1 \times N_0$	27.50	2.10	35.00
$St_1 \times N_{50}$	30.00	3.40	43.75
$St_1 \times N_{100}$	35.00	3.40	45.00
$St_2 \times N_0$	72.13	6.31	130.25
$St_2 \times N_{50}$	58.50	18.13	99.25
$St_2 \times N_{100}$	74.00	6.53	136.88
$St_3 \times N_0$	56.25	15.13	158.75
$St_3 \times N_{50}$	51.25	9.88	151.25
$St_3 \times N_{100}$	51.25	4.54	130.00
SE			
CD	NS	NS	NS

v) Stages: The K uptake by shoot increased with crop growth in a phased manner and was significantly high at 90 days stage but was on par with 60 days stage.

Interaction effects

The interactions viz., St x S, and St x Stages attained statistical significance. The negative effect on K uptake by shoot under sterilized condition was observed in the black soil, while it was marginal in the red soil under non-sterilized condition and also it caused a significant reduction at 60 days stage.

4.8.2. Effect on uptake of micronutrients by shoot (Table 38)

4.8.2.1. Effect on Fe uptake

Individual effects

All the individual effects viz., sterilization, soil types, P levels, N levels and stages failed to show significant effect on Fe uptake by shoot.

Interaction effects

The interactions viz., St x S and St x N showed statistical significance. Under sterilized condition Fe uptake was more in the red soil than that in the black soil,

while a positive influence on Fe uptake due to N application at 100 kg level at 30 days stage alone was observed.

4.8.2.2. Effect on Mn uptake

Individual effects

i) Sterilization: Under sterilized condition of the soil, Mn uptake by shoot was increased from 710 to 1366 $\mu\text{g/plant}$.

ii) Soil types: The soil types showed no significant effect on Mn uptake.

iii) P levels: The P application showed no significant effect on Mn uptake.

iv) N levels: The N application showed no significant effect on Mn uptake.

v) Stages: Mn uptake was significantly increased and it was the highest at 90 days stage. A stepwise increase was observed with advancement of crop growth.

Interaction effects

The interactions viz., St x S and St x Stages attained statistical significance. Though the red soil recorded higher Mn uptake value than the black soil under

sterilized condition, Mn uptake in the black soil under normal and sterilized condition of the soil was on par. Under sterilized condition of the soil at 90 days stage Mn uptake was significantly increased as compared under normal condition of the soil.

4.8.2.3. Effect on Cu uptake

Individual effects

i) Sterilization: Under normal condition of the soil Cu uptake was increased from 349 to 596 μg /plant.

ii) Soil types: The soil types showed no significant effect on Cu uptake.

iii) P levels: The P application showed no significant effect on Cu uptake.

iv) N levels: The N application also showed no significant effect on Cu uptake.

v) Stages: The Cu uptake was significantly high at 90 days stage registering 861 μg /plant and it increased stepwise with advancement of crop growth.

Interaction effects

The interactions viz., St x S, Stages x P and ... attained statistical significance. Under

TABLE 38. EFFECT OF TREATMENTS ON Fe, Mn, Cu AND Zn UPTAKE BY SHOOT OF SORGHUM PLANT IN BLACK AND RED SOILS

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Treatments (1)	Fe uptake (mg/plant) (2)	Mn uptake (µg/plant) (3)	Cu uptake (µg/plant) (4)	Zn uptake (µg/plant) (5)
St	9.63	1366	399	983
NSt	10.64	710	596	1410
S ₁	8.53	812	505	1156
S ₂	11.73	1264	490	1237
P ₀	8.65	919	495	1173
P ₅₀	11.61	1158	499	1219
SE		199	51	95
CD	NS	565	143	214
N ₀	9.37	1092	504	1170
N ₁	8.89	920	500	1263
N ₂	12.14	1093	488	1158
St ₁	9.79	624	71	480
St ₂	9.21	770	559	1240
St ₃	11.39	1777	861	1869
SE		244	44	92
CD	NS	692	123	262
St x S ₁	5.79	846	334	733
St x S ₂	13.45	1886	463	1233
NSt x S ₁	11.27	778	675	1579
NSt x S ₂	10.01	643	516	1240
St x P ₀	6.45	1220	370	872
St x P ₅₀	12.80	1512	427	1094
NSt x P ₀	10.85	617	619	1474
NSt x P ₅₀	10.43	804	572	1344
S ₁ x P ₀	8.08	782	519	1121
S ₁ x P ₅₀	9.02	842	490	1191
S ₂ x P ₀	9.26	1055	471	1226
S ₂ x P ₅₀	14.20	1473	508	1248
SE	2.11	282	51	33
CD	5.99	799	143	95
St x St ₁	10.94	673	58	513
St x St ₂	7.10	705	335	845
St x St ₃	10.82	2720	802	1592
NSt x St ₁	8.63	574	83	447
NSt x St ₂	11.33	834	783	1635
NSt x St ₃	11.97	724	920	2147

(1)	(2)	(3)	(4)	(5)
St x N ₀	8.06	1480	408	912
St x N ₅₀	7.03	1150	360	983
St x N ₁₀₀	13.78	1468	427	1054
NSt x N ₀	10.67	703	600	1427
NSt x N ₅₀	10.75	711	639	1547
NSt x N ₁₀₀	10.50	717	548	1261
S ₁ x St ₁	5.84	613	57	404
S ₁ x St ₂	7.59	695	475	1085
S ₁ x St ₃	12.16	1129	982	1978
S ₂ x St ₁	13.73	633	85	555
S ₂ x St ₂	10.84	844	644	1395
S ₂ x St ₃	10.63	2315	740	1760
S ₁ x N ₀	8.65	720	515	1153
S ₁ x N ₅₀	8.82	804	549	1163
S ₁ x N ₁₀₀	8.12	913	449	1053
S ₂ x N ₀	10.08	1464	492	1186
S ₂ x N ₅₀	8.96	1056	450	1262
S ₂ x N ₁₀₀	16.16	1272	526	1263
N ₀ x P ₀	9.59	757	501	1145
N ₀ x P ₅₀	9.13	1426	506	1193
N ₁ x P ₀	7.82	661	506	1160
N ₁ x P ₅₀	9.96	1200	493	1364
N ₂ x P ₀	8.54	1337	476	1215
N ₂ x P ₅₀	15.74	848	498	1100
St ₁ x P ₀	6.25	587	63	384
St ₁ x P ₅₀	13.32	660	78	575
St ₂ x P ₀	8.06	609	477	1132
St ₂ x P ₅₀	10.36	930	641	1348
St ₃ x P ₀	11.63	1560	943	2004
St ₃ x P ₅₀	11.15	1884	778	1734
SE	2.59	346	62	131
CD	7.34	979	175	370
St ₁ x N ₀	5.67	589	59	394
St ₁ x N ₅₀	6.59	688	82	478
St ₁ x N ₁₀₀	17.09	593	71	568
St ₂ x N ₀	9.99	755	568	1221
St ₂ x N ₅₀	7.50	669	478	1176
St ₂ x N ₁₀₀	10.15	885	631	1323
St ₃ x N ₀	12.42	1931	884	1893
St ₃ x N ₅₀	12.57	1435	939	2132
St ₃ x N ₁₀₀	9.19	1800	760	1583
SE			31	
CD	NS	NS	88	NS

sterilized condition Cu uptake was not reduced in the red soil to a marked extent in contrast to that in the black soil. The negative effect of sterilization on Cu uptake was confined to 30 and 60 days stages, while at 90 days stage the difference under sterilized and normal conditions of the soil was not marked.

4.8.2.4. Effect on Zn uptake

Individual effects

i) Sterilization: Under normal condition of the soil Zn uptake was significantly increased from 983 to 1410 $\mu\text{g/plant}$.

ii) Soil types: The soil types showed no significant effect on Zn uptake.

iii) P levels: The P application showed no significant effect on Zn uptake.

iv) N levels: The N application exhibited no significant effect on Zn uptake.

v) Stages: The Zn uptake was significantly higher at 90 days stage (1869 $\mu\text{g/plant}$) than at 60 and 30 days stages and Zn uptake was increased stepwise with advancement of crop growth.

Interaction effects

The interactions viz., St x S and St x Stages attained statistical significance. Under sterilized condition a significant reduction in Zn uptake was observed in the black soil, while this was not so in the red soil. The negative effect of sterilization on Zn uptake was observed only at 60 and 90 days stages and the difference between sterilized and normal condition of the soil at 30 days stage was not marked.

4.9. Effect on nutrient uptake by grain

4.9.1. Effect on N, P and K uptake by grain (Table 39)

4.9.1.1. Effect on N uptake

Individual effects

i) Sterilization: Under sterilized condition of the soil N uptake by grain was significantly reduced from 257 to 79 mg/plant.

ii) Soil types: The N uptake by grain was more in the black soil (222 mg/plant) than that in the red soil (113 mg/plant).

iii) P levels: The P application showed no significant effect on N uptake.

iv) N levels: The N_{100} level recorded significantly higher N uptake by grain (189 mg/plant) but was on par with N_{50} level.

Interaction effects

The interactions viz., St x S, St x N, St x P and P x N attained statistical significance. The salient inferences drawn are: (i) under sterilized condition N uptake by grain was reduced both in the black and the red soils; (ii) N levels which had no influence on N uptake under sterilized condition was favourable under normal condition of the soil; (iii) under sterilized condition P application had a positive effect on N uptake; and (iv) P application increased N uptake at N_0 and N_{50} levels, while at N_{100} level it had no effect.

4.9.1.2. Effect on P uptake

Individual effects

i) Sterilization: Under sterilized condition of the soil P uptake by grain was significantly reduced from 21.98 to 5.96 mg/plant.

ii) Soil types: The soil types showed no significant effect on P uptake by grain.

TABLE 39. EFFECT OF TREATMENTS ON N, P AND K UPTAKE IN GRAIN OF SORGHUM IN BLACK AND RED SOILS (mg/plant)

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Treatments	N uptake	P uptake	K uptake
St	79	5.96	30.46
NSt	257	21.98	101.67
S ₁	222	14.39	79.54
S ₂	113	13.55	52.58
P ₀	164	9.09	57.40
P ₅₀	171	18.85	74.73
SE	5	2.00	10.40
CD	14	5.78	30.30
N ₀	134	14.00	52.84
N ₅₀	180	7.24	55.00
N ₁₀₀	189	20.87	90.37
SE	6	2.50	
CD	17	7.08	
St x S ₁	108	6.03	36.08
St x S ₂	50	5.88	24.83
NSt x S ₁	337	22.75	123.00
NSt x S ₂	176	21.21	80.33
St x P ₀	65	2.13	25.87
St x P ₅₀	93	8.79	35.04
NSt x P ₀	263	15.04	88.93
NSt x P ₅₀	250	28.72	114.41
S ₁ x P ₀	214	12.56	50.58
S ₁ x P ₅₀	230	16.22	108.50
S ₂ x P ₀	113	5.61	64.22
S ₂ x P ₅₀	112	21.48	40.95
SE	7	2.80	13.90
CD	20	8.10	40.10
St x N ₀	71	7.07	27.23
St x N ₅₀	81	3.80	28.34
St x N ₁₀₀	84	7.00	35.80
NSt x N ₀	196	20.93	78.45
NSt x N ₅₀	279	10.67	81.63
NSt x N ₁₀₀	294	34.35	144.94
S ₁ x N ₀	179	14.76	63.54
S ₁ x N ₅₀	245	6.88	57.06
S ₁ x N ₁₀₀	243	21.53	118.03
S ₂ x N ₀	88	13.24	42.14
S ₂ x N ₅₀	116	7.59	52.90
S ₂ x N ₁₀₀	135	19.81	62.71
N ₀ x P ₀	109	2.06	36.00
N ₀ x P ₅₀	158	25.94	68.68
N ₅₀ x P ₀	175	3.23	48.76
N ₅₀ x P ₅₀	185	11.24	61.20
N ₁₀₀ x P ₀	207	21.96	87.44
N ₁₀₀ x P ₅₀	171	19.38	93.30

iii) P levels: The P fertilization resulted in increased P uptake from 9.09 to 18.85 mg/plant.

iv) N levels: The beneficial effect of N application on P uptake by grain was not consistent since N_{100} level recorded increased P uptake, but was on par with N_0 level which in turn differed only marginally with N_{50} level.

Interaction effects

The interactions viz., S x P, St x N and P x N attained statistical significance. The important inferences drawn are: (i) P application which had no significant effect in the black soil, resulted in significant increase of P uptake in the red soil; (ii) N_{100} level was superior under normal condition of the soil than under sterilized condition; and (iii) P at 50 kg level and N at 100 kg level were found to be favourable on P uptake by grain.

4.9.1.3. Effect on K Uptake

Individual effects

i) Sterilization: Under sterilized condition of the soil K uptake by grain was significantly reduced from 30.46 to 101.67 mg/plant.

ii) Soil types: The soil types showed no significant effect on K uptake.

iii) P levels: The P application did not result in increased K uptake by grain.

iv) N levels: The N application did not result in increased K uptake by grain.

Interaction effects

Interaction effect of S x P revealed that P application had a positive effect in the black soil while it had opposite effect in the red soil.

4.9.2. Effect on micronutrient uptake by grain (Table 40)

4.9.2.1. Effect on Fe uptake

Individual effects

i) Sterilization: Under sterilized condition, Fe uptake by grain was significantly reduced from 8.57 to 2.59 mg/plant.

ii) Soil types: The Fe uptake by grain was more in the black soil (6.55 mg/plant) than the red soil (4.60 mg/plant).

iii) P levels: The P application did not result in increased Fe uptake by grain.

iv) N levels: The N application also did not result in increased Fe uptake by grain.

Interaction effect

The significant interaction of S x P revealed that P application which had favourable effect on Fe uptake by grain in the black soil got reversed its positive influence in the red soil.

4.9.2.2. Effect on Mn uptake

Individual effects

i) Sterilization: Under sterilized condition Mn uptake by grain was significantly reduced from 1.930 to 0.456 mg/plant.

ii) Soil types: The soil types did not show any significant effect on Mn uptake.

iii) P levels: The P application did not result in increased Mn uptake by grain.

iv) N levels: The N application also did not exhibit any significant effect on Mn uptake.

Interaction effect

The significant interaction P x N revealed that P application had a positive influence on Mn uptake at N₀ level.

TABLE 40. EFFECT OF TREATMENTS ON Fe, Mn, Cu AND Zn UPTAKE BY SORGHUM GRAIN IN BLACK AND RED SOILS (mg/plant)

Treatments (1)	Fe uptake (2)	Mn uptake (3)	Cu uptake (4)	Zn uptake (5)
St	2.59	0.456	20.47	0.466
NSt	8.57	1.930	92.03	1.929
S ₁	6.55	2.00	61.33	1.200
S ₂	4.60	1.196	51.16	1.196
P ₀	5.28	1.118	73.09	1.118
P ₅₀	5.88	1.278	39.40	1.278
SE	0.44	0.095	5.9	0.090
CD	1.27	0.275	17.1	0.278
N ₀	4.81	1.219	52.35	1.219
N ₅₀	6.08	1.067	74.11	1.067
N ₁₀₀	5.84	1.307	42.28	1.306
SE			7.3	
CD	NS	NS	20.9	NS
St x S ₁	3.12	0.481	23.49	0.481
St x S ₂	2.05	0.450	17.44	0.450
NSt x S ₁	9.98	1.918	99.17	1.918
NSt x S ₂	7.15	1.941	84.88	1.941
St x P ₀	2.15	0.438	26.00	0.439
St x P ₅₀	3.02	0.492	14.93	0.492
NSt x P ₀	8.40	1.796	120.18	1.796
NSt x P ₅₀	8.73	2.062	63.86	2.062
S ₁ x P ₀	5.18	1.000	83.03	1.000
S ₁ x P ₅₀	7.92	1.399	39.63	1.400
S ₂ x P ₀	5.37	1.235	63.15	1.235
S ₂ x P ₅₀	3.83	1.156	39.16	1.156
SE	0.62			
CD	1.79	NS	NS	NS
St x N ₀	2.22	0.504	19.42	0.504
St x N ₅₀	2.61	0.435	26.18	0.435
St x N ₁₀₀	2.93	0.457	15.80	0.456
NSt x N ₀	7.40	1.933	85.28	1.933
NSt x N ₅₀	9.56	1.699	122.04	1.699
NSt x N ₁₀₀	8.74	2.156	68.75	2.156
SE	0.76	0.165	8.3	0.13
CD	2.20	0.477	24.2	0.39
S ₁ x N ₀	5.78	1.098	62.94	1.100
S ₁ x N ₅₀	7.83	1.110	84.84	1.110
" "	6.04	1.280	36.21	1.389

ii) Soil types: The soil types did not exhibit any significant effect on Zn uptake by grain.

iii) P levels: The P application showed no significant effect on Zn uptake by grain.

iv) N levels: The N application showed no significant effect on Zn uptake by grain.

Interaction effect

The significant interaction P x N revealed that P application had a positive effect on Zn uptake at N_0 level.

4.10. Effect on root growth characteristics

4.10.1. Effect on number of roots/ plant (Table 41)

Individual effects

i) Sterilization: The mean value for this main effect fell within the range of 14.6 to 33.6. Under sterilized condition of the soil number of roots/plant was significantly reduced at all the three stages of crop growth.

ii) Soil types: The mean value for this main effect ranged from 14.5 to 34.5. The red soil significantly produced more number of roots/plant than the black soil at all the three stages of crop growth.

TABLE 41. EFFECT OF TREATMENTS ON NUMBER OF ROOTS/PLANT OF BORGHUM
IN BLACK AND RED SOILS

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Treatments	30 days	60 days	90 days
St	17.2	25.4	14.6
NSt	22.4	33.6	17.8
S ₁	15.3	26.5	14.5
S ₂	24.3	34.5	17.8
P ₀	16.5	25.6	14.4
P ₅₀	23.1	33.3	17.9
SE	0.2	0.5	0.1
CD	0.5	1.4	0.4
N ₀	16.6	27.0	16.6
N ₅₀	21.4	29.7	14.1
N ₁₀₀	21.4	31.8	17.8
SE	0.2	0.6	0.2
CD	0.6	1.7	0.5
St x S ₁	10.0	15.5	12.1
St x S ₂	24.3	35.3	17.1
NSt x S ₁	20.5	33.4	16.9
NSt x S ₂	24.3	33.8	18.6
St x P ₀	13.4	29.3	12.2
St x P ₅₀	20.9	31.4	17.0
NSt x P ₀	19.5	32.2	16.7
NSt x P ₅₀	25.3	35.1	18.8
S ₁ x P ₀	20.5	21.3	15.7
S ₁ x P ₅₀	10.0	27.7	13.3
S ₂ x P ₀	24.3	30.3	13.2
S ₂ x P ₅₀	24.3	38.8	22.5
SE	0.2	0.7	0.2
CD	0.7	2.0	0.6
St x N ₀	12.1	21.4	14.9
St x N ₅₀	20.4	26.3	13.1
St x N ₁₀₀	19.0	28.5	15.8
NSt x N ₀	21.1	32.6	18.3
NSt x N ₅₀	22.4	33.1	15.1
NSt x N ₁₀₀	23.8	35.1	19.9
S ₁ x N ₀	15.1	19.3	14.0
S ₁ x N ₅₀	15.0	27.5	12.3
S ₁ x N ₁₀₀	15.6	26.6	17.3
S ₂ x N ₀	18.1	34.8	19.1
S ₂ x N ₅₀	27.8	31.9	16.0
S ₂ x N ₁₀₀	27.1	37.0	18.4
N ₀ x P ₀	12.1	24.1	12.6
N ₀ x P ₅₀	21.1	29.9	20.5
N ₅₀ x P ₀	19.5	25.5	12.6
N ₅₀ x P ₅₀	23.3	33.9	15.6
N ₁₀₀ x P ₀	17.8	27.6	18.0
N ₁₀₀ x P ₅₀	25.0	36.0	17.6

iii) P levels: The mean value for this main effect fell within the range of 14.4 to 33.3. The P application significantly increased the number of roots/plant at all the three stages of crop growth.

iv) N levels: The mean value for this main effect remained within the range of 14.1 to 31.8. Though the effect of N application at 100 kg level was on par with N₅₀ level at 30 days stage, but its effect was more pronounced at 60 and 90 days of crop growth.

Interaction effects

At 30th day, the interactions viz., S x N, S x St, N x P, N x St and P x St showed the level of significance. The important inferences drawn are: (i) greater proliferation of root was observed in the red soil than in the black soil at all levels of N and under both the sterilized and normal conditions of the soil; (ii) the combined application of N₅₀ P₀ and N₁₀₀ P₅₀ increased the proliferation of root than the other combined applications; and (iii) under normal condition of the soil N₁₀₀ and P₅₀ levels and under sterilized condition N₅₀ and P₅₀ levels enhanced the number of roots/plant.

At 60th day, the interactions viz., S x N, S x St, N x P, N x St and P x St showed statistical significance. The salient inferences drawn are: (i) as in the previous case at

all levels of N there was greater proliferation of roots in the red soil than that in the black soil at all levels of N application; (ii) the black soil under normal condition and the red soil under sterilized condition but on par with normal condition increased the number of roots/plant; and (iii) the combined application of $N_{100}P_{50}$ and $N_{100}P_0$ significantly increased the number of roots/plant and at all levels of N and P under normal condition greater number of roots/plant was observed than under sterilized condition.

At 90th day, the interaction effects viz., S x N, S x P, S x St, N x P, N x St and P x St attained statistical significance. The important inferences drawn are: (i) at all level of N application greater proliferation of root/plant was observed in the red soil than that in the black soil; (ii) the red soil required P application for increasing the root proliferation; (iii) the same trend as was observed at 60 days stage, the combined application of $N_{100}P_{50}$ and $N_{100}P_0$ significantly increased the number of roots/plant and (iv) all levels of N and P as well as in both the soils, the normal condition of the soil showed increased number of roots/plant.

4.10.2. Effect on root volume (Table 42)

Individual effects

i) Sterilization: The mean value for the main effect remained within the range of 2.45 to 15.79 ml. The

sterilized condition significantly reduced root volume at all the three stages of crop growth.

ii) Soil types: The mean value for this main effect ranged from 2.01 to 18.89 ml. The red soil significantly recorded higher root volume than the black soil at all the three stages of crop growth.

iii) P levels: The mean value for this main effect ranged from 2.58 to 17.30 ml. The P application enhanced root volume significantly at all the three stages of crop growth.

iv) N levels: The mean value for this main effect fell within the range of 3.06 to 17.81 ml. Though N_{100} level showed marginal increase of root volume at 30 days stage, it significantly registered higher values at 60 and 90 days stages than N_{50} and N_0 levels.

Interaction effects

At 30th day, the interactions viz., $S \times N$, $S \times P$, $N \times P$ and $N \times St$ attained statistical significance. The important inferences drawn are; (i) at all levels of N and P root volume was greater in the red soil than that in the black soil; (ii) the black soil at N_0P_{50} level and the red soil at $N_{100}P_{50}$ increased root volume; and (iii) under normal

TABLE 42. EFFECT OF TREATMENTS ON VOLUME OF ROOT OF SORGHUM IN BLACK AND RED SOILS(ml)

Treatments	30 days	60 days	90 days
St	2.45	14.21	11.11
NSt	3.81	15.79	14.26
S ₁	2.01	11.11	7.80
S ₂	4.25	18.89	16.57
P ₀	2.58	12.70	10.00
P ₅₀	8.69	17.30	14.38
SE	0.05	0.20	0.70
CD	0.14	0.97	0.19
N ₀	3.10	12.84	10.47
N ₅₀	3.06	14.36	12.24
N ₁₀₀	3.23	17.81	13.84
SE	0.06	0.24	0.08
CD	0.17	0.70	0.24
St x S ₁	1.41	8.06	5.62
St x S ₂	3.50	20.37	16.60
NSt x S ₁	2.62	14.17	9.98
NSt x S ₂	5.00	17.42	16.53
St x P ₀	2.00	11.08	9.33
St x P ₅₀	2.92	17.35	12.89
NSt x P ₀	3.16	14.33	10.65
NSt x P ₅₀	4.46	17.25	15.87
S ₁ x P ₀	1.14	7.45	6.41
S ₁ x P ₅₀	2.88	14.78	9.19
S ₂ x P ₀	4.00	17.96	13.57
S ₂ x P ₅₀	4.49	19.83	19.57
SE	0.07	0.28	0.09
CD	0.20	0.81	0.27
St x N ₀	2.30	10.81	9.56
St x N ₅₀	2.13	11.21	9.61
St x N ₁₀₀	2.94	20.61	14.16
NSt x N ₀	3.90	14.88	11.38
NSt x N ₅₀	4.00	17.50	14.88
NSt x N ₁₀₀	3.53	15.00	13.53
S ₁ x N ₀	2.83	9.04	6.58
S ₁ x N ₅₀	1.80	12.84	6.99
S ₁ x N ₁₀₀	1.41	11.46	9.84
S ₂ x N ₀	3.38	16.65	14.36
S ₂ x N ₅₀	4.33	15.88	17.50
S ₂ x N ₁₀₀	5.05	24.15	17.84
N ₀ x P ₀	1.83	13.13	8.78
N ₀ x P ₅₀	4.38	12.56	12.16
N ₅₀ x P ₀	2.83	10.15	9.01
N ₅₀ x P ₅₀	3.30	18.56	15.48
N ₁₀₀ x P ₀	3.08	14.84	12.18
N ₁₀₀ x P ₅₀	3.39	10.78	15.50

condition of the soil root volume was increased significantly at all levels of N application.

At 60th day, the interactions viz., S x N, S x P, S x St, N x P, N x St and P x St attained statistical significance. The important inferences drawn are: (i) as in the previous case at all levels of N and P applications root volume was greater in the red soil than that in the black soil; (ii) the black soil at $N_{50}P_{50}$ level and the red soil at $N_{100}P_{50}$ level increased the volume of root; (iii) irrespective of the soil conditions the red soil registered higher root volume than the black soil; and (iv) under the sterilized condition of the soil $N_{100}P_{50}$ level, while under normal condition of the soil $N_{50}P_{50}$ level increased the root volume.

At 90th day, the interactions viz., S x N, S x P, S x St, N x P, N x St and P x St attained statistical significance. The important inferences drawn are: (i) at all levels of N and P applications and irrespective of the soil conditions the red soil registered greater root volume than the black soil; (ii) though N_{100} level registered increased root volume in both the soils, N_{100} level on par with N_{50} level in the red soil and P application at 50 kg level was needed to increase root volume in both the soil types; and (iv) the combined applications of $N_{100}P_0$ and $N_{100}P_{50}$ increased root volume, but $N_{100}P_{50}$ level was on par with $N_{50}P_{50}$ level and the sterilized condition of the soil required higher N and P levels to increase root volume.

4.10.3. Effect on root mass (Table 43) (Fig.11)

Individual effects

i) Sterilization: The mean value for the main effect remained within the range of 2.70 to 7.58 g. Under the sterilization condition of the soil root mass was significantly reduced at all the three stages of crop growth.

ii) Soil types: The mean value for the main effect ranged from 2.33 to 7.43 g. The red soil registered significantly higher root mass than the black soil at all the three stages.

iii) P levels: The mean value for the main effect ranged from 2.95 to 7.30 g. The P application registered significantly higher root mass than no P application at all the three stages.

iv) N levels: The mean value for the main effect remained within the range of 2.48 to 7.86 g. The N application at 100 kg level registered significantly higher root mass than N_{50} and N_0 levels at all the three stages of crop growth.

Interaction effects

At 30th day, the interactions viz., S x N, S x P, S x St, N x P, N x St and P x St attained statistical

TABLE 43. EFFECT OF TREATMENTS ON ROOT MASS OF SORGHUM IN BLACK AND RED SOILS (g)

246

Treatments	30 days	60 days	90 days.
St	2.93	2.70	6.46
NSt	4.19	3.87	7.58
S ₁	2.72	2.35	6.61
S ₂	4.41	4.22	7.43
P ₀	2.95	3.14	6.74
P ₅₀	4.18	3.43	7.30
SE	0.016	0.022	0.06
CD	0.046	0.063	0.18
N ₀	3.41	3.36	6.88
N ₅₀	3.27	2.48	6.31
N ₁₀₀	4.01	4.02	7.86
SE	0.019	0.026	0.07
CD	0.056	0.077	0.22
St x S ₁	1.99	0.76	4.73
St x S ₂	3.87	4.64	8.19
NSt x S ₁	3.45	3.94	8.48
NSt x S ₂	4.94	3.81	6.67
St x P ₀	2.90	2.28	6.08
St x P ₅₀	2.96	3.12	6.84
NSt x P ₀	3.00	4.00	7.40
NSt x P ₅₀	3.40	3.75	7.75
S ₁ x P ₀	1.74	2.13	6.28
S ₁ x P ₅₀	3.71	2.57	6.94
S ₂ x P ₀	4.16	4.14	7.20
S ₂ x P ₅₀	4.65	4.30	7.66
SE	0.022	0.031	0.085
CD	0.065	0.089	0.25
St x N ₀	2.48	2.67	6.45
St x N ₅₀	2.37	1.47	4.87
St x N ₁₀₀	3.95	3.96	8.06
NSt x N ₀	4.34	4.04	7.31
NSt x N ₅₀	4.18	3.49	7.76
NSt x N ₁₀₀	4.07	4.08	7.66
S ₁ x N ₀	3.49	2.74	7.25
S ₁ x N ₅₀	2.37	2.12	5.98
S ₁ x N ₁₀₀	2.31	2.18	6.58
S ₂ x N ₀	3.33	3.97	6.51
S ₂ x N ₅₀	4.18	2.84	6.64
S ₂ x N ₁₀₀	5.71	5.85	9.14
N ₀ x P ₀	2.08	4.41	5.35
N ₀ x P ₅₀	4.74	2.30	8.41
N ₅₀ x P ₀	3.25	1.89	6.45
N ₅₀ x P ₅₀	3.30	3.08	6.18
N ₁₀₀ x P ₀	3.51	3.11	8.41
N ₁₀₀ x P ₅₀	4.51	4.92	7.31
SE	0.027	0.037	0.10
CD	0.079	0.100	0.28

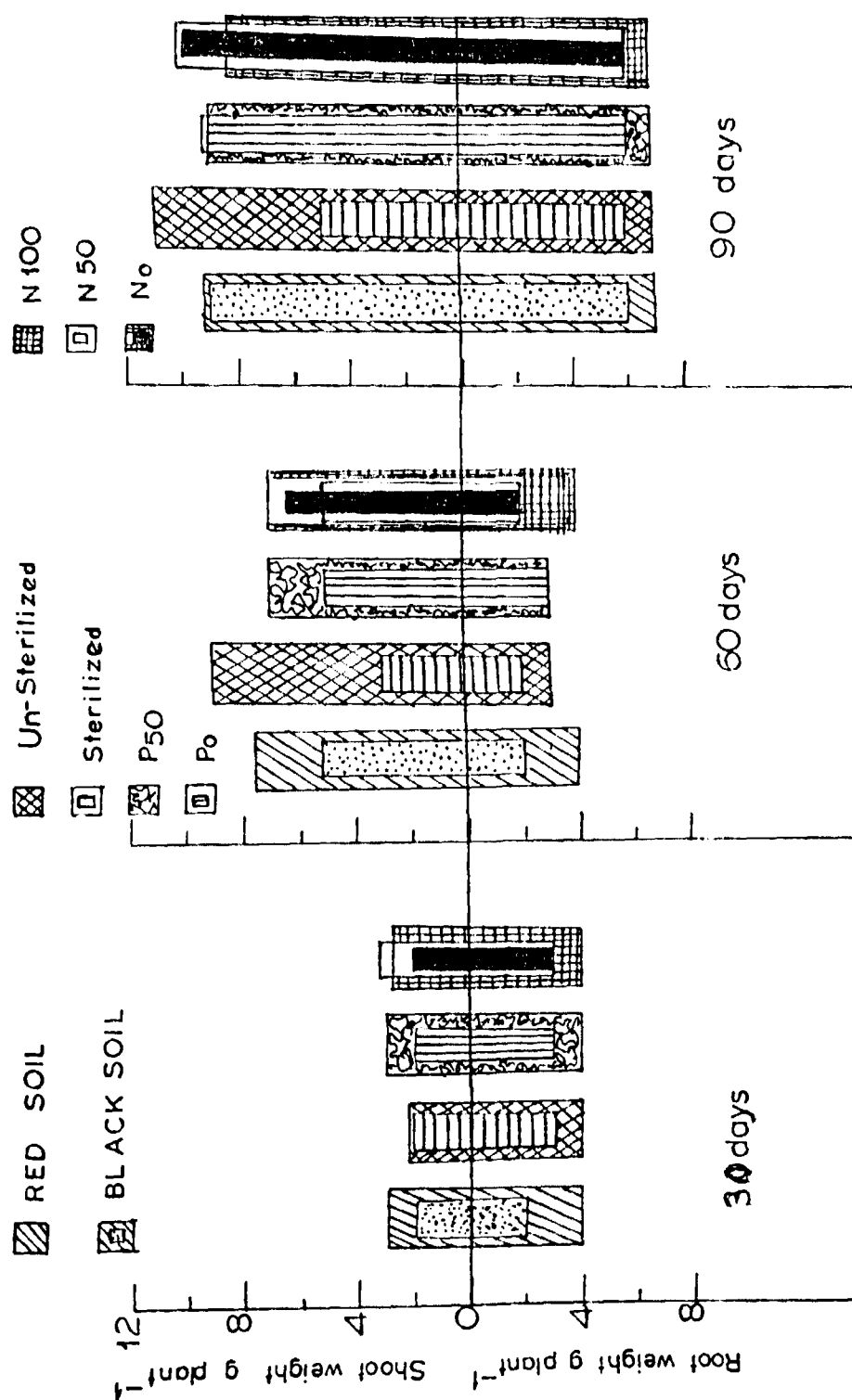


FIG. 11 ROOT AND SHOOT WEIGHT OF SORGHUM CROP AS INFLUENCED BY TREATMENTS AT DIFFERENT STAGES OF CROP GROWTH

significance. The important inferences drawn are; (i) the red soil at N_{50} and N_{100} levels and at P_0 and P_{50} levels registered higher root mass than the black soil; (ii) the black soil at N_0P_{50} level increased the root mass; however in the case of red soil P_{50} level was on par with P_0 level; (iii) under the normal condition of the soil the root mass was increased in both the soil types; (iv) the combined applications of $N_{100}P_0$ and N_0P_{50} registered higher root mass than the other combined applications; and (v) under the normal condition of the soil root mass was enhanced at all levels of N and P applications.

At 60th day, the interactions viz., $S \times N$, $S \times P$, $S \times St$, $N \times P$, $N \times St$ and $P \times St$ attained statistical significance. The important inferences drawn are: (i) at all levels of N and P applications the red soil registered higher root mass than the black soil and the black soil at N_0P_{50} level and the red soil at $N_{100}P_{50}$ level increased the root mass; (ii) the black soil under normal condition and the red soil under sterilized condition enhanced the root mass; (iii) the combined application of $N_{100}P_{50}$ increased the root mass; and (iv) irrespective of the condition of the soil at N_{100} level and irrespective of P fertilization under the normal condition of the soil the root mass was enhanced.

At 90th day, the interactions viz., S x N, S x St, N x P, N x St and P x St attained statistical significance. The main inferences drawn are: (i) the red soil at N₅₀ and N₁₀₀ levels while the black soil at N₀ level registered increased root mass; (ii) as observed at 60th day the black soil under normal condition and the red soil under sterilized condition enhanced the root mass; however under normal condition of the soil, N₅₀ level was on par with N₁₀₀ level.

4.10.4. Effect on total root length (Table 44)

Individual effects

i) Sterilization: The mean value for the main effect fell within the range of 1177 to 13941 cm. Under the sterilized condition of the soil total root length at 30 days stage exhibited a marginal increase than that under normal condition of the soil, but it showed significant increase at 60 and 90 days stage.

ii) Soil types: The mean value for the main effect remained within the range of 683 to 10602 cm. The red soil registered significantly higher total root length than the black soil at all the three stages of crop growth.

iii) P levels: The mean value for this main effect ranged from 868 to 10502 cm. The P application

TABLE 44. EFFECT OF TREATMENTS ON TOTAL ROOT LENGTH OF SORGHUM IN BLACK AND RED SOILS (cm)

250

Treatments	30 days	60 days	90 days
St	1242	9667	13941
NSt	1177	9385	7371
S ₁	683	8666	7435
S ₂	1736	10386	10602
P ₀	868	8549	9824
P ₅₀	1550	10502	8212
SE	168	243	284
CD	491	712	831
N	1159	7815	6579
N ₅₀	1463	8108	9821
N ₁₀₀	1006	12654	10656
SE	206	298	348
CD	601	872	1017
St x S ₁	498	9614	8714
St x S ₂	1986	9719	12511
NSt x S ₁	867	7717	6156
NSt x S ₂	1486	11053	8694
St x P ₀	867	8662	12819
St x P ₅₀	1618	19671	8406
NSt x P ₀	876	8436	6831
NSt x P ₅₀	1484	10333	8019
S ₁ x P ₀	343	7134	8079
S ₁ x P ₅₀	1023	10197	6791
S ₂ x P ₀	1394	9964	11571
S ₂ x P ₅₀	2079	10807	9634
SE	168	344	402
CD	NS	1007	1175
St x N ₀	975	7105	7624
St x N ₅₀	1777	6746	10273
St x N ₁₀₀	976	15149	13941
NSt x N ₀	1343	8525	5535
NSt x N ₅₀	1150	9471	9370
NSt x N ₁₀₀	1037	10159	7271
S ₁ x N ₀	907	7037	5498
S ₁ x N ₅₀	601	7264	7580
S ₁ x N ₁₀₀	541	11696	9228
S ₂ x N ₀	1411	8593	7661
S ₂ x N ₅₀	2326	8953	12063
S ₂ x N ₁₀₀	1472	13612	12084
N ₀ x P ₀	633	9811	7655
N ₀ x P ₅₀	1684	5819	5503
N ₅₀ x P ₀	933	7311	10305
N ₅₀ x P ₅₀	1994	8906	9338
N ₁₀₀ x P ₀	1038	8526	11514
N ₁₀₀ x P ₅₀	975	16782	9797

recorded higher total root length than no P application at ²⁵¹30 and 60 days stage, but the trend was reversed at 90 days stage.

iv) N levels: The mean value for this main effect ranged from 1006 to 12654 cm. The N_{100} level significantly produced higher total root length than N_{50} and N_0 levels at 60 and 90 days stage, but at 30 days stage, N_{50} level recorded only marginal increase.

Interaction effects

No interaction was significant at 30th day.

At 60th day, the interactions viz., $S \times P$, $S \times St$, $N \times P$ and $N \times St$ attained the level of significance. The important inferences drawn are: (i) in both the soil types P application increased total root length; (ii) the black soil under sterilized condition and the red soil under non-sterilized condition increased total root length and irrespective of the condition of the soil, the red soil and N_{100} level registered enhanced total root length; and (iii) the combined application of $N_{50}P_0$ on par with $N_{100}P_0$ level and $N_{100}P_{50}$ recorded significantly increased total root length.

At 90th day, the interactions viz., $N \times St$ and $P \times St$ showed statistical significance which revealed that under sterilized condition of the soil total root length at all levels of N and P applications was increased and that the $N_{50}P_{50}$ level under normal condition of the soil and $N_{100}P_0$ level under sterilized condition of the soil increased total

4.10.5. Effect on root diameter (Table 45)

Individual effects

i) Sterilization: The mean value for the main effect remained within the range of 0.36 to 0.64 mm. Under sterilized condition of the soil root diameter was significantly reduced at all the three stages of crop growth.

ii) Soil types: The mean value for the main effect fell within the range of 0.37 to 0.61 mm. The red soil registered significantly higher root diameter than the black soil at 60 and 90 days stage but the difference was small at 30 days.

iii) P levels: The mean value for the main effect ranged from 0.36 to 0.61 mm. The P application enhanced the root diameter at 60 and 90 days stage of crop growth but at 30th day stage, it exhibited no beneficial trend.

iv) N levels: The mean value for this main effect ranged from 0.38 to 0.65 mm. The N_{100} level at 30 days stage and N_{50} level at 60 days stage significantly increased root diameter but at 90 days stage, N application did not enhance root diameter.

TABLE 45. EFFECT OF TREATMENTS ON ROOT DIAMETER OF SORGHUM IN BLACK AND RED SOILS (mm)

253

Treatments	30 days	60 days	90 days
St	0.57	0.42	0.36
NSt	0.64	0.47	0.47
S ₁	0.61	0.39	0.37
S ₂	0.60	0.50	0.46
P ₀	0.61	0.40	0.36
P ₅₀	0.60	0.49	0.47
SE	0.008	0.002	0.005
CD	0.023	0.006	0.013
N ₀	0.60	0.43	0.45
N ₅₀	0.56	0.48	0.38
N ₁₀₀	0.65	0.42	0.41
SE	0.008	0.002	0.006
CD	0.029	0.007	0.016
St x S ₁	0.58	0.30	0.28
St x S ₂	0.56	0.54	0.43
NSt x S ₁	0.64	0.49	0.45
NSt x S ₂	0.64	0.46	0.49
St x P ₀	0.54	0.34	0.28
St x P ₅₀	0.59	0.50	0.44
NSt x P ₀	0.69	0.47	0.45
NSt x P ₅₀	0.60	0.48	0.49
S ₁ x P ₀	0.62	0.33	0.33
S ₁ x P ₅₀	0.60	0.46	0.40
S ₂ x P ₀	0.60	0.48	0.39
S ₂ x P ₅₀	0.60	0.52	0.53
SE	0.011	0.003	0.007
CD	0.033	0.008	0.019
St x N ₀	0.60	0.39	0.39
St x N ₅₀	0.49	0.47	0.34
St x N ₁₀₀	0.62	0.40	0.35
NSt x N ₀	0.61	0.47	0.51
NSt x N ₅₀	0.64	0.50	0.43
NSt x N ₁₀₀	0.68	0.44	0.47
S ₁ x N ₀	0.66	0.35	0.38
S ₁ x N ₅₀	0.60	0.47	0.36
S ₁ x N ₁₀₀	0.57	0.36	0.36
S ₂ x N ₀	0.55	0.51	0.52
S ₂ x N ₅₀	0.53	0.50	0.41
S ₂ x N ₁₀₀	0.72	0.48	0.46
N ₀ x P ₀	0.63	0.37	0.39
N ₀ x P ₅₀	0.58	0.49	0.51
N ₅₀ x P ₀	0.61	0.42	0.32
N ₅₀ x P ₅₀	0.52	0.55	0.45
N ₁₀₀ x P ₀	0.61	0.42	0.38
N ₁₀₀ x P ₅₀	0.69	0.42	0.44

Interaction effects

At 30th day, the interactions viz., S x N, N x P, N x St and P x St attained statistical significance. The main inferences drawn are: (i) the black soil at N_0 level and the red soil at N_{100} level recorded enhanced root diameter; (ii) the combined application of $N_{100}P_{50}$ increased the root diameter and (iii) irrespective of the condition of the soil N_{100} level and P application at 50 kg level under sterilized condition enhanced this parameter.

At 60th day, the interactions viz., S x N, S x P, S x St, N x P, N x St and P x St attained statistical significance. The important inferences drawn are: (i) at all levels of N and P applications the red soil registered greater root diameter; in both the soils N_{50} and P_{50} levels increased root diameter; however in the red soil N_{50} level was on par with N_0 level; (ii) the black soil under normal condition and the red soil under sterilized condition increased root diameter; (iii) at both the levels of P, N_{50} level enhanced root diameter; however at P_0 level, N_{50} level was on par with N_{100} level and (iv) irrespective of the condition of the soil N_{50} and P_{50} levels increased root diameter.

At 90th day, the interactions viz., S x N, S x P, S x St, N x P, N x St and P x St attained statistical

significance. The salient inferences drawn are: (i) at all levels of N and P applications the red soil registered higher root diameter than the black soil; the black soil at N_0 level being on par with N_{50} and N_{100} levels and P_{50} level increased root diameter, while the red soil at N_0 and P_{50} levels increased root diameter; (ii) both the soils under normal condition enhanced root diameter; at P_0 level, N_0 level being on par with N_{100} level and at P_{50} level N_0 level was found to increase root diameter in a significant manner and (iii) irrespective of the condition of the soil N_0 level and P_{50} level increased this parameter.

4.10.6. Effect on shoot weight (Table 46) (Fig.11)

Individual effects

i) Sterilization: The mean value for this main effect ranged from 2.69 to 11.54 g. Under normal condition of the soil significantly higher shoot weight was recorded than that under sterilized condition at all three stages of crop growth.

ii) Soil types: The mean value for the main effect ranged from 2.07 to 9.79 g. The red soil registered significantly higher shoot weight than the black soil at all the three stages of crop growth.

iii) P levels: The mean value for this main effect ranged from 2.14 to 9.73 g. The P application at 50 kg level registered significantly higher shoot weight at 30 and 60 days stage than no P application but such difference was not observed at 90 days stage.

iv) N levels: The mean value for this main effect remained within the range of 2.23 to 10.46 g. The N_{50} level showed significantly higher shoot weight than N_{100} and N_0 levels at 30 and 90 days stages, but at 60 days stage N_{100} level registered higher shoot weight than the other N levels.

Interaction effects

At 30th day, the interactions viz., S x N, S x P, S x St, N x P, N x St and P x St attained statistical significance. The important inferences drawn are: (i) the black soil at P_{50} level and the red soil at N_{50} and P_{50} levels registered increased shoot weight; (ii) irrespective of the condition of the soil the red soil registered higher shoot weight than the black soil; (iii) irrespective of P application N_{50} level registered higher shoot weight than other N levels; however at P_0 level N_{50} level was on par with N_{100} level; and (iv) under sterilized condition N_{50} and P_{50} level applications were required to exhibit increased shoot weight while such fertilizer application was not needed under normal condition of the soil to increase shoot weight.

TABLE 46. EFFECT OF TREATMENTS ON SHOOT WEIGHT OF SORGHUM IN BLACK AND RED SOILS(g)

257

Treatments	30 days	60 days	90 days
St	2.69	3.63	7.66
NSt	2.82	9.32	11.54
S ₁	2.07	5.21	6.40
S ₂	3.45	7.75	9.79
P ₀	2.14	5.63	9.73
P ₅₀	3.38	7.33	9.46
SE	0.023	0.072	0.071
CD	0.067	0.212	0.207
N ₀	2.23	6.50	9.87
N ₅₀	3.20	5.87	10.46
N ₁₀₀	2.84	7.07	8.46
SE	0.028	0.089	0.086
CD	0.082	0.259	0.253
St x S ₁	1.58	1.47	6.69
St x S ₂	3.81	5.80	8.61
NSt x S ₁	2.56	8.94	12.11
NSt x S ₂	3.09	9.71	10.97
St x P ₀	1.87	2.78	7.20
St x P ₅₀	3.52	4.49	8.10
NSt x P ₀	2.41	8.49	12.26
NSt x P ₅₀	3.23	10.16	10.82
S ₁ x P ₀	1.66	4.32	9.79
S ₁ x P ₅₀	2.47	6.09	9.01
S ₂ x P ₀	2.62	6.95	9.67
S ₂ x P ₅₀	4.28	8.56	9.91
SE	0.033	0.102	0.100
CD	0.095	0.300	0.29
St x N ₀	1.92	3.33	7.79
St x N ₅₀	3.49	2.63	8.45
St x N ₁₀₀	2.67	4.94	6.72
NSt x N ₀	2.55	9.67	11.96
NSt x N ₅₀	2.90	9.10	12.47
NSt x N ₁₀₀	3.01	9.20	10.20
S ₁ x N ₀	2.24	5.56	9.41
S ₁ x N ₅₀	1.98	4.79	9.95
S ₁ x N ₁₀₀	1.98	5.27	8.84
S ₂ x N ₀	2.23	7.44	10.33
S ₂ x N ₅₀	4.41	6.95	10.97
S ₂ x N ₁₀₀	2.71	8.87	8.08
N ₀ x P ₀	1.56	6.59	9.19
N ₀ x P ₅₀	2.90	6.41	10.55
N ₅₀ x P ₀	2.45	4.51	10.34
N ₅₀ x P ₅₀	3.95	7.23	10.58
N ₁₀₀ x P ₀	2.41	5.79	9.66
N ₁₀₀ x P ₅₀	3.28	8.34	7.26
SE	0.039	0.125	0.12

At 60th day, the interactions viz., S x N, S x St, N x P and N x St were found to be significant. The main inferences drawn are: (i) at all levels of N, the red soil registered higher shoot weight than the black soil; (ii) irrespective of the soil condition the red soil registered greater shoot weight than the black soil; (iii) at N_{50} and N_{100} levels, P_{50} level recorded increased shoot weight and (iv) N_{100} level was needed to show enhanced shoot weight under sterilized condition while under normal condition no N application was needed and at all levels of N normal condition of the soil proved to be better than the sterilized condition in increasing shoot weight.

At 90th day, the interactions viz., S x N, S x P, S x St, N x P, N x St and P x St showed statistical significance. The salient inferences drawn from the above interactions are: (i) the black soil at N_{50} level with no P application and the red soil at N_{50} and P_{50} levels showed increased shoot weight; (ii) in both the soils types under normal condition, shoot weight was increased; (iii) at P_0 and P_{50} levels N_{50} level increased shoot weight; however at P_{50} level, N_{50} level was on par with N_0 level; (iv) irrespective of the soil condition N_{50} level showed higher shoot weight than the other levels of N; and (v) at all levels of N and P applications and under normal condition of the soil, shoot weight was increased and P application was needed under sterilized condition to increase shoot weight.

TABLE 47. CORRELATION STUDIES - RELATIONSHIP OF ROOT LENGTH, ROOT MASS AND GRAIN YIELD WITH SOIL CHARACTERISTICS AND OTHER FACTORS

S.No.	Dependent variable Y	Independent variable X	Stage of the crop	'r' value	Regression Equation
1.	Root length	Available K	30 days	-0.4807*	$Y = 2330 - 1.6923 X_K$
2.	"	P content in root	"	-0.5442**	$Y = 2271.4 - 1828.5 X_P$
3.	"	Fe content in root	"	-0.4108	$Y = 2551.2 - 2.168 X_{Fe}$
4.	"	N uptake by shoot	"	0.6307**	$Y = -105.02 + 42629 X_N$
5.	"	K uptake by shoot	"	0.6667**	$Y = -249.72 + 35372 X_K$
6.	"	Zn uptake by shoot	"	0.5831**	$Y = -77.721 + 2683.78 X_{Zn}$
7.	"	P content in shoot	60 days	0.6136**	$Y = 3752.78 + 60928.8 X_P$
8.	"	Fe uptake by shoot	"	0.4181*	$Y = 5024 + 518.99 X_{Fe}$
9.	"	Available Fe	90 days	0.4459*	$Y = 2427.84 + 187.19 X_{Fe}$
10.	Root mass	N content in root	30 days	-0.4368*	$Y = 5.6674 - 5.351 X_N$
11.	"	P content in root	"	-0.5863**	$Y = 5.6821 - 3.545 X_P$
12.	"	Fe content in root	"	-0.4428*	$Y = 6.2408 - 0.0043 X_{Fe}$
13.	"	N content in shoot	"	-0.4757*	$Y = 6.671 - 2.605 X_N$
14.	"	K uptake by shoot	"	0.6311**	$Y = 1.0098 + 61.942 X_K$
15.	"	Zn uptake by shoot	"	0.5862**	$Y = 1.1712 + 4.991 X_{Zn}$
16.	"	Available N	60 days	-0.4124*	$Y = 8.203 - 0.027 X_N$
17.	"	Available K	"	-0.4212*	$Y = 5.422 - 0.00633 X_K$
18.	"	N content in root	"	-0.5048*	$Y = 4.6085 - 2.9631 X_N$
19.	"	P content in root	"	-0.5454**	$Y = 6.4004 - 11.036 X_P$
20.	"	Fe content in root	"	-0.6089**	$Y = 7.9742 - 0.01197 X_{Fe}$
21.	"	Zn content in root	"	-0.5917**	$Y = 6.9527 - 0.1021 X_{Zn}$
22.	"	Fe content in shoot	"	-0.5113*	$Y = 4.747 - 0.0006 X_{Fe}$
23.	"	N uptake by shoot	"	0.7842**	$Y = 0.07099 + 44.398 X_N$
24.	"	K uptake by shoot	"	0.5329**	$Y = 1.6303 + 13.523 X_K$
25.	"	Fe uptake by shoot	"	0.7569**	$Y = -0.1436 + 0.3718 X_{Fe}$
26.	"	Zn uptake by shoot	"	0.7694**	$Y = 0.3066 + 2.399 X_{Zn}$
27.	Root mass	Available Mn	90 days	0.4895*	$Y = -21.598 + 0.4894 X_{Mn}$
28.	"	Fe content in root	"	-0.4248*	$Y = 10.957 - 0.01 X_{Fe}$
29.	"	N content in shoot	"	-0.6540**	$Y = 2.1825 + 8.802 X_N$
30.	"	N uptake by shoot	"	0.5587**	$Y = 3.672 + 62.363 X_N$
31.	"	K uptake by shoot	"	0.4445*	$Y = 3.826 + 21.454 X_K$
32.	Grain yield	N uptake by grain	"	0.9194**	$Y = 3.4043 + 64.999 X_N$
33.	"	P uptake by grain	"	0.5807**	$Y = 10.4144 + 310.028 X_P$
34.	"	K uptake by grain	"	0.8478**	$Y = 3.7523 + 185.85 X_K$
35.	"	Fe uptake by grain	"	0.7979**	$Y = 5.0363 + 1.7140 X_{Fe}$
36.	"	Zn uptake by grain	"	0.7511**	$Y = 5.997 + 7.2659 X_{Zn}$

* Significant at 5% probability level

Correlation studies (Table 47)

Co-efficient of correlation of grain yield and root growth parameters with availability of nutrients in soil, nutrient content in roots, nutrient content and uptake by shoot at different growth stages of sorghum crop were worked out after consolidating the data for types of soils and sets of soils. The data is presented in table 47.

5

N

CHAPTER 5

DISCUSSION

The concept of availability of plant nutrients in the soils is a complex phenomena. A plithora of evidences have accumulated to indicate that there exists considerable differences in the nutrient status between rhizosphere and non-rhizosphere soils. In view of several physico- chemical and biological changes continuously encountered in the soil. There are significant changes in the nutrient availability, transformation, and absorption of nutrients. These processes differ between rhizosphere and non-rhizosphere soils, again contributed by several plant factors like root exudation, solughing off root tissues, absorption, adsorption, root interception, etc. Therefore, a case study with sorghum as test crop was taken up employing various experimental factors viz., soil types, sterilization, N levels, P levels and site of soil collection in order to have a clear understanding of chemistry of rhizosphere soils in relation to nutrient availability, transformation, flow rate, crop nutrition and yield. The salient points emanating from the above experiments are briefly discussed in this chapter.

5.1. Studies on the root exudation pattern

In order to find out the exudation pattern of sorghum plant, root exudate study was conducted as explained under 'Materials and Methods'.

5.1.1. Root exudation pattern in sorghum plant at different stages of plant growth

The results of this study (Table 2a, b and c) indicated that there were qualitative and quantitative changes in the exudation of aminoacids and sugars by roots over the period of growth. In general, the number and concentration of the aminoacids and sugars exuded by the plant roots increased upto 30 days of growth after which they declined. Such reduction in the exudate with plant age has been observed by many workers (Rovira, 1959 and 1962; Balasubramaniam and Rangaswamy, 1978).

5.1.2. Pot experiment to study the nutrient availability transformation, flow rate and crop relationships

This experiment involved an indepth appraisal of the physico-chemical differences in the root environment, yield and nutrient uptake by sorghum crop in two predominant soil types as influenced by varying levels of N and P application under sterilized and normal conditions of the soil. The rhizosphere and non-rhizosphere soil samples under each of the above cases were investigated separately for the above said phenomena, apart from assessing the variation in the growth characteristics.

As is well known, the red and black soils differ considerably in many properties. The nutrient environment in the rhizosphere and non-rhizosphere also vary considerably (Barber, 1971, Kozlowski, 1973, Arunachalam, 1975 and Marschner, 1983). The availability of plant nutrients in the red and black soils is considerably influenced by the soil microflora and perhaps the nutrient availability in most cases is conditioned by the organic matter content in conjunction with the quality and quantity of microbes existing in the soil. It is also obvious that due to several physico-chemical and biological phenomena, the rhizosphere soil of any plant remains little different from the non-rhizosphere soil, (Balasubramanian and Rangaswamy, 1978 and Marschner, 1983) and this is accomplished by such effects like mass flow of nutrients (Barber, 1971), exudation of organic substances by the roots etc., (Rovira, 1959 and 1962, Balasubramanian and Rangasamy, 1978). On account of these factors, the pot experiment involved different soil types, induced fertility variation, sterilized and unsterilized condition and also consideration of rhizosphere and non-rhizosphere soils. Thus the pot experiment covered many of the normal variations encountered in growing sorghum crop and provided an opportunity to have an indepth understanding of nutrient availability - plant growth relationships as applied to sorghum.

5.1.2.1. Pot culture experiment

Studies on nutrient availability, transformation and flow rate in rhizosphere and non-rhizosphere soils of sorghum crop as influenced by soil types, fertilization and sterilization were carried out under pot culture experiment.

5.1.2.2. Characteristics of soils used for the experiment

The physico-chemical characteristics of the black soil and red soil used for the experiment are presented in table 3. These two soils occupy a major area in the state of Tamil Nadu varying widely in textural make up, thus imparting perceptible differences in the physico-chemical characteristics which would give sufficient scope for the study.

Sorghum crop constitutes the main millet grown in the soils both under rainfed and irrigated conditions and occupies a unique position among the cultivated crops in Tamil Nadu and forms the staple food for hundred millions in the country. It is cultivated in nearly 10.0 lakh hectares in the state. The suitability of the crop to all the three seasons viz., South West monsoon season, North East monsoon and summer irrigated season offers scope to substantially increase the production by stabilizing sorghum yield (Anon., 1985).

The black soil was clayey in nature, while red soil was sandy loam. The CEC was higher in the black soil than in the red soil due to the content and type of clay minerals (Chinnadurai, 1967). Earlier works on the black and red soils of Tamil Nadu have shown that these soils exhibited marked differences in some of their properties (Menon and Mariakulandai, 1957 a; Ray Chaudhury and Govindarajan, 1958; Dhanapalan Mosi, 1960; Manickam, 1961; Krishnamoorthy, 1966; Chinnadurai, 1967; Jose, 1973; Kothandaraman, 1975; and Ramanathan, 1977). These workers observed that black soils were characterized by higher clay content and greater CEC while red soils were relatively rich in iron oxides. In the present study also, the differences between the black and red soils were quite marked and this may be attributed to the difference in the kind of parent material from which they have been derived and the degree of weathering undergone by them (Menon and Mariakulandai, 1957b; RayChaudhury and Govindarajan, 1958). The wide variation in the total contents of both macro and micro nutrients in soils is attributed to the differences in the nature of their parent material and soil forming processes in different climatic conditions (Kanwar and Randhawa, 1967; Arunachalam and Dhanapalan Mosi, 1973).

5.2. Dynamics of rhizosphere soils in relation to nutrient availability

5.2.1. Effect on availability of N, P and K in soils

5.2.1.1. Effect on available N (Table 4)

The status of available N was found to be influenced, not by the varying levels of N, but by the other factors such as rhizosphere soil, soil types and sterilization. The increasing trend of available N status in the black soil under sterilized condition and in the rhizosphere soil is attributable to several factors. The black soil by virtue of high colloidal material and organic matter content (Kanwar, 1976) obviously favoured greater accumulation of available N status in the black soil than in the red soil. A relatively high available N in the rhizosphere soil might be attributed to the mass flow phenomena (Barber, 1971). This is evidenced by the work of Marschner (1983) who stated that at the soil-root interface, i.e., rhizosphere, the availability of nutrients can be considerably influenced by the plant root itself.

Under sterilized condition of the soil, the build^{up} of microflora was inhibited resulting in poor mineralization rates and prevention of leaching and volatile losses. The more or less same trend was reflected in the other stages of crop growth as well. Possible reason for the absence of any build^{up} of available N with increasing levels of N

attributable to the present conditions of the experiment, where the entire dose of N was basally applied and tropical conditions that existed have favoured rapid transformation with the result what one would visualise large scale differences in available N upon enhanced fertilization has not been observed in this case. Further, the highly mobile nature of the nutrient has nullified any difference that would arise in different levels of N. Such experimental results were also reported by Cornish and Raison (1976) in the case of rye seedlings. The available N content was the highest at 30 days stage and thereafter it declined progressively its value being low at 90 days stage. Such a result could also be expected since there was a continuous removal of N by the growing crop. Similar results of decrease of available N during crop growth have been reported by different workers in sorghum crop (Ramalingam, 1975; Bhalerao et al., 1976; Viswanathan, 1976; Durairaj Muthiah, 1978 and Muthukrishnan, 1979).

5.2.1.2. Effect on available P (Table 5)

The forms and amounts of P in the soil have a considerable effect on the availability of P to crops. The rhizosphere region contained more available phosphorus in relation to non-rhizosphere region (Barber et al., 1963; Lewis and Quirk, 1967; and Riley and Barber, 1971). The red soil inherently contained more of available P as was observed by Kandasamy et al. (1973) and Krishnasamy (1982). The

sterilized condition and N addition tended to decrease the available P content in soil, while P addition favoured greater accumulation of available P. Phosphorus is usually absorbed from a small volume of soil surrounding the root because P diffuses very slowly through the soil (Barber et al., 1963; Lewis and Quirk, 1967). Thus the status of available P was found to be conditioned by several factors. The effect of sterilization resulting in decrease of the available P might be ascribed to the poor decomposition of organic matter on account of reduced microflora and formation of favourable organic compounds for mobile P (Arunachalam, 1975).

As is the case with N, the rhizosphere soil accumulated relatively more available P (Arunachalam, 1975) and this effect might be due to not only the solubilizing effect of root exudates, but also enhanced microbial population e.g., phosphate solubilizing bacteria (Chandrasekaran, 1965 and 1968). in the region. Riely and Barber (1971) recognised that the rhizosphere microflora and exudates from the roots have been postulated as factors influencing P availability. Olsen's P values were higher in the rhizosphere soil than that in the non-rhizosphere soil and this might be attributed to the solubilization of insoluble phosphate compounds because of organic acids as a result of increased microbial activity in the rhizosphere

(Duff et al., 1963; Sharma and Saxena, 1982). In addition to this, the P movement and absorption in soil might have occurred through diffusion and interception which influenced the availability of phosphorus in the rhizosphere soil (Sharma and Saxena, 1982).

Another point of interest is that the N addition brought about decrease in available P in the earlier stages i.e., from 3.17 to 3.07 ppm at 30th day and from 3.85 to 3.23 ppm at 60th day of crop growth and this effect got reversed near about the harvest stage. Perhaps the influence of N on microbes and the enhanced utilization of P brought about by enhanced growth of plant by N might have accounted for such a phenomena (Fried and Broeshart, 1967).

5.2.1.3. Effect on available K (Table 17)

The black soil contained more available K (434 ppm at 30 days, 394 ppm at 60 days and 370 ppm at 90 days) than the red soil (204 ppm at 30 days, 180 ppm at 60 days and 163 ppm at 90 days) obviously attributable to the higher clay content (Jayaraj and Dhanapalan Mosi, 1973). The rhizosphere region recorded higher available K than non-rhizosphere region which could be accounted for the twin effects of enhanced solubilization of K on the one hand and the interaction of other elements with fixed K on the other

(Arunachalam, 1975). The rhizosphere region of black soil had high quantities of available-K content than the non-rhizosphere region of red soil. The application of P did not bring about any significant effect on available K content in the soil and this was contrary to the findings of Negi et al. (1981) who stated that application of higher dose of P decreased the available K status. The available K content decreased significantly with advancement of stages of crop growth. It was possible that such progressive reduction was brought about by crop uptake or by continuing transformation leading to conversion of water soluble-K into insoluble forms or fixation of K in the crystal lattice of clay minerals. Earlier workers like Antony Joseph (1969), Raju (1977) etc. also adduced similar reasoning to the decrease of available-K content of the soil with advancement of crop growth.

5.2.2. Effect of availability of micronutrients

5.2.2.1. Effect on available Fe (Table 6)

The available Fe content found to be high in the black soil could be attributed to the inherent nature of the black soil and higher clay content (Kanwar, 1976). The available Fe content was observed to be increased at all the three stages of crop growth. Similar results were also reported by Francis (1976). Lower concentration of available Fe was recorded in the black soil (Arunachalam, 1975). The effect of sterilization on available Fe was found to be a

time-bound process. During the initial stages, under sterilized condition of the soil microbial build-up was lowered thereby providing less opportunities for chelation and this resulted in lowered available Fe. But with time the microbial build up proceeded, decomposition processes setting up providing more opportunities for such mechanisms like chelation (Himes and Barber, 1957) solubilization, mineralization, etc. and these processes favoured more available Fe. The rhizosphere region recorded higher available Fe attributable to the lowered pH and solubilization effect (Sauchelli, 1969; Arunachalam, 1975; Mortvedt et al., 1972 and 1977).

5.2.2.2. Effect on available Mn (Table 7)

A comparison of soils with regard to their influence on available Mn content showed that the red soil which recorded increased initial value of available Mn content as 20.6 ppm was found to record increased values of available Mn content and this may be attributable to the inherent nature and low soil pH. But Arunachalam (1975) and Krishnasamy (1982) reported higher concentration of available Mn content in the black soil than that in the red soil. Under sterilized condition of the soil, the available Mn content was diminished and this could be explained by the fact that the availability of Mn was closely linked to the organic matter-microflora relationships (Katznelson, 1965, Ramasamy

and Raj, 1973). Contrary to this observation, Boyd (1971) reported Mn-toxicity in autoclaved soil resulting from the release of the Mn complexed with soil organic matter and the killing of microorganisms which normally transform available Mn to higher oxides. But Jager *et al.* (1969 a and 1969 b) reported increased buffer soluble Mn content in the soil. Arunachalam (1975) recorded higher concentration of available Mn under sterilized condition.

As is the case with Fe, the rhizosphere region contained more available Mn than the non-rhizosphere region, obviously associated with solubility, chelatability and pH relationships associated with rhizosphere region soils and this is in line with the findings of Arunachalam (1975). Nitrogen application at 100 kg ha^{-1} level increased the available Mn content in the soil at 60th day. Phosphorus application at 50 kg ha^{-1} increased the available Mn content at 30 and 60 days growth stage and this was not in confirmity with the findings of Gupta and Bhadra (1980) who studied the Mn-P relationship in rice in an alluvial soil of West Bengal. They reported that P application reduced Mn availability in the first and second sampling stage, but increased it in the third sampling stage of rice crop.

5.2.2.3. Effect on available Cu (Table 8)

The black soil contained more available Cu content in view of higher clay content associated with it, as

was observed by Arunachalam (1975) and the higher initial available Cu content in the soil. This is in consonance with the findings of Krishnasamy (1982). Under sterilized condition of the soil the available Cu content was increased. This might be due to lessening of release of organic compounds by way of decomposition which was known to immobilise Cu (Mortvedt *et al.*, 1972). As in the case of Fe and Mn, more available Cu was observed in the rhizosphere region (Arunachalam, 1975) and the reasons already attributed for Fe and Mn hold good for Cu as well. Moreover, the strong binding effect of Cu with organic ligands is well established (Fried and Broeshart, 1967). The effect of N addition was found to increase available Cu in the soil and this was more pronounced at later stages. The addition of N could be expected to enhance the microbial content and also the rate of decomposition of available organic substances. This effect might result in the temporary lock up of available Cu in the initial stages. With time the cessation of microbial multiplication could be expected and the available Cu got enhanced again.

5.2.2.4. Effect on available Zn (Table 9)

The red soil was associated with higher Zn availability at all the three stages of crop growth and this is in line with the results observed by Krishnasamy (1982)

and Nagarajan (1984). But Kanakaraj (1979) reported that available Zn was lower at maturity stage than at flowering stage. Arunachalam (1975) reported a higher concentration of available Zn in the black soil. Under sterilized condition of the soil the available Zn content was found to be decreased at initial stages and perhaps this might be due to absence of organic matter-zinc interaction (Himes and Barber, 1957). The effect of organic matter in diminishing Zn availability had been reported by several workers like Fried and Broeshart, 1967 and Mortvedt et al., 1972 . But Arunachalam (1975) reported that Zn availability was more under sterilized condition. As was the case with other micronutrients, Zn availability was found to be more in the rhizosphere region (i.e., 0.50 ppm at 30 days; 1.30 ppm at 60 days and 0.90 ppm at 90 days stage) than that in the non-rhizosphere region and the reasons already stated hold good for this effect as well (Arunachalam, 1975). The effect of lowered pH values, root exudates and microbial content in enhancing Zn availability are well evidenced by several earlier workers (Barber, 1962; Katznelson, 1965; Balasubramaniam and Rangaswamy, 1978). The effect of N application in increasing the availability of Zn was observed only at later stages of crop growth and this is in confirmity with the findings of earlier workers.

5.3. Dynamics of rhizosphere soils in relation to nutrient transformations

5.3.1. Effect of transformation of N, P and K in soils

5.3.1.1. Effect on N transformation (Tables 10 and 11)

i) $\text{NH}_4\text{-N}$:

A consideration of the build up of $\text{NH}_4\text{-N}$ revealed that among the five factors, under sterilized condition of the soil, rhizosphere environment and P levels brought about significant differences in the $\text{NH}_4\text{-N}$ content. Sterilization kept down the $\text{NH}_4\text{-N}$ content to a marked degree from 26.6 to 21.3 ppm at 30th day, from 51.2 to 42.2 ppm at 60th day and from 10.0 to 7.6 ppm at 90th day, obviously attributable to the absence of nitrification process by bacteria. The effect due to sterilization was very highly pronounced suggesting the significant role of microflora in conditioning the soil N transformation (Katznelson, 1946; Rouatt et al., 1960). Sonneveld et al. (1970) reported that although steam sterilization killed most of the nitrifying microorganisms little NH_4^+ or NO_3^- was found at 40-50 days after treatment.

The other point of interest is that the rhizosphere soil contained relatively higher $\text{NH}_4\text{-N}$ content at 30 days growth stage and this is in conformity with results reported by Tinker (1969). This might perhaps be due

to a more congenial environment for microbes in the rhizosphere soil as compared to non-rhizosphere soil and the processes viz., the mass flow and the adsorption mechanisms could be expected to be higher during the younger stages of the plant (Barber, 1962 and Marschner, 1983). The lowered values of $\text{NH}_4\text{-N}$ content at 90th day was ascribed to the overall diminishing effect in the microbial activity apart from utilization of nitrogen by the crop. The matter of interest also lies in the fact that the soil differences and N application have not resulted in any differential build-up of $\text{NH}_4\text{-N}$ content (Cornish and Raison, 1976); however, differences in $\text{NH}_4\text{-N}$ content occurred during the advancement of the growth of the crop. The red soil accumulating more $\text{NH}_4\text{-N}$ again at 60th day, all N levels associating with more $\text{NH}_4\text{-N}$ again at 60th day were observed. This might be due to enhanced adsorption of $\text{NH}_4\text{-N}$ ions in the black soil in relation to the red soil (Fried and Broeshart, 1967). Another possible reason is that the black soil on account of its organic matter content, higher clay content, CEC and adsorption capacity (Kanwar, 1976) and the conducive environment in the black soil may result in rapid nitrification of any NH_4^+ that is formed (Katznelson, 1965 and Allison, 1973). The effect of P on $\text{NH}_4\text{-N}$ content at all the three stages of crop growth was found to be antagonistic. This might be due to the effect of P on microflora resulting in greater nitrification of $\text{NH}_4\text{-N}$ and enhanced root growth (Rouatt and Katznelson,

ii) $\text{NO}_3\text{-N}$:

A consideration of $\text{NO}_3\text{-N}$ gave evidence for the more important nature of rhizosphere soil and the effect of sterilization to cause pronounced differences in $\text{NO}_3\text{-N}$ accumulation. The rhizosphere soil was associated with higher $\text{NO}_3\text{-N}$ content (41.8 and 47.3 ppm at 30 and 60 days growth stages respectively). This is ascribable to the higher microflora associated with rhizosphere soils (Rouatt et al., 1960) and higher mass flow rate could be expected to be more during active growth stage (Barber, 1971). Under sterilized condition of the soil the $\text{NO}_3\text{-N}$ accumulation was found to be observed obviously due to lack of sufficient microflora for nitrification process. The above trend of results are in line with the findings of earlier workers like Katznelson (1965) and Sonneveld et al. (1970). But Burgos (1964) reported that soils sterilized with gamma radiation increased total N, $\text{NO}_3\text{-N}$ and P probably through releasing these nutrients after the destruction of the living microflora. The effect of N levels depended again on the stage of sampling. Nitrogen application was associated with lowered $\text{NO}_3\text{-N}$ content on 30th day, the reverse was the case at later stages as was observed by Parkinson and Thomas (1969). It is again a factor associated with microbial content as it is well known that soon after N addition, there is a build-up of microflora (Mosolov et al., 1959) and decline of the same with time.

Phosphorus application also reacted in a similar manner viz., higher $\text{NO}_3\text{-N}$ content at the initial stage and declined thereafter again-a case closely linked to microbial activity.

5.3.1.2. Effect on P transformation (Tables 12 to 15)

Transformation of phosphorus in soil is a dynamic process which is influenced by rhizosphere besides other soil and plant characteristics. The sum of the contents of saloid-P (NH_4Cl extractable), Al-P ($\text{NH}_4\text{-F}$ extractable), Fe-P (NaOH extractable) and Ca-P (H_2SO_4 extractable) may be collectively designated as active inorganic P because these are the soil P fractions which are usually related with plant availability and undergo enrichment or depletion by fertilization or crop removal (Volk and McLean, 1963; Singh *et al.*, 1966).

i) Saloid-bound P

The saloid-bound P also showed variation due to treatments. This was observed to be maximum at 30 days growth stage, which might be due to hydrolysis of added and native phosphates and the decrease thereafter, might be due to the transformation of water soluble-P into other insoluble fractions with time (Singh and Bahaman, 1976). Among the two soils the red soil was associated with higher saloid-P than the black soil since the red soil provided a more congenial environment for saloid-P in view of high anion exchange capacity associated with Kaolinitic clay. The evidence for

high AEC in kaolinitic clay could be deduced from the work of Buckman and Brady (1967) and Grimshaw (1971). The effect of sterilization was synergistic in the earlier stages and vice versa at later stages.

The rhizosphere region recorded relatively low saloid-P at 30 days stage (4.84 ppm) as compared to non-rhizosphere region (9.65 ppm). It might be attributable to a slightly more acidic nature in the rhizosphere soil accomplished by root exudates (Rovira, 1959). This, coupled with the acid root exudates, could be expected to solubilise the saloid-bound P in the rhizosphere region. This also signified the natural ability of the plant roots to obtain phosphorus by such mechanisms. However, at 90 days stage this was not the case obviously due to lowered activity of the roots (Scott, 1977). The amount of saloid-bound P in the soil was found to be related to the microbial activity. Under sterilized condition of the soil, the absence of microbial content in the soils resulted in poor P utilization by microbes and this tended to enhance saloid-bound P i.e., .95 ppm as against 6.54 ppm under normal condition of the soil. This was further evidenced by the fact that at 90 days stage the effect due to sterilization was not evident and the microbial factor became prominent and consequently the saloid-bound P got reduced.

ii) Al-P:

Unlike saloid-P, the black soil recorded more Al-P than the red soil and sterilized condition tended to cause increased Al-P content in the soil. As was the case with other forms of P, the rhizosphere soil contained more Al-P than the non-rhizosphere soil. This is in line with the observation of Jain and Sarkar (1980) who suggested that a major portion of the applied P was transformed into Al-P and Fe-P during the initial stages. The effect of N addition was to diminish Al-P while that of P addition tended to enhance the same. The higher Al-P content in the black soil than that in the red soil might be attributed to high clay content (Kothandarman, 1975 and Singaram, 1988). The lowered microflora, caused by sterilized condition accompanied by reduced decomposition of available organic matter might have contributed to the enhanced accumulation of Al-P in the soil (Allison, 1973). The enhanced Al-P in the rhizosphere soil was attributable to slightly more acidic nature of the soil than that of non-rhizosphere soil (Sharma et al., 1980), combined with the release of Al-P that could be expected due to acid exudates. The interaction effect between Al-P accumulation and added N though significant did not reflect any consistent trend. The effect of P application was to increase Al-P with time obviously due

the more time available for the fixation. It was well evidenced that any P applied remains unfixed initially but becomes unavailable due to fixation by such elements like Fe and Al at a later stage (Bapat and Badekar, 1965).

iii) Fe-P:

The Fe-P content differed among the experimental factors due to soil, sterilized condition and also the stages of sampling. The red soil contained more Fe-P on account of higher Fe content associated with it. Under sterilized condition Fe-P content was enhanced since the decomposition mechanism was upset by lowered microbial activity and lowered chemical effects on Fe-P formed. The effect of N addition to decrease Fe-P content in the earlier stages was again a phenomenon related to the microbial effect conditioned by N addition. It was also observed that at 90 days stage the effect of N application was not seen and the Fe-P content enhanced due to lowered microbial activity (Rovira, 1959) and this might be due to the reduction of insoluble ferric phosphates to soluble ferrous phosphates (Singh and Bahaman, 1976). The effect of P addition causing enhanced Fe-P accumulation in the soil was attributable to greater access of P to Fe existing in the soil (Kothandraman, 1975, Thakur et al., 1975, Singaram, 1988) and with advancement of crop growth Fe-P content decreased as against the observation made by Chang and Chu (1961).

iii) Ca-P:

The black soil registered more Ca-P content than the red soil on account of higher Ca content in soil. Under sterilized condition of the soil Ca-P content was decreased due to lowered microflora and enhanced Fe activity. The rhizosphere soil contained more Ca-P mainly attributable to the release of more Ca on account of solubility effect of the root exudates. The acid extractable Ca-P made comparatively smaller contribution (2.93 to 7.56 ppm) as was reported by Mishra and Khanna (1982). The effect of P addition was to enhance Ca-P content attributable to the enhanced reactivity of Ca with added P (Thakur *et al.*, 1975) and also the possible conversion of Al-P and Fe-P into Ca-P (Jain and Sarkar, 1980). The above observations indicated that the plant feeds initially on Al-P and Fe-P and subsequently on Ca-P which is not readily available to the crop as suggested by Jain and Sarkar (1980).

5.3.1.3. Effect on K transformation (Tables 16 to 18)

i) Water soluble-K

The rhizosphere soil contained more water soluble-K content than the non-rhizosphere soil. Nitrogen application showed no beneficial effect in enhancing the water soluble-K content at all the three stages of crop growth. Phosphorus application tended to decrease the water soluble-K content at 30 days of crop growth stage. Under

sterilized condition of the soil the water soluble-K content was increased in the soil at 30 days growth stage. This falls in line with the findings of Jager et al. (1969 a and 1969 b) who reported that soil steaming enhanced the K solubility. Higher water soluble-K in the red soil (61.5 ppm) than in the black soil (50.4 ppm) was attributable to its inherent nature and low CEC of the red soil (Kanwar, 1976) and higher clay content of the black soil (Subramanyeswara Rao and Rajagopal, 1981). Higher water soluble-K content in the rhizosphere soil was again a case of solubilization effect of root exudates.

ii) Exchangeable-K:

Since the exchangeable-K was considered as available-K due to small fraction of water soluble-K content in the soil, the discussion put forth under available K holds good for exchangeable-K also.

iii) HNO_3 extractable-K

The black soil on account of its expanding clay type registered more HNO_3 extractable-K (377 ppm at 30 days stage) than the red soil (296 ppm at 30 days stage) (Prasad et al., 1971). Ramanathan (1978) reported a value of 100 to 1400 ppm for HNO_3 extractable-K in the alluvial soil groups of South India. The rhizosphere soil also influenced the

HNO_3 extractable-K content and this could be attributed to the possible ammonium-K interaction and $\text{K-H}_2\text{O}$ interchange (Bear, 1964; Buckman and Brady, 1967). Nitrogen addition at 50 kg ha^{-1} tended to decrease HNO_3 extractable-K content. Perhaps the ammonium ions resulting from mineralization dislodged the exchangeable-K and the phenomenon of equilibration had operated (Narayanan Nambiar, 1972).

5.4. Dynamics of rhizosphere soil in relation to nutrient flow rate or flux or uptake rate in sorghum plant (Tables 19 and 20)

The higher flow rate of all the nutrients in the sorghum plant grown in the black soil than that in the red soil may be attributed to the higher fertility status of soil (Kanwar, 1976 and Viswanath et al., 1978). The nutrient uptake rate of N and K were the highest followed by P, Fe, Mn, Zn and Cu as was observed by Patel and Ghildyal (1980) in the case of rice crop. The rate of uptake of micronutrients was approximately one per cent of the rate of uptake of macronutrients.

In the case of N, P, K, Cu and Zn flow rates the sterilized condition of the soil did not produce any significant influence in the concerned nutrient flow rate as was expected and this might be due to lower dry matter yield. The enhanced Mn flow rate in the plant under sterilized condition might be due to higher Mn content in the root

under sterilized condition and this is in agreement with the findings reported by Arunachalam (1975). Under sterilized condition of the soil Fe flow rate was decreased in the plant and this might be due to the lowered Fe content in the plant, lowered availability of the element and poor dry matter yield.

The rate of uptake of major and micronutrients increased rapidly and recorded maximum at the vegetative stage (30 days stage) and the rate then decreased as the plant advanced from the vegetative to the reproductive stage of growth. Similar findings were reported by Brewster and Tinker (1972). These results gained experimental evidence from the work of Warncke and Barber (1974) and Mengel and Barber (1974) who reported similar results in the case of root development and rate of nutrient uptake in corn crop and from the work of Patel and Ghildyal (1980) in rice roots. The decrease in the nutrient uptake rate was due to more rapid increase in root length than in the rate of nutrient uptake from vegetative to reproductive stage of growth (Rovira and Bowen, 1968 ; Mengel and Barber, 1974).

By and large, the effect of N and P application on the nutrient flow rate of the major and micronutrients was not observed because of the significant increase in root length at vegetative and preflowering stages (Mengel and Barber, 1974) and this may be the reason for the of the applied nutrients on the nutrient flow

5.5. Effect on crop nutrition

5.5.1. Effect on N, P and K content in root (Tables 21 to 23)

Higher values of root N content was recorded in the black soil obviously due to higher available N associated with the black soil. This is in line with the findings of Viswanath et al. (1978). But Krishnasamy (1982) reported that the effect of soil was not significant on the root N content in sorghum crop. Francis (1976) reported that the treatments imposed did not influence the N content of roots of sorghum crop in both the black and red soils. The varying doses of N employed had no differential impact on the content of N in the root. This may be attributable to the nutrients available in the root zone might have been depleted due to continuous uptake. The results gained support from the work of Kandasamy et al. (1973). Further, the added N enhanced the root growth and the extra nitrogen taken up by the plant underwent dilution effect with the result the content remained on par with no nitrogen treatment. The effect of P application on root N content was observed to be negative. Here again it was the dilution phenomenon that had operated, since P is known to enhance the root growth and this can be expected to result in the dilution of the absorbed N.

The black soil recorded higher value of root P (0.69 and 0.30 per cent at 30 and 60 days growth stage respectively) than the red soil (0.43 and 0.23 at 30 and 60

days growth stage respectively). But Krishnasamy (1982) reported that the red soil recorded higher value of root P than the black soil. The inherent high P supplying capacity of the soil may be responsible for such variation. Francis (1976) reported that the treatments imposed did not influence the root P content of sorghum crop in both the black and red soils. Under sterilized condition of the soil available P content in the soil was decreased as already discussed and this resulted in lowered content of P in the root. This observation is in line with the work of Arunachalam (1975) who also observed reduced P content in the root due to sterilized condition. The addition of N and P had no impact on the content of P. This might be attributed to the dilution effect on account of root growth that accompanied by N and P fertilization. Similar results were also reported by Singaram (1988).

Higher values of root K content were observed in the black soil and this might be due to the high available K status associated with black soil (Viswanath et al., 1978). Krishnasamy (1982) also reported similar results. The effect of sterilization decreased root K content, attributable to the lowered available-K status in soil on account of sterilized condition. Similar results were also reported by Arunacalam (1975). Nitrogen addition enhanced root K content

particularly at later stages of crop growth and this might be ascribed to the release of K in conjunction with NH_4^+ ion liberation. Similar results were reported by Kanwar (1976). Phosphorus application decreased the root K content and this is a case of dilution effect of absorbed K due to enhanced root growth accompanying P application.

5.5.2. Effect on micronutrient content in root (Tables 24 to 2

The black soil registered higher concentration of Fe (633 and 426 ppm at 30 and 60 days respectively) than the red soil (598 and 358 ppm at 30 and 60 days respectively). This could be ascribed to the enhanced available Fe content in the black soil combined with the concentration effect on account of lowered root yield. Similar observations were reported by Viswanath et al. (1978). It was reported that accumulation of Fe in root was governed by available status of the element in the soil. Francis (1976) reported a higher concentration of Fe in 30 and 60 days old root of sorghum crop in the red soil than that in the black soil. But Krishnasamy (1982) reported that soil types had no significant effect on root Fe content. The root Fe content under sterilized condition was considerably more-a case of concentration effect again. The addition of P decreased the root Fe content at all the three stages giving evidence to a strong Fe antagonistic effect both in the matter of availability and uptake of Fe (Dev and Mann, 1972; Velu, 1977 ; Verma and Tripathi, 1986). The

root Fe content decreased with the progress of growth of the crop indicating the absorption of Fe to be more during the early stages of crop growth. Such a phenomenon was also evidenced from the work of Tiffin (1972) and Francis (1976).

Similar to Fe content in root, the black soil recorded higher value of Mn content than the red soil attributable again to the inherent initial high Mn availability in the soil. Similar results were also reported by Francis (1976). But Viswanath et al. (1978) reported that the root of maize crop grown in the red soil accumulated more Mn content followed by black and laterite soils. Krishnasamy (1982) reported that soil types had no significant effect on root Mn content. Under sterilized condition of the soil root Mn content was enhanced as was reported by Arunachalam (1975) and this might be due to concentration effect on account of reduced root growth. The P-Mn antagonistic effect had also operated as evidenced by lower Mn concentration (40.5 ppm at 30th day, 28.0 ppm at 60th day and 31.1 ppm at 90th day) in the root due to P application. This is supported by the findings of earlier workers like Baser and Ram Deo (1967) who reported P-Mn antagonistic effect in jowar and maize plant.

The above trend of results were also reflected in respect of root Cu content more or less in a similar fashion. The red soil showed higher root Cu content at 30 days growth stage than the black soil as was observed by Viswanath et al.

(1978). Krishnasamy (1982) also reported that the red soil recorded an increase of 10 per cent of root Cu content over the black soil. But Francis (1976) reported that the black soil recorded higher root Cu content than the red soil and that the root Cu content decreased with advancement of crop growth. However, the effect of N in increasing root Cu content was also observed. This might be due to the possible nitrifying bacteria organic matter decomposition factor by which Cu availability was enhanced (Mortvedt et al., 1972). The P-Cu interaction was again found to be negative.

The black soil showed higher root Zn content than the red soil and this might be attributable to the concentration effect. But Viswanath et al. (1978) and Krishnaswamy (1982) reported that the red soil accounted for increased concentration of root Zn. Under sterilized condition of the soil root Zn content was enhanced. The decrease of root Zn at later stages of crop growth might be attributable to the dilution effect of the absorbed Zn. Similar results were also reported by Francis (1976) and Singaram (1988). This also suggests that much of the Zn is taken up by the plant during the early stages of crop growth. The decrease in root Zn content at the three stages of crop growth with the application of N might be due to translocation of more Zn from root to shoot. This investigation is in consonance with the findings of Satinder Dev and Shukla (1980).

5.5.3. Effect on N, P and K contents in shoot (Tables 28 to 30)

The salient results include high shoot N content in the black soil, enhanced N content under sterilized condition of the soil and due to N and P fertilization. Enhanced values of shoot N content in the black soil and under sterilized condition are also cases of concentration effects. This is in consonance with the experimental evidence of Jager et al., (1969 a and 1969 b) who reported that soil steaming increased N and Mn contents, fresh and dry matter production of lettuce.

Krishnasamy (1982) reported that the soil types had no influence on the shoot N content of sorghum. Under sterilized condition of the soil despite reduced N availability in the soil both root and shoot recorded higher N content and this might partly be on account of reduced growth and lower dry matter yield both in the case of root and shoot. This finds support from the work of Satinder Dev and Shukla (1980). The plant could get N even under sterilized condition, but it could not have been utilized for the growth due to limitation of other factors induced by sterilization. This observation gains experimental support from the results of Jenkinson et al. (1972) who reported that irradiation of soil increased the growth and N uptake of wheat and ryegrass in pots. With wheat, the increase in growth could be solely attributed to extra mineral N released by irradiation. As it

could be expected, N application enhanced N in the shoot (Hanway, 1962; Roy and Wright, 1974). Higher N content was recorded in the plant at 30 days stage thereby indicating the stage at which higher absorption occurs. The shoot N content declined at 90 days growth stage. At the early stage the plants are active enough to absorb higher proportion of N and this may be due to increased availability of N in the soil and better absorption of nutrients by extensive root system caused by higher doses of N. This is in agreement with earlier findings of Ramalingam (1975), Durairaj Muthiah (1978) and Muthukrishnan (1979). At the early stage of crop growth the N content was the highest which further declined at 90 days growth stage. This is in accordance with the findings of Kamalam (1964) who reported a sudden decline in the N content of straw at maturity stage due to translocation of accumulated N to the grain sorghum. Kaf Kafi (1967) reported that all the nutrients decreased after the appearance of flower primordia. At 60 days growth stage, there was higher concentration of N in the shoot. Similar results were observed by Chhabda et al., (1979) in different sorghum cultivars.

The black soil registered higher P concentration in the shoot than the red soil and this may be due to the inherent high P supplying capacity of the black soil and

lowered shoot dry matter yield. But Krishnasamy (1982) recorded higher shoot P content in sorghum crop grown in the red soil. The shoot P content of sorghum indicated variation at various growth stages and this finding gains support from the work of Chhabda et al. (1979). In spite of sterilized condition favouring reduced availability of P in the soil, the shoot carried higher concentration of P again attributable to the concentration effect and to the poor shoot growth under sterilized condition. Nitrogen addition in enhancing the P content might be attributable to the indirect effect of enhanced root growth and enhanced P availability in the soil (Hanway, 1962; Roy and Wright, 1974). Krantz (1958) also obtained increased concentration of P in oat which was top dressed with fertilizer. Phosphorus content in the shoot was higher in the primary stage of growth. This is in agreement with the results of Francis (1976) who recorded similar results in sorghum crop and Singh and Singh (1981) who reported similar results in rice and wheat crop.

The black soil recorded significantly higher shoot K content than the red soil and similar results were reported by Krishnasamy (1982). Under sterilized condition shoot K content was decreased due to reduced K availability in the soil and in turn reduced K diffusion to the root since the

effect of the root on the inorganic ion distribution in the rhizosphere is less (Barber, 1971). The N and P application favoured higher shoot K content in the crop grown in the black soil (Chhabda et al. 1979). The effect of N and P application in increasing the shoot K content might be attributable to the natural tendency of the plant to balance the enhanced absorption of N and P (Hanway, 1962; Roy and Wright, 1974). It also implies that both red and black soil provide a congenial medium in respect of K requirement and once N and P are sufficiently available, K absorption also proceeds uninterrupted and more rapid in the early stages of plant growth as was observed by Roy and Wright (1974) and Singh and Singh (1981).

5.5.4. Effect on micronutrient content in shoot (Tables 31 to 34)

The black soil recorded higher shoot Fe content than the red soil at all the three stages of crop growth. This might be attributable to greater availability of Fe and relatively reduced growth in the black soil. But Krishnaswamy (1982) reported that soil types produced no difference in shoot Fe content. Under sterilized condition of the soil the shoot Fe content was decreased at 30 days stage but was increased at later growth stages. The lowered availability of the element and poor dry matter yield under sterilized

condition are primarily responsible for this effect. The increase in shoot Fe content with growth is attributable to the progressive nullifying effect of sterilization with time (Sonneveld et al., 1970). In other words the effect of sterilization was not seen in the early stages though favourable conditions like high CEC, organic matter etc. were found. Similar results were reported by Arunachalam (1975).

The results observed for shoot Fe content were more or less reflected in the case of shoot Mn concentration as well. The black soil registered enhanced shoot Mn content. Krishnasamy (1982) reported that the black soil enhanced shoot Mn content over the red soil to the extent of 36.0 per cent. The N and P applications significantly reduced the shoot Mn content at all the three stages and the Mn content decreased with advancement in growth stage. In the case of jowar and maize crop, Baser and Ram Deo (1967) and Mishra and Tripathi (1973) in the case of wheat crop reported that availability and uptake of Mn was adversely affected by phosphorus fertilization.

As is the case with other micronutrients, the black soil registered higher shoot Cu content and this effect was observed only at later stages of crop growth. At 30 days stage of crop growth the black soil registered shoot Cu

content as 26.8 ppm as against 27.6 ppm for the red soil. This might be due to the lowered Cu availability in the black soil and lowered absorption of the element that could be expected due to formation of unstable Cu complexes due to higher organic matter content of the black soil. Krishnasamy (1982) reported that soil types attributed no significant difference in shoot Cu content. The shoot Cu content of 98.7 ppm and 107.0 ppm recorded under sterilized condition at 60 and 90 days growth stages respectively might be ascribed to increased Cu availability under sterilized conditions of the soil on the one hand and concentration effect arising out of poor shoot dry matter production on the other hand. Phosphorus application showed no effect on shoot Cu content in the shoot was observed by Ellis et al., (1964) who reported that P application decreased Cu concentration in beans and maize. Nitrogen application at 100 kg ha^{-1} level increased the shoot Cu content at 60 days growth stage and this is in confirmity with the results of Ebert et al. (1972) who reported that high rates of N increased Cu, Mn, Mo and Zn uptake by crops especially rye grass and beet by 10-20 per cent.

The black soil registered enhanced shoot Zn content due to concentration effect of the element brought about by lowered shoot dry matter production. Krishnasamy (1982)

observed no significant difference in shoot Zn content due to soil types. Under sterilized condition of the soil the shoot Zn content at 30 days growth stage was increased and this might be attributable to the concentration effect. This is in consonance with the findings of Arunachalam (1975). Nitrogen application at 100 kg ha^{-1} level significantly increased the shoot Zn content at 30 days growth stage which indicated the efficiency of native Zn utilization by the crop as was observed by Satinder Dev and Shukla (1980) for maize crop and by Ebert et al. (1972) for rye grass and beet crop. Phosphorus application had no significant effect on shoot Zn content at the later stages of crop growth. This is in line with the work of Verma and Tripathi (1986) who reported that P application reduced Cu and Zn content of rice plants P-Zn antagonistic effect was proved by many workers.

5.5.5. Effect on N, P and K content in grain (Table 35)

The black soil recorded higher N content (1.11%) in sorghum grain than the red soil (1.01%) and this might be attributable to the initial fertility status of soil, cation exchange capacity and added fertilizers to the crop. Under sterilized condition soil microbes were absent around the root zone and this caused reduction in the N, P and K contents of the grain (Chandrasekaran, 1965; Katznelson, 1965; Chandrasekaran, 1968; Balasubramaniam and Rangaswami,

1978). The N and P application increased the N and P contents in grain and similar results were reported by Muthukrishnan (1979) in sorghum crop. The utilization of P was found to be greater in the presence of N.

The root P content at 90 days stage decreased considerably which might have been utilised for the formation of the root at the earlier stages of the crop growth and this resulted in the subsequent increase in grain P content. This coincides with the results of Chhabda et al. (1979) who reported that P content in the plant at harvest stage decreased considerably with subsequent increase in grain P content. The K content in the shoot declined at 90 days growth stage and accumulated in grain which is in conformity with the findings of Chhabda et al. (1979). There were marked differences in the P content of grain between the two soils studied. This finding is in agreement with the work of Muthuswamy (1972) and Muthukrishnan (1979).

The red soil recorded higher grain K content (0.48%) than the black soil (0.34%) and this might be ascribable due to greater fixation of K in the black soil than the red soil because of the presence of increasing clay content which impeded K diffusion (Grimme et al., 1971). In the case of red soil in addition to the added K at constant

dose, exchangeable K and fixed K were increased by the oxidation of the organic matter (Ross, 1971). Potassium content was less in the grain as compared to that in the shoot. This is in confirmity with the observations of Singh and Singh (1981) who reported that K content was low in wheat grain than in shoot.

5.5.6. Effect on content of micronutrients in grain (Table 36)

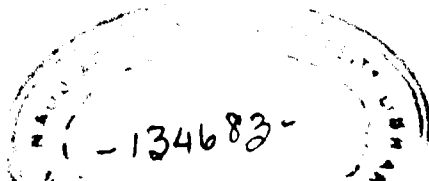
The red soil recorded higher accumulation of Fe (414 ppm); Cu (420 ppm) and Zn (100.3 ppm) in sorghum grain than the black soil. This might perhaps be due to higher accumulation of native and available Fe, Cu and Zn content in soil during the growth phase of the crop. The black soil recorded higher accumulation of Mn (48 ppm) in sorghum grain and this might be attributable to the higher native available Mn content in the soil. Under sterilized condition of the soil Fe, Mn, Cu and Zn contents in grain were decreased due to the absence of microorganisms around the root zone (Chandrasekaran, 1965; Katznelson, 1965; Chandrasekaran, 1968; Balasubramanian and Rangasamy, 1973). Nitrogen application increased the Fe, Mn and Cu contents but decreased Zn content in grain.

Phosphorus application at 50 kg ha⁻¹ level depressed Fe, Cu and Zn content in grain and increased Mn

content in grain thereby showing an antagonistic effect of P on Fe, Cu and Zn. This is evidenced by many workers like Verma and Tripathi, (1986). Jozsa and Gyori (1982) reported that NPK application at increased levels had not affected Mn and Zn concentrations and increased Cu concentration in grain of sweet sorghum. Higher accumulation of Zn in shoot might have reduced Zn content in grain (Satinder Dev and Shukla, 1980).

5.5.7. Effect on uptake of N, P and K by shoot (Table 37)

The uptake values are generally related to the content and dry matter production. Eventhough the availability of N in the soil did not differ between two types of soils, the higher shoot N content at 90 days stages in the red soil caused higher uptake of N in the shoot in the red soil. This is in line with the work of Krishnasamy (1982) who reported increased N uptake by sorghum crop in the red soil to an extent of 23.0 per cent over the black soil. Though the availability of N and K in soil was increased under sterilized condition of the soil from the beginning of crop growth, the reduced N and K uptake in the shoot would have been caused by the reduced growth, dry matter production and lower absorption of nutrients (Barber and Loughman, 1967 and Barber and Frankenburg, 1972). The increased N uptake at 60 days stage and decline at 90 days stage (Mohamed Ali and



Morachan, 1973) might be attributable to the translocation of N from shoot to grain. A conspicuous effect for N and P uptake was not observed for N and P application due to lower dry matter production and utilization of P by the crop at the early stages (Vig and Dev, 1982). The soil types showed no significant effect on K uptake by shoot. But Krishnasamy (1982) reported that the red soil enhanced the total K uptake to the extent of 15.5 per cent over the black soil.

5.5.8. Effect on uptake of micronutrients by shoot (Table 38)

Iron uptake was not influenced by any of the main effects due to reduced Fe content in the shoot. The soil types also failed to exhibit their influence on Fe uptake by shoot. Krishnasamy (1982) also reported similar results. Eventhough under sterilized condition of the soil dry matter yield and Mn availability in the soil were reduced, the effect of sterilization turned to be favourable towards Mn nutrition as revealed by Mn content and uptake by the shoot. The soil types showed no significant effect on Mn uptake by the shoot. krishnaswamy (1982) reported that the total Mn uptake was promoted by the black soil.

Copper uptake by shoot was significantly higher under non-sterilized i.e., normal condition of the soil due to increased availability of Cu in the soil (Moore, 1972). The negative effect of sterilization on Cu uptake by shoot

was clearly felt in the study due to reduced dry matter production under sterilized condition. The soil types showed no significant effect on Cu uptake contrary to the findings of Krishnasamy (1982) who reported that the red soil promoted total Cu uptake by sorghum plant to the extent of 43.0 per cent over the black soil. Though under sterilized condition of the soil available Zn status in the soil and Zn content in the shoot at preharvest stage were increased, the reduced Zn uptake by the shoot due to sterilization effect might be attributable to the lesser dry matter yield. The higher dry matter yield at 90 days stage caused $4\frac{1}{2}$ times more of Zn uptake by the shoot than at 30 and 60 days stage. The soil types showed no significant effect on Zn uptake by the shoot. Krishnasamy (1982) reported that the red soil recorded increased total Zn uptake by sorghum plant to the extent of 55.0 per cent over the black soil.

5.5.9. Effect on uptake of N, P and K by grain (Table 39)

The black soil registered higher N uptake by grain than the red soil due to enhanced grain N content and increased grain yield. The adverse effect of sterilization on N, P and K uptake by grain was clearly felt and this might be due to lower grain N, P and K contents and reduced grain yield. A concomittant increased N uptake with increased

levels of N was observed in spite of the fact that the yield was more at N₅₀ level, but the grain N content truly followed the trend of N uptake by grain. The grain N uptake was not influenced by P application, but Singaram (1988) reported increased grain N uptake by blackgram crop due to P application. Though P fertilization did not increase the grain N uptake, but it increased the P uptake by grain due to the increased grain yield and increased P availability in the soil (Sheik Dawood, 1986; Singaram, 1988).

5.5.10. Effect on uptake of micronutrients by grain (Table 40)

Higher grain Fe uptake in the black soil might be explained by higher availability of Fe in the rhizosphere region, despite the fact that the red soil recorded higher Fe content in grain. Under sterilized condition of the soil the decrease of grain Fe, Mn, Cu and Zn uptake might be attributable to the reduced grain Fe, Mn, Cu and Zn content and reduced Fe, Mn, Cu and Zn availability in the soil. Following P-Cu antagonistic effect in grain Cu content, P fertilization exhibited an antagonistic effect on grain Cu uptake (Bingham, 1963; Verma and Tripathi, 1986).

5.6. Effect on root growth characteristics (Tables 41 to 46)

The production of more number of roots/plant, enhanced root volume, increased root mass, increased total

root length, increased root diameter and shoot weight in the red soil might be attributed to the light textured nature of the soil which helped in the easy penetration of roots for absorbing plant nutrients and water requirement. Krishnasamy (1982) reported that the red soil increased the root mass and shoot weight of sorghum crop over the black soil. The number of roots/plant, root volume, root mass, root diameter and shoot weight at all the three stages were reduced due to sterilized condition of the soil because of the fact that the microbial activity was considerably reduced in the soil which is mostly needed for various nutrient transformations taking place in the soil. The observations gain experimental support from the work of Kluge (1971) who reported decreased shoot and root elongation, stunting of roots, a low number of small and chlorotic leaves and decreased yield of different crops when grown in the sterilized soil and the effects of sterilization could not be eliminated, even after storing the soil for 3-12 months at room temperature and with an additional supply of NPK + Fe fertilization. There was increased total root length at 60 and 90 days stage due to sterilized condition which may be attributable to the attainment of normal conditions in the sterilized soil after 60 days (Sonneveld et al., 1970; Kluge, 1971).

At the early stages the levels of N used did not increase the root production, while at later stages of crop growth, the highest level of N i.e., 100 kg N ha^{-1} recorded

the soil N might have been utilized by the crop, while at later stages the added N through fertilization might have been utilized. The significant increase in the number of roots/plant, root volume, root mass, total root length, and root diameter at all the three stages of crop growth for N application at 100 kg ha^{-1} and P application at 50 kg ha^{-1} indicated that P nutrition is required for the proliferation and development of roots. This is in agreement with the findings of Jena et al., (1980) on wheat crop and Krishnamoorthy and Iruthayaraj (1984) on sorghum crop. The root system consisting of long roots would contact more of soil volume and hence can utilize both nutrients and water to the maximum extent (Jena et al., 1980). At higher level of N the root diameter increased at 30 days of crop growth stage showing that higher level of N is required for the root to become thicker so that there will be strong foothold for the crop.

5.7. Effect on grain yield (g/plant) (Table 36)

Among the two soil types, the black soil registered higher grain yield per plant than the red soil. It was associated with an overall mean yield increase of 73.2 per cent over the red soil. In other words, the black soil proved more congenial for sorghum growth. Francis (1976) reported that the red soil recorded higher grain yield than the black

soil. Although in the black soil less number of roots/plant were produced and shoot weight, by way of mass factor it carried equal amounts of nutrients and favoured greater mobilization of nutrients through roots thereby accounting for enhanced yield. The sorghum grain yield was considerably different for sterilized and non-sterilized conditions registering 8.5 g/plant and 21.0 g/plant respectively. It is a matter of interest to note that the sterilized soil under the experimental conditions could be expected to move to normalcy at a faster rate. Yet this made considerable difference and the yield was markedly affected (Kluge, 1971). Nitrogen application at 50 kg ha^{-1} level also significantly increased the grain yield registering a mean yield of 15.4 g/plant as compared to 13.7 g/plant at N_0 level and 15.18 g/plant at 100 kg ha^{-1} level. Thus the optimum requirement of N remained within the limits of N levels tried. The grain yield was also found to be enhanced by P application. P application at 50 kg ha^{-1} level accounted for an yield 17.2 g/plant as compared to 12.3 g/plant with P_0 level thus representing 39.8 per cent increased yield thereby revealing the beneficial role of P on root growth and grain formation. This is in conformity with the results of Subbarao (1986) who reported that increased levels of phosphorus significantly increased the grain yield.

5.8. Interrelationships among root length, root mass and grain yield with soil chemical characteristics and other factors

Data relating to nutrient availability in soil, concentration and uptake of nutrients by plant as also the biometric data during different stages of crop growth were collected and this provided an excellent opportunity to have an understanding of the interrelationships that had existed among the different characteristics. Hence simple correlations were worked out by the method of Panse and Sukhatme (1978). Out of a number of interrelationships worked out, the significant correlations were found to be confined to the root growth characteristics viz., root length and root mass. The meaningful and significant correlations are presented in Table 47.

As could be seen, the grain yield was positively correlated with uptake of nutrients like N, P, K, Fe and Zn. This implies that the accumulation of the above nutrients possess a favourable effect on the grain yield.

The studies brought to light the profound influence of the root length and root mass on the several parameters investigated. The root growth either by way of increase of

root length or mass seemed to contribute significantly for the uptake of nutrients. The existence of a positive correlation between root length and the uptake of N, K and Zn revealed that a higher degree of proliferation is quite conducive for enhanced accumulation of N, P, K, Fe and Zn in the shoot, perhaps attributable to the enhanced rhizosphere volume and increased forage area that can be expected to occur with increased root length. Such beneficial effects of root growth on the impact of enhanced uptake of nutrients by plant, more particularly by shoot have been evidenced by earlier several workers. It may, however, be pointed out that the increase in root length resulted in decreased concentration of P and Fe in the root. This is obviously attributable not only to the dilution effect, but also to the enhanced translocation of nutrients as already explained above.

The root mass was also found to influence significantly the content of nutrients in the shoot such as N, K and Zn and N, K, Fe and Zn nutrient uptake by shoot. The increase in root mass can obviously be expected to account for enhanced forage area thereby facilitating enhanced utilization of the available nutrients in the soil. Such root mass - nutrient uptake synergistic influence have been reported by a number of earlier workers.

The root mass was also found to be negatively correlated with the content of nutrients like N, P, Fe and Zn in root, possibly due to the dilution effect on account of enhanced root volume. The existence of such negative relationships between root mass and nutrient concentration have been illustrated by workers like Jena et al. (1980).

CHAPTER 6

Y AND CONCLUSIONS

CHAPTER 6

SUMMARY AND CONCLUSIONS

An appraisal of the nutrient availability, transformation and mobility of plant nutrients in the root environment of sorghum crop with particular reference to nutrient flow rate and uptake was thought to be of great interest from the point of view of fertilization of sorghum crop and hence studies were carried out in this investigation.

Pot culture experiment was carried out in black and red soils collected from the farm of Tamil Nadu Agricultural University, Coimbatore with sorghum Co.24 as test crop employing various experimental factors viz., soil types, sterilization, N levels (0, 50, 100 kg N ha⁻¹), P levels (0, 50 kg P₂O₅ ha⁻¹) and site of soil collection (rhizosphere and non-rhizosphere regions). The initial and stagewise soil samples as well as stagewise plant samples were collected and analysed for the respective parameters to understand the differences prevailing in the rhizosphere and non-rhizosphere regions with reference to nutrient availability, transformation and absorption of nutrients mainly contributed by factors viz., treatment effect, exudation, absorption, adsorption, root interception, etc. The various relevant biometric data were also recorded for the test crop and subjected to statistical scrutiny. Simple correlations were also worked

out to find the strength of relationship between any two variables. From the salient results obtained, the inferences and conclusions emanating from the various phases of study are briefly summarized in this chapter.

* Sorghum plant root exuded relatively more number and greater quantity of amino acids and sugars at 30 days than at 15 and 45 days of crop growth thereby exhibiting decline in the quantity of exudates with advancement of crop growth.

The effects of the different treatments on the various fractions of macronutrients and on the availability of macro- as well as micronutrients bring to light the following important points:

* The presence of microorganisms possessed a strong influence on the availability of macro and micronutrients. In most cases, the presence of microorganisms favoured the availability of plant nutrients in the rhizosphere soils. This is evidenced by the sterilized condition of the soil tending to depress the build up of available nutrients.

* The rhizosphere soils carried relatively higher amounts of both macro and micronutrients than the non-rhizosphere soils. The organic acids accumulating

within the vicinity of root environment, the origin of these organic acids being the root exudates themselves, formation of organic acids formed from sugars present in the exudate and by way of encouraging microbial growth within the vicinity of root environment as reflected under normal condition of the soil that may aid in complexing and chelating reactions play a vital role in the availability and transformation of plant nutrients in the soil.

* The concentration difference of the different nutrients in the root is closely linked to the root dry matter production rather than any appreciable treatment effect. The black soil was associated with reduced root growth and this has resulted in higher concentration of the different nutrients in general. So also, the effect of sterilization reduced the root growth due to lowered availability of many plant nutrients and absence of micro-organisms and root exudates. However, this had not reflected in the lowered concentration of the element in the root, but on the contrary, the concentration of some of the nutrients viz., available Cu content in soil N and P contents in the shoot, Fe, Mn, Cu and Zn contents both in root and shoot of the crop under sterilized condition were found to be higher than under non-sterilized condition, obviously attributed to the concentration effect, whatever nutrients the root would absorb. It also gave evidence that though the sterilized

condition could interfere with nutrient availability by way of reducing nutrient content, it had little effect on the amount of nutrients entering into the root. In the present study, whether the soil was sterilized or not, the root could absorb sufficient nutrients, but in view of the other limiting factors, the root growth got depressed under sterilized condition, thereby causing higher concentration of the nutrients.

* Phosphorus - micronutrient interactions were well projected. It is appropriate to indicate that P not only tended to decrease the availability of micronutrients but also hindered their absorption as in the case of P-Fe and P-Mn interactions which proved antagonistic. However, this antagonism was more a dilution effect of the absorbed nutrients due to better growth brought about by P application.

* With reference to the concentration of plant nutrients in the shoot, more of them in general, accumulated in the shoot relating to the black soil. This was due to concentration effect rather than enhanced absorption. In the present study, the black soil could produce relatively lesser shoot dry matter than the red soil and the absorbed nutrients tended to concentrate. This implied that there had not been any absorption problem, but on account of other factors, the dry matter got reduced in the black soil

resulting in greater accumulation of the absorbed nutrients. The enhanced concentration of the plant nutrients in the shoot viz., N, P, Fe, Cu, Mn and Zn due to sterilized condition is again a similar phenomenon. In other words, even under sterilized condition which had caused lowered availability of most of the nutrients, the amount of nutrients going into the plant system had not appreciably altered. The point of focus is that both under sterilized and normal conditions of the soil, sufficient nutrients moved into the system and got distribution over a larger mass in the red soil and vice versa in the black soil.

* The black soil possessed more clay content thereby possessing higher CEC and several other advantageous factors such as more organic matter and as a result, the black soil recorded higher availability of N, K, Fe and Cu.

* The reduction in microbial content due to sterilized condition of the soil which had brought forth many undesirable effects such as lowering of nutrient availability, lowering of nutrient transformation and mobility and interference with nutrient absorption thereby causing poor root formation interfered with the early vigour of emerged seedlings and accounted for lowered yields in the long run.

* Sorghum, being a cereal and C₄ tropical photosynthetic crop, responded to N fertilization and the curvilinear response had been evidently exhibited as well. Phosphorus application at 50 kg ha⁻¹ level brought about yield improvement to the tune of 39.8 per cent over control thereby suggesting that the zinc availability had not been reduced to the point of critical condition.

* The nutrient flow rate into the plant at vegetative stage was the most rapid and decreased with the advancement of plant growth. The high nutrient flow rate in the young sorghum plant indicated that a much higher quantity of available plant nutrients in the soil is needed during the early plant growth stage than at later stages of the plant growth cycle. The amount and length of root grown in the soil would appear to be important during the early growth stage of the crop.

* The nutrient uptake both by shoot and grain is related not only to the yield of dry matter and grain but also to the nutrient availability in the rooting environment of the soil. The sterilized condition of the soil depressed the uptake of macro and micronutrients both in the shoot and grain. The uptake of nutrients by the plant was annihilated by the absorption mechanism.

* The root growth parameters viz., number of roots/plant, root volume, root mass, total root length, root diameter and shoot weight were observed to be more in the red soil than that in the black soil, mainly attributed to the light textured nature of the soil which helped in the easy penetration of roots for absorbing plant nutrients and water requirement. The same got reduced under sterilized condition of the soil.

* Although the black soil produced lesser amount of plant growth parameters, by way of mass factor it carried equal amounts of nutrients and favoured greater mobilization of nutrients through the root system as evidenced by the nutrient flow rate, thereby accounted for enhanced grain yield as compared to that of the red soil.

* With reference to the grain yield of sorghum crop, N P and K application at 50:50:50 kg N, P₂O₅ and K₂O ha⁻¹ was observed to be favourable for getting increased yield.

* The root length was positively correlated with N, K and Zn uptake by shoot at vegetative growth stage while the root mass was positively correlated with K and Zn uptake by shoot at vegetative stage of crop growth. The grain yield was positively correlated with N, P, K, Fe and Zn uptake by grain.

56. Copper status in soils

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* Originals not seen

APPENDICES

Effects	df	Available N					Available P					Available K					Available Fe					Available Mn					Available Cu					Available Zn																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																			
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Rhizosphere	1	A	A	-	A	A	-	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A

A - Significant at 1% level
B - Significant at 5% level
- - Non significant

[illegible]

EFFECTS	df	Uptake rate							Shoot uptake						
		N	P	K	Fe	Mn	Cu	Zn	N	P	K	Fe	Mn	Cu	Zn
<u>I. MAIN EFFECTS</u>															
1. Soils	1	A	A	A	A	A	A	A	A	-	-	-	-	-	-
2. Sterilization	1	-	-	-	A	A	-	-	A	-	A	-	A	A	A
3. N levels	2	B	-	-	B	-	A	-	-	-	-	-	-	-	-
4. P levels	1	B	A	A	A	A	A	-	-	-	-	-	-	-	-
5. Stages	2	A	A	A	A	A	A	A	A	-	A	-	A	A	A
<u>II. INTERACTIONS</u>															
1. Soil x Sterilization	1	-	-	A	A	-	-	B	A	-	A	B	B	A	A
2. Soil x Nitrogen	2	A	A	A	-	B	B	-	-	-	-	-	-	-	-
3. Soil x Phosphorus	1	A	A	A	-	A	A	A	-	-	-	-	-	-	-
4. Soil x Stages	2	A	A	A	A	A	A	A	-	-	-	-	-	A	-
5. Sterilization x Nitrogen	2	-	-	-	A	A	-	-	-	-	-	-	-	-	-
6. Sterilization x Phosphorus	1	-	B	-	A	A	A	-	-	-	-	-	-	-	-
7. Sterilization x Stages	2	A	-	A	A	A	A	A	A	-	A	-	A	A	A
8. Nitrogen x Phosphorus	2	-	A	B	-	B	A	B	-	-	-	-	-	-	-
9. Phosphours x Stages	2	A	A	A	A	A	A	A	-	-	-	-	-	B	-
10. Stages x Nitrogen	4	B	B	-	A	-	A	B	-	-	-	-	-	A	-

APPENDICES (Contd.)

Sl. No.	Effects of	Roots/ plant			Voulme of root			Length of root			Root mass			Root diameter			Shoot weight			Grain yield
		Days			Days			Days			Days			Days			Days			
		30	60	90	30	60	90	30	60	90	30	60	90	30	60	90	30	60	90	
I. MAIN EFFECTS																				
1.	Soils	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2.	Sterilization	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3.	N levels	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4.	P levels	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
II. INTERACTIONS																				
1.	Soil x Sterilization	1	A	A	A	-	A	A	-	A	-	A	A	-	A	A	A	A	A	A
2.	Soil x Nitrogen	2	A	A	A	A	A	A	-	-	-	A	A	A	A	A	A	A	A	A
3.	Soil x Phosphorus	1	-	-	A	A	A	A	-	B	-	A	A	-	A	A	A	-	A	A
4.	Sterilization x Nitrogen	2	A	B	A	A	A	A	-	A	A	A	A	-	A	B	A	A	A	-
5.	Sterilization x Phosphorus	1	A	A	A	B	A	A	-	-	A	A	B	A	A	A	-	A	-	-
6.	Nitrogen x Phosphorus	2	A	-	A	A	A	A	-	A	-	A	A	A	A	A	A	A	A	A
A - Significant at 1% level ; B - Significant at 5% level ; - Non significant																				

A - Significant at 1% level ; B - Significant at 5% level; - - Non significant

APPENDICES

(Contd.)

S	df	N			P			Root content			In			N			P			Shoot content			Grain content			Grain uptake		
		days			days			days			days			days			days			days			days			days		
		30	60	90	30	60	90	30	60	90	30	60	90	30	60	90	30	60	90	30	60	90	30	60	90			
TREATS	1	B	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A		
	1	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A		
	2	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A		
	1	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A		
FACTORS	1	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A		
	2	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A		
	1	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A		
	2	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A		
Phosphorus	1	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A		
	2	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A		
	1	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A		
	2	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A		

A - Significant at 1 per cent level

B - Significant at 5 per cent level

- - Non significant

PLATES

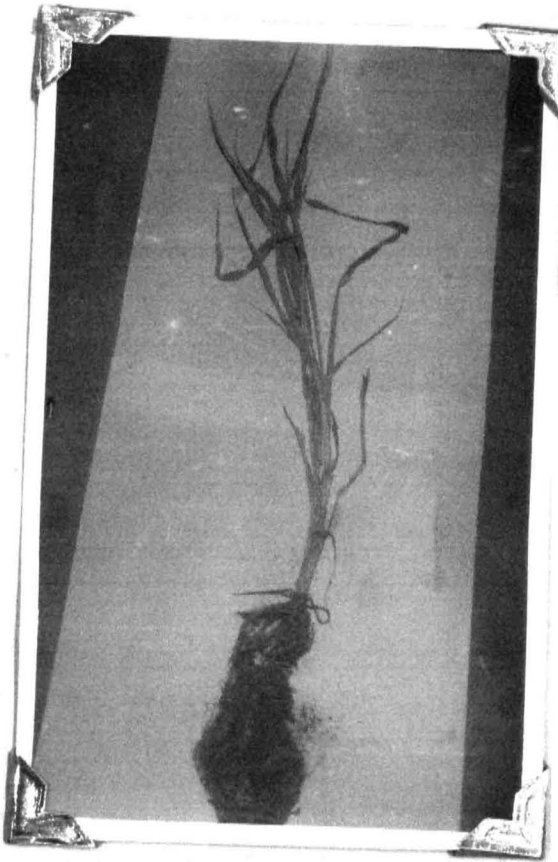


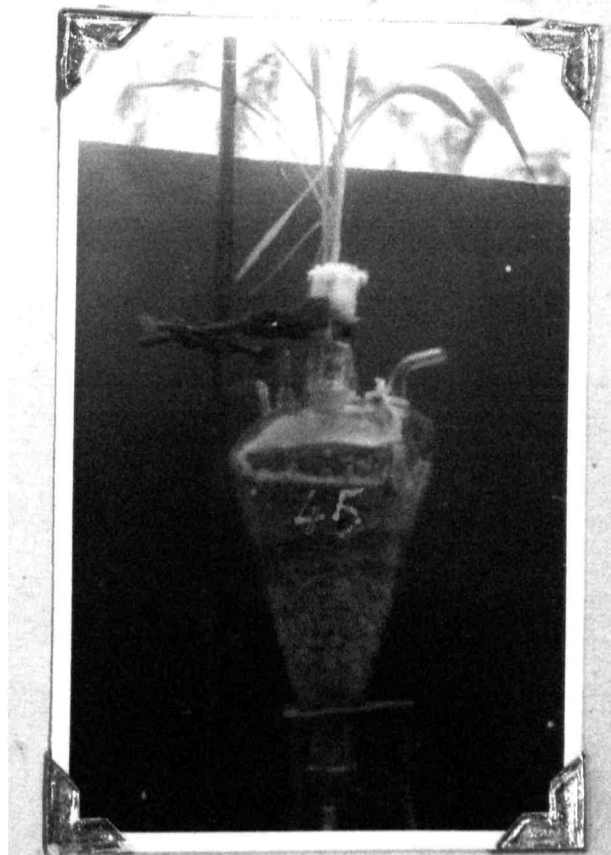
PLATE 1



PLATE 2



PLATE 3



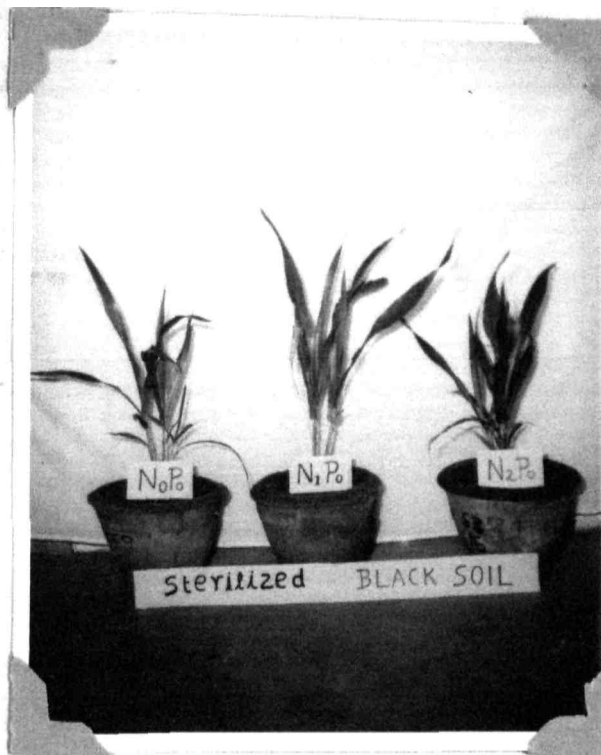
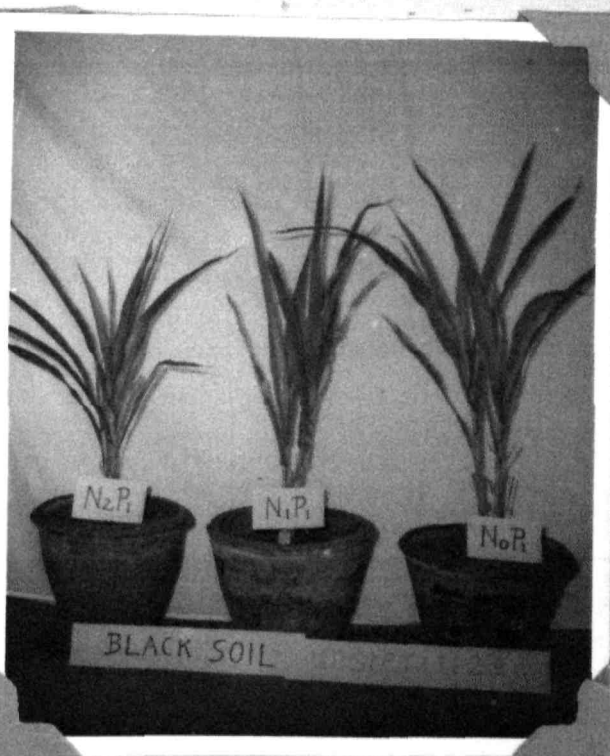
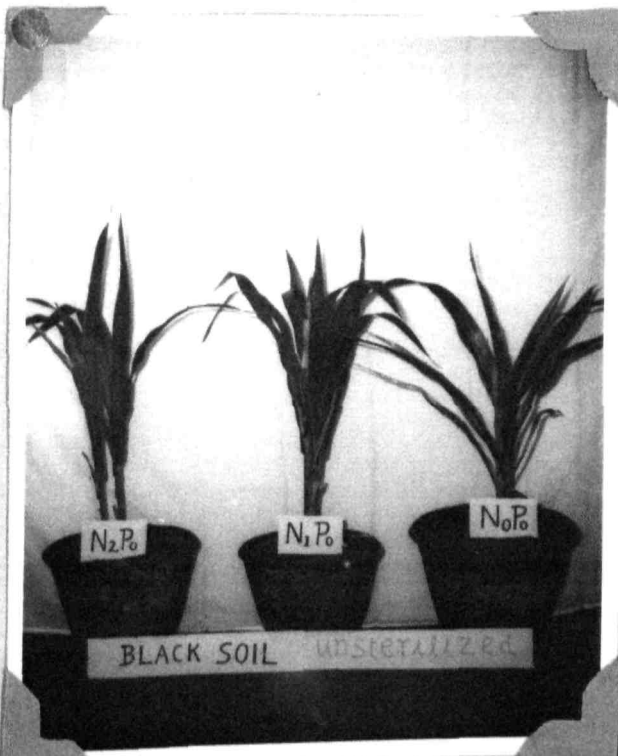


PLATE 5 (i)



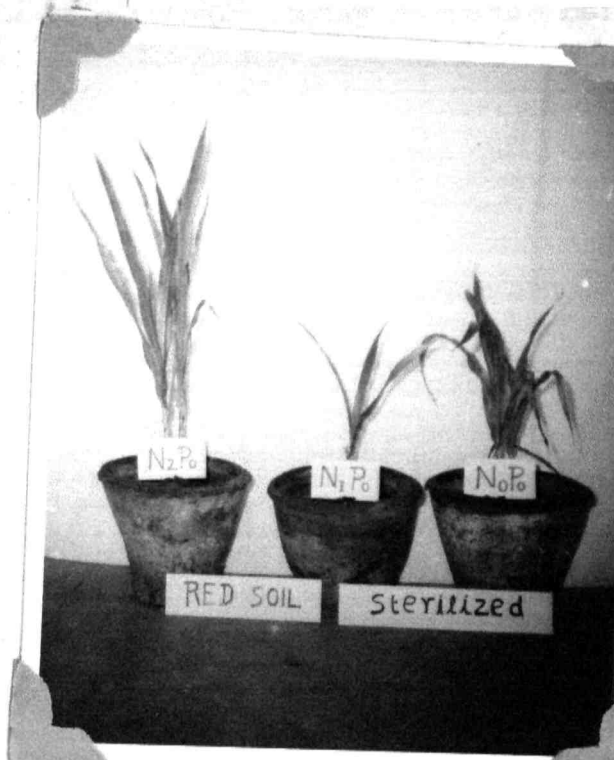
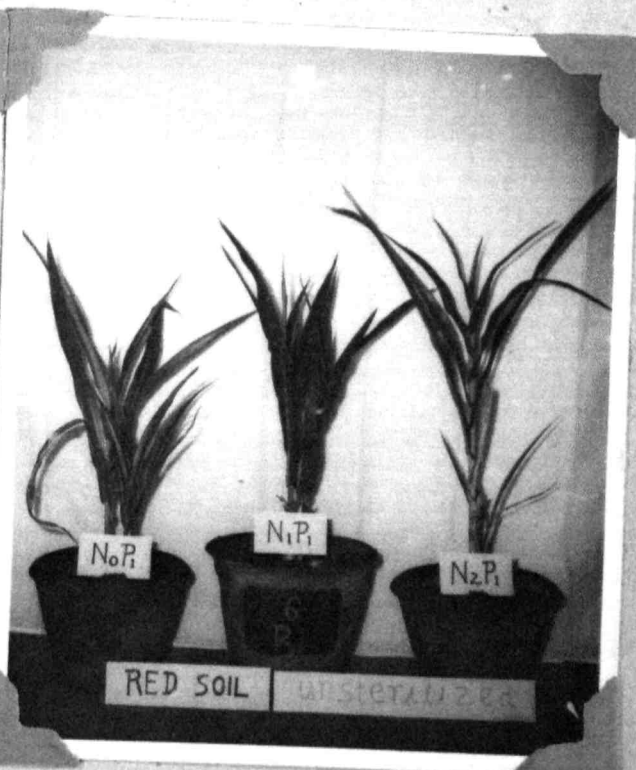
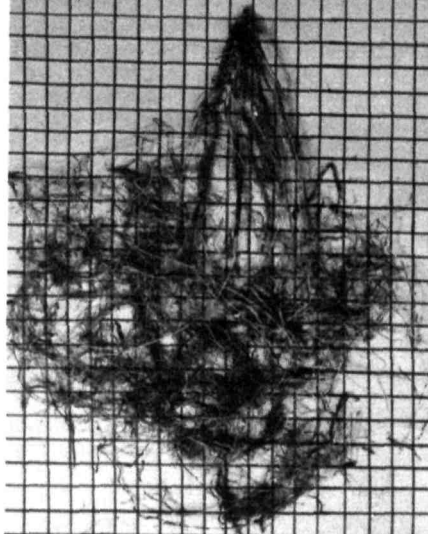


PLATE 6 (i)



BLACK SOIL UNSTERILIZED



BLACK SOIL STERILIZED

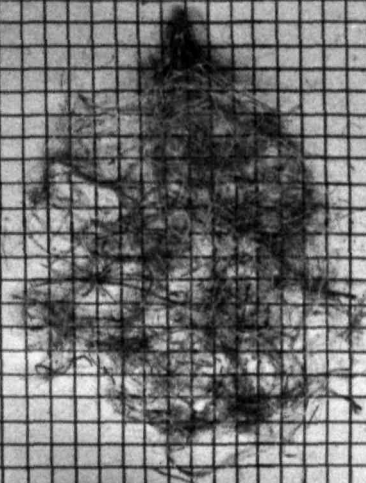
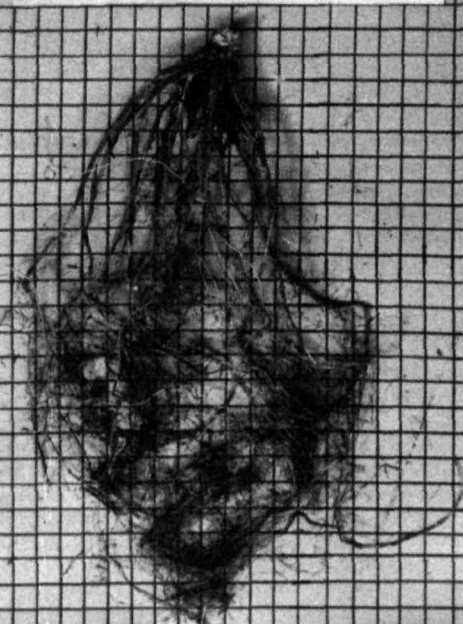
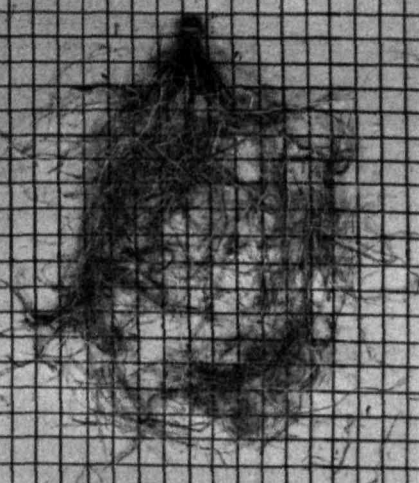


PLATE 7

RED SOIL UNSTERILIZED



RED SOIL STERILIZED



STUDIES ON THE RELATIONSHIP BETWEEN CERTAIN PROPERTIES
RHIZOSPHERE SOILS AND THE NUTRITION OF SORGHUM
(*Sorghum vulgare* Pers.)

Thesis submitted in part fulfilment of the requirements for the degree of
Doctor of Philosophy in Soil Science and Agricultural Chemistry
to the Tamil Nadu Agricultural University
Coimbatore

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By

P. THYAGARAJAN, M.Sc., A.I.C., B.T.

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COIMBATORE - 641 003

1989

25 JAN 2006

CERTIFICATE

This is to certify that the thesis entitled '**STUDIES ON THE RELATIONSHIP BETWEEN CERTAIN PROPERTIES OF RHIZOSPHERE SOILS AND THE NUTRITION OF SORGHUM** (Sorghum vulgare Pers.) submitted in part fulfilment of the requirements for the degree of DOCTOR OF PHILOSOPHY IN SOIL SCIENCE AND AGRICULTURAL CHEMISTRY to the Tamil Nadu Agricultural University, Coimbatore is a record of *bona fide* research work carried out by Thiru.P.THYAGARAJAN under my supervision and guidance and that no part of this thesis has been submitted for the award of any other degree, diploma, fellowship or other similar titles and that the work has not been published in part or full in any scientific or popular journal or magazine.

Place : Coimbatore - 3

Date : 3.8.1989



[Dr.K.M.RAMANATHAN]

Chairman

Approved by

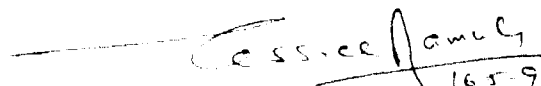


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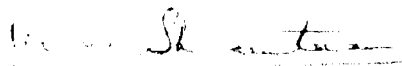
[Dr.K.M.RAMANATHAN]

Members :

[Dr.P.VIDHYASEKARAN]


[Dr.U.S.SREE RAMULU]
16.5.9

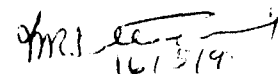
Date : 16/5/90



External Examiner

[Dr.M.GOPALAN]

Nominated Member:


16/5/90

[Dr.M.R.IRUTHAYARAJ]

ABSTRACT

STUDIES ON THE RELATIONSHIP BETWEEN CERTAIN PROPERTIES OF RHIZOSPHERE SOILS AND THE NUTRITION OF SORGHUM

(Sorghum vulgare Pers.)

By

P. THYAGARAJAN

DEGREE : DOCTOR OF PHILOSOPHY (AGRICULTURE) IN SOIL
SCIENCE AND AGRICULTURAL CHEMISTRY

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COIMBATORE - 641 003

1989

A detailed investigation was carried out to study the nutrient availability, transformation and mobility of plant nutrients in the root environment of sorghum crop with particular reference to nutrient flow rate and uptake of nutrients by sorghum (Sorghum vulgare Pers. Var. Co.24) grown in two major soil types of Tamil Nadu. A pot experiment, using black and red soils collected from Tamil Nadu Agricultural University farm, was carried out for investigating the above said characteristics. In addition, laboratory studies were conducted to study the root development and root exudation patterns of sorghum crop.

The results revealed that the sorghum plant root exuded relatively more number and greater quantity of amino acids and sugars at 30 days than at 15 and 45 days of crop growth thereby exhibiting decline in the quantity of exudates with advancement of crop growth. The presence of microorganisms and the root exudates accumulating within the vicinity of root environment played a vital role in the availability and transformation of plant nutrients in the rhizosphere region soils.

The black soil recorded higher availability of N, K, Fe and Cu nutrients. Phosphorus addition not only tended to decrease the availability of micronutrients, but also hindered the absorption as in the case of P-Fe and P-Mn interaction which proved antagonistic.

The transformation pattern of major nutrients depended on the initial fertility status of soil and type of soil. Under sterilized condition of the soil, the transformation pattern of major nutrients was found to be greatly decreased due to the absence of microorganisms and low availability of plant nutrients in the soil.

The flow rate of nutrients in the sorghum plant grown in the black soil was observed to be higher than that in the red soil due to higher fertility status of the black soil.

The results revealed that the sorghum plant root exuded relatively more number and greater quantity of amino acids and sugars at 30 days than at 15 and 45 days of crop growth thereby exhibiting decline in the quantity of exudates with advancement of crop growth. The presence of microorganisms and the root exudates accumulating within the vicinity of root environment played a vital role in the availability and transformation of plant nutrients in the rhizosphere region soils.

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The transformation pattern of major nutrients depended on the initial fertility status of soil and type of soil. Under sterilized condition of the soil, the transformation pattern of major nutrients was found to be greatly decreased due to the absence of microorganisms and low availability of plant nutrients in the soil.

The flow rate of nutrients in the sorghum plant grown in the black soil was observed to be higher than that in the red soil due to higher fertility status of the black soil.

The nutrient flow rate into the plant at vegetative stage was the most rapid and decreased with advancement of plant growth. The absence of microbial content due to sterilized condition of the soil brought forth many undesirable effects such as lowering of nutrient availability, lowering of nutrient transformation and mobility and interference with nutrient absorption. However, some of the nutrients viz., available Cu content in soil, N and P contents in the shoot, Fe, Mn, Cu and Zn contents both in root and shoot of the crop under sterilized condition were found to be higher than under normal condition of the soil, obviously attributed to the concentration effect. Though the sterilized condition interfered with nutrient availability by way of reducing nutrient content, it had little effect on the amount of nutrients entering into the root.

Most of the plant nutrients accumulated in the shoot relating to the black soil. The black soil produced relatively lesser shoot dry matter than the red soil and the absorbed nutrients tended to concentrate. The enhanced concentration of the plant nutrients in the shoot viz., N, P, Fe, Cu, Mn and Zn due to sterilized condition indicated that the amount of nutrients going into the plant system had not appreciably altered. Both under sterilized and normal conditions of the soil, sufficient nutrients moved into the system and got distributed over a large mass in the red soil and vice versa in the black soil.

The black soil was associated with reduced root growth and this resulted in higher concentration of the different plant nutrients. Under sterilized condition of the soil, root growth characteristics were found to be reduced in the black soil. The root growth parameters were observed to be more in the red soil than that in the black soil, mainly attributed to the light textured nature of the soil which helped in the easy penetration of roots for absorbing plant nutrients and water requirement.

The nutrient uptake both by shoot and grain is related not only to the yield of dry matter and grain but also to the nutrient availability in the rooting environment of the soil. Under sterilized condition of the soil, the uptake of macro and micronutrients both in the shoot and grain was depressed and this was annihilated by the absorption mechanism.

Sorghum responded to N fertilization and the response trend was found to be curvilinear. Phosphorus application at 50 kg ha^{-1} level brought about yield improvement to the tune of 39.8 per cent over control. Although the black soil produced lesser amount of plant growth parameters, it favoured greater mobilization of plant nutrients through the root system as evidenced by the nutrient flow rate, thereby accounted for enhanced grain yield as compared to that of the red soil.

From the foregoing, it becomes apparent that

i) the rhizosphere region soil contributed much to the growth and nutrition of sorghum crop;

ii) the black soil provided relatively favourable environment for the nutrition and growth of sorghum crop;

iii) Sterilization of the soil had definite deleterious effects on the nutrient availability and concomittant plant growth; and

iv) While the response trend was curvilinear in respect of N application, the dose of 50 kg P_2O_5 ha⁻¹ accounted for increased sorghum grain yield.

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ABBREVIATIONS USED

ha	= Hectare
kg	= Kilogram
g	= gram
mg	= milligram
µg	= microgram
ppm	= parts per million
ml	= millilitre
cm	= centimetre
m.e. 100 g ⁻¹ soil	= Milliequivalents per 100 g of soil
CEC	= Cation exchange capacity
AEC	= Anion exchange capacity
EC	= Electrical conductivity
N	= Nitrogen
P	= Phosphorus
K	= Potassium
Fe	= Iron
Mn	= Manganese
Cu	= Copper
Zn	= Zinc
Rh	= Rhizosphere region
NRh	= Non-rhizosphere region
St	= Sterilization
NSt	= Non-sterilization
S ₁	= Black soil
S ₂	= Red soil
St ₁	= Stage 1
St ₂	= Stage 2
St ₃	= Stage 3

Statistical analysis

S.E.	= Standard error of mean
C.D.	= Critical difference at 0.05 level
r	= Coefficient of simple correlation
*	= Significant at 0.05 level
**	= Significant at 0.01 level
NS	= Non-significant

CHAPTER I

INTRODUCTION

The growth of root and shoot is interdependent and their relationship is complex. Study of root of crops has been the subject not fully investigated largely because of difficulty of gaining access to and experimenting upon them in soil. Moreover, the study of rhizosphere by non-destructive methods has not been perfected. The term 'Rhizosphere' is applied, to an ill-defined narrow zone of soil (about 1-3 mm wide) surrounding the root and root hairs. Obsession that destructive methods will not provide full information to understand the complexity of the rhizosphere phenomena is another reason for such limited interest in this aspect. Only at the soil-root interface, the plants interact with the soil environment. If growth and nutrient uptake of plant in soil is to be understood and predicted, the physico-chemical and biological reactions that are taking place at the soil root interface are to be understood well. Hence the subject is receiving increasing attention now and the emphasis is being given on root behaviour and properties including their relationship with soil fertility.

Eversince the term, 'Rhizosphere' was introduced in 1904 by the German Botanist, Hiltner, to denote the region of the soil which is subject to the influence of plant root,

many scientists attempted to define it based on increasing scientific informations available at that time. However, the integral components of the rhizosphere are root, soil and microorganisms. These components, individually and collectively exert influence on the plant or crops. This calls for a system approach to understand the various aspects of the rhizosphere in its entirety and gestalt view to be taken.

Roots not only act as 'sink' only for nutrients transported to the root surfaces by mass flow and diffusion, but can also actively modify conditions within the rhizosphere by changing the pH and oxygen concentration, release of chelating and/or reducing substances and by root exudates as substrates for rhizosphere microorganisms. As rightly pointed out by Nye and Tinker (1977), the absorbing roots are often in a chemical environment, quite different from that of the bulk soils. Concentration of different nutrients in plants vary with the rate of plant growth and nutrient absorption as well as with the movement of the nutrients within and between different plant parts. Proper understanding of the pattern of accumulation of different nutrients by the plants is essential for planning a judicious fertilizer application schedule.

The dynamics and availability of nutrients in soils are determined not only by chemical equilibria and

binding of nutrients in the bulk soil, but also by nutrient mobility, root growth and root induced changes in the rhizosphere. At the soil-root interface, the availability of plant nutrients can be considerably influenced by many factors such as mobilization and immobilisation of nutrients, relative accumulation of ions at the root-soil interface, release of nutrients due to the changes in redox-potential etc. The ability of the microorganisms to change the chemical composition of rhizosphere and hence to alter the chemical availability of nutrients is a proven fact. Therefore, studying the chemistry of rhizosphere soils in relation to nutrient availability transformation and mobility is of paramount importance.

Among the soil orders of Tamil Nadu, Alfisols and Vertisols occupy major portion. They differ markedly in morphological and in physico-chemical properties. They occur both under dry and irrigated agriculture.

Due to differing morphological and physico-chemical properties, the nutrient availability, transformation of applied nutrients, native fertility of **soil** vary to a great extent in these two soil orders. Much informations on the above aspects in bulk soils of these soil orders are available through extensive research work in this aspect. However, informations in rhizosphere soils in these two major soil orders are few in relation to the above aspects.

According to projection by ICRISAT, there will be a deficit of 16.28 lakh tonnes at the current level of production by 1990 in the case of millets in Tamil Nadu. Among the millets, sorghum occupies the pride of place and is raised in Tamil Nadu in large areas as irrigated and rainfed crops. The deficit in the production of millets can be made good only by increasing the yield of sorghum, as bringing new area under sorghum cultivation in Tamil Nadu is not possible. Moreover scientific information in respect of rhizosphere chemistry with sorghum crop grown in major soils of the state-vertisols and Alfisols are scanty. Management practices and fertilization of sorghum crop will cause changes in the nutrient transformation and availability of plant nutrients and much work has not been done in this aspect. This study requires sufficient amount of soil sample from the rhizosphere region and because of lateral and secondary root system, sorghum plant provides an ideal situation for such study. In view of the above, the present study was taken up with the following objectives:

- i) To study root development pattern of sorghum crop;
- ii) To determine root exudation pattern at different stages of growth of sorghum crop;

- iii) To determine the transformation and availability of nutrients in the rhizosphere and non-rhizosphere soils as influenced by soil types, sterilization of soil and fertilization of sorghum crop;
- iv) To study the nutrient content and uptake pattern of plant nutrients by the various plant parts of the test crop, under varying soil types, levels of N and P fertilization and under two sets of soil conditions;
- v) To determine the nutrient flow rate in the plant at different stages of crop growth; and
- vi) To determine the root growth characteristics of the test crop.

CHAPTER 2

REVIEW OF LITERATURE

The experiment involved investigations on chemistry of rhizosphere soils in relation to nutrient availability and transformation of nutrients as also the mobility with the test crop of sorghum. The pertinent literature are reviewed and the salient aspects in relation to some specific topics are briefly summarised below:

2.1. Significance of rhizosphere

The root in soil is dynamic interacting three component system in series, i.e., the soil, a somewhat discontinuous microbial layer and the plant root itself. Only at the soil-root interface, the plant interacts with the soil environment. The soil environment and condition of the shoot affect the behaviour and properties of root. The soil-root interface viz., the rhizosphere is influenced by the elements of climate, by water on the soil surface and beneath the soil by chemical, physical and biological factors (Fig. 1).

Solute concentrations have been often shown to be greatly altered in the rhizosphere (Nye and Tinker, 1977) and there can be no doubt that absorbing roots are often in a chemical environment quite different from that of the bulk

soil. This establishes that nutrients can be depleted by uptake by the root, after which they are to be supplied by diffusion processes.

2.1.1. Definition of rhizosphere

In 1904, the German Botanist Hiltner introduced the term 'rhizosphere' to denote the region of the soil which is subject to the influence of plant roots. Rhizosphere is applied to an ill-defined narrow zone of soil (about 1-3 mm wide) surrounding the root and root hairs. Katznelson (1965) stated that the term 'rhizosphere soil' refers to the thin layer adhering to a root after the loose soil and clumps have been removed by shaking. The soil coating varies in thickness with the kind of root, and the nature and moisture conditions of the soil. This may influence the magnitude of the rhizosphere effect but will not obscure it nor alter its characteristic features. The degree of stimulation of activity in rhizosphere soil varied according to the stage of plant growth with maximum activity corresponding to the stage of maximum vegetative growth (Parkinson and Thomas, 1969).

Magyalogy and Hancock (1972) indicated that the zone of influence of below ground stems be designated as rhizosphere; the combining form from 'rhiza' (Greek) means 'root', a plant organ, anatomically and functionally distinct from the shoot. According to broader definition of Scott

(1977) the term 'soil-root interface' could imply merely the boundary between the outermost tissues and the particles of soil which are closest to them. Comparing non-rhizosphere and rhizosphere soil, he observed that the bulk of non-rhizosphere soil is not directly influenced by the growing roots except by the withdrawal of water and nutrients. However, the rhizosphere and the bulk soil merge into the other and the boundary between them cannot be rigidly defined. It is reasonable to assume, however, that the diameter of the rhizosphere atleast equals that of the cylinder of soil which the root hairs explore and into which they may release exudates. The living roots occupy only a small fraction of the total soil volume.

2.2. Bio-dynamics of root system

Newman (1969 c) concluded that the root systems were usually much more extensive than necessary for water uptake. Since the major resistance to the movement of water is associated with the root, the uptake of water per unit volume of soil would be proportional to rooting density, other factors being equal. Weatherly (1975) and Faiz et al. (1977) observed that the diameter of roots could decrease appreciably under water stress and suggested that the gap at the root-soil interface may contribute to the overall resistance under conditions of water stress.

Roots, however, do not act only as 'sink' for nutrients transported to the root surfaces by mass flow and diffusion (Brewster et al., 1976), but can also modify conditions within the rhizosphere by changing the pH and O₂ concentration, release of chelating and/or reducing substances and by root exudates as substrates for rhizosphere microorganisms. Long root hairs ensure better contact between soil and plant and improve water movement from fine soil pores to the plant.

Mucigel, occurring on the root-surface in the zone of differentiation, largely establishes the contact between growing roots and the solid matrix of the soil rather than the walls of the root cells themselves and also influences the transfer of nutrients to roots (Juniper and Bask, 1973).

2.3. Root exudate and rhizosphere effect

A wide range of compounds is exuded from intact plant roots and these exudates consist of soluble organic materials like aminoacids, sugars, organic acids, vitamins, nucleotides and many other unidentified substances and these are responsible for their rhizosphere effect. A compendium of the chemicals exuded by roots of different plants have been given in an excellent review by Rovira (1965).

Root exudate plays a major role influencing nutrient availability in the rhizosphere. Apical meristems of

roots produce continuously 'mucigel' which contains a substantial proportion of polygalacturonic acid, a quite effective substance in mobilizing both phosphorus and iron (Nagarajah et al., 1970). Root exudates seem to be responsible also for the ability of plant roots to take up micronutrients like zinc from soil layers with extremely low water availability (Nambiar, 1976). Root exudates with distinct chelating and/or reducing properties are released by roots in response to iron deficiency (Takagi, 1976; and Olsen et al., 1981). These root exudates enhance the iron mobilization from iron III oxides (Olsen et al., 1981) and manganese oxide (Marschner et al., 1982) which create manganese toxicity on calcareous soils (Moraghan, 1979). The organic acids present in the root exudates of wheat crop are responsible for dissolving manganese oxides (Godo and Reisenaner, 1980) and for mobilizing phosphate from root phosphate (Moghimi et al., 1978).

Balasubramaniam and Rangaswami (1969) found that sorghum (Sorghum vulgare pers.) exuded atleast 14 different amino acids and also reported the presence of glucose and absence of sucrose in the exudate.

2.3.1. Role of micoorganisms in the rhizosphere

Soil micoorganisms play a very significant role in making P available to plants by dephosphorylating P

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bearing organic compounds and also by bringing about favourable changes in soil reaction in the soil micro-environment leading to solubilization of inorganic phosphate sources. Besides, metabolic byproducts of soil microorganisms such as organic acids and humic substances, primarily emanating from organic matter decomposition, form complexes with iron and aluminium compounds, thereby reducing inorganic phosphate fixation to a remarkable degree and thus increasing its availability indirectly (Chhonkar, 1979; Wani, 1980; and Raj, 1981).

It has been observed that a reduction in soil organic P content is associated with a simultaneous increase in the number of microorganisms capable of dephosphorylating these substances (Halstead et al., 1963) showing inter alia, their involvement in the mineralization process. However, the significance of the direct involvement of soil microflora in the release of inorganic P from organic phosphatic compounds in soils is not clearly understood.

Soil microorganisms can oxidise divalent manganese, which is the most easily plant available form, to insoluble oxides. These oxides can supply manganese to plants at a low rate, but the overall effect is to diminish plant uptake (Bromfield, 1978).

Between 20-40 per cent of the photosynthetic products are translocated into the roots and utilized for root growth and respiration or released into the rhizosphere (rhizo deposition according to Sauerbeck and Johnen, 1976; Sauerbeck et al., 1981 and Barber and Martin, 1976). The majority of the rhizodeposition is utilized as substrate for the rhizosphere microorganisms. This high microbial activity at the root-soil interface has various effects on the dynamics of mineral nutrients in the rhizosphere and on the availability of nutrients for the plants. Higher rates of denitrification in the rhizosphere can be observed at low redox potentials (Trolldenier, 1971), particularly when root exudation is enhanced by deficiency of potassium or phosphorus (Kraffezyk and Trolldenier, 1979).

2.4. Dynamics of nutrients in the rhizosphere region of crops

Among the factors influencing the availability of plant nutrients, rhizosphere soil plays a significant role by interacting with nutrient diffusion phenomena, moisture relationship, etc. Depending on soil and plant factors, the ion concentration at the soil-root interface usually differs substantially from the bulk soil. Furthermore, at this interface root induced changes in pH and redox-potential and the release of organic compounds (root exudates) can considerably affect the solubility and availability of mineral nutrients (Marschner, 1983).

2.4.1. Mobility of nutrients

The two main driving forces by which the nutrients move towards plant root surface are mass flow and diffusion. The importance of nutrient mobility in soils for nutrient availability has been stressed by Barber (1962) in his theory on 'Mass flow-diffusion concept'.

2.4.1.1. Mass flow

At high water availability, nutrient ions which can diffuse freely in the soil, reach plants primarily by mass flow in the water, which move towards roots to satisfy the requirements of transpiration. Upon reaching the root surface, the nutrients may then be taken into the plant by the active uptake mechanisms (Barber, 1971). The localized enrichment with nutrients can modify root form and nutrient uptake. The accumulation of ions near the root surface (e.g., Calcium or Sulphate) may affect the mobility of other ions (Marschner, 1983). Wiersum (1961) stated that average distance over which nutrients are extracted from water saturated soil were P = 2.5 mm; Ca, Mg and Mn = 5 mm; K and Na = 7.5 mm and mobile ions = 20.0 mm. If water is absorbed by the plant roots relatively faster than ions (high transpiration rates in combination with high salt concentration in the soil solution) an accumulation of ions at the root surface can be predicted (Barber et al., 1963; Elgawhary et al., 1972; Renger and Strebel, 1976).

When the nutrients reach the root surface, the root must make a place for itself in the soil and in doing this, it will usually increase the bulk density of the soil immediately around the root. This causes a higher concentration of adsorbed ions in the rhizosphere than would be present if no change in bulk density occurred. This process of increasing nutrient availability has been called 'root interception' by Barber et al. (1963). If the processes do not supply the root with nutrients as fast as they are absorbed, the concentration at the root surface is reduced causing a concentration gradient along which nutrients diffuse to the root (Barber, 1971). Nutrients such as Ca and Mg usually reach the root by mass-flow particularly for plants which are not high calcium absorbers.

The chemical changes in the rhizosphere soil due to the action of the root are mainly a result of changes in the concentration of one ion in the soil affecting the solubility of a second ion. For example, calcium may accumulate in the soil near the root, by mass-flow, as more of calcium is moved to the root than it is absorbed (Riley and Barber, 1969). Conversely, there may be depletion of calcium when the absorption rate exceeds the rate of movement to the root by mass-flow (Barber and Ozanne, 1970). This wide variation in the level of the calcium ion plus its associated anion will frequently alter the solution level of ions such

as borate, phosphate and potassium (Barber, 1971). Where a larger quantity of the nutrient moves to the root by mass-flow than the root absorbs, the concentration at the root surfaces increases and this may increase uptake, however, above a certain concentration, increasing the concentration does not greatly increase uptake of many nutrients.

2.4.1.2. Diffusion

The other main driving force for nutrient movement towards plant root surface is diffusion, driven by ion uptake and a corresponding decline in the ion concentration at the root surface (depletion zone). When the mass-flow supplies only a small portion of the plant's requirement, diffusion becomes an important factor, the level of nutrients at the root surface will be less than that initially present in the soil (Barber, 1971). The importance of diffusion and its role in the nutrient supply to plant roots depends upon both soil and plant factors. Scott (1977) stated that the rate of absorption of nutrients ions by plants is dependent on the rate of diffusion of ions through the soil towards roots. He further showed that an appreciable volume of the root exterior to the endodermis is accessible to ions which enter by diffusion or mass flow. When the roots are transferred from a solution of lower to higher concentration, a rapid initial uptake of ions occurs at within a

period of 30 minutes because of the ready physical movement of ions into the free space. The influx of cations is greater than that of anions because of the predominance of negatively charged sites on the surface of cell walls. On most soils, almost all of the phosphorus will reach the root by diffusion. Potassium has also been frequently observed to move by diffusion. Most of the nutrients diffusing to the root come from soils within 3 mm of the root surface.

Renger et al. (1981) stated that the relative contribution of mass-flow and diffusion for ion transport to plant root surfaces also depends upon the plant species as both rates of transpiration and ion uptake vary considerably between species. Potassium transport to the root surfaces in maize is primarily by diffusion, but in onion, mass-flow is of major importance (Baligar and Barber, 1978). Since mass-flow and diffusion occur simultaneously in solute transport to the root surfaces, the term 'apparent mass flow' = transport of ions to the root-soil interface, has been recommended by Nye and Tinker (1977).

2.5. Changes of pH at the soil-root interface

Monitoring pH continuously in an undisturbed soil plant system supplied with ammonium, Schaller and Fischer (1981) demonstrated changes in pH at the soil-root interface

of peanut from 5.5 (bulk soil) to 3.5 (interface); with maize, however, pH remained as 5.5 or decreased only slightly. Plant species which show preferential uptake of cations over anions even with nitrate nitrogen supply are quite efficient in acidification of the rhizosphere and in utilization of rock phosphate (Fried, 1953; Raij and Diest, 1979). If the pH in the rhizosphere decreases, this leads to an increase in desorption of phosphorus, solubilization of non-exchangeable phosphorus and increase in P concentration in the rhizosphere soil solution. Enhanced H^+ efflux from roots corresponding to acidification of the rhizosphere is also a typical response of the so-called 'Fe-deficient' plant species to iron deficiency. These plant species are therefore able to dissolve and utilize effectively sparingly soluble iron-III compounds (Marschner et al., 1974) as long as the bicarbonate concentration in the rhizosphere does not counteract this acidification (Venkatraju and Marschner, 1981).

2.6. Availability and transformation of nitrogen in soils

It is well known that the concept of nutrient availability in the soil is a complex phenomena, much so with respect to nitrogen. Apart from physical disintegration and chemical decomposition, a matrix of microbial decomposition is also involved in the transformation processes of both native and added N forms.

2.6.1. Effect of N fertilization

2.6.1.1. Root system

The effect of N fertilization is reflected on the growth of the root system. Davidson (1969 b) reported that the size of the root systems relative to their shoots is commonly reduced when the external supply of N is raised thereby depressing the root/shoot ratio, though the actual weight of roots usually increases, but not as greatly as that of shoots.

2.6.1.2. Nutrient availability and transformation

Cooke (1962) indicated that the capacity of soils to supply the mobile anions viz., nitrate, sulphate and chloride that form very sparingly soluble compound is governed only by the total amounts present in the soil solution plus any added by fertilizers or mineralized by decomposing organic substances.

Ramalingam (1975) observed that soil application of N increased the available N in red soils of Coimbatore district when sorghum CSV-4 was grown. He further noted that the available nutrients were more during initial stages and the same decreases during post-harvest stage. The application of N resulted in significantly higher available N in soil at

70 and 120 kg N ha⁻¹ level than in 0 kg ha⁻¹. In contrast, the highest available P was recorded in the control plot of nitrogen. Again applied N did not produce significant difference in available K.

Viswanathan (1976) reported that available N of red soil ranged from 26 to 89 ppm and that of P ranged from 2.0 to 8.6 ppm. In case of available K, the values recorded were 78 and 120 ppm. The availability of all the major nutrients progressively decreased with advancement in crop growth. Durairaj Muthiah (1978) reported that available N status of soil increased progressively with increased dose of N in a field experiment conducted on red loam soil with three levels of N at 0, 60 and 120 kg ha⁻¹ with fine varieties of sorghum.

2.6.1.3. Changes in the rhizosphere zone

The immobilization of N by rhizosphere micro-organisms eventhough temporary, will reduce the amount available to the plant. Nitrogen losses by denitrification were demonstrated with N¹⁵ labelled nitrate to be greater with living root systems, owing to decreased oxygen tension in the rhizosphere and to root excretions that functioned as hydrogen donors for the large number of denitrifying bacteria in this zone (Woldendrop, 1962 and 1963).

Sapozhnikov et al. (1968) found by split plot technique that application of fertilizer N increased the plant utilization of soil N although there was no contact between the fertilizer and the soil. They attributed this to the increased metabolism of the fertilized plant and to the increased absorbing power of the root system, uptake of soil N, however was even higher when the fertilizer was placed in contact with the soil. Nitrogen transformations that were thought to take place at the root-soil interface of rice were mainly due to nitrogen fixation and N losses through the process of nitrification and denitrification in the root zone (Anon., 1964 and 1968).

Riley and Barber (1971) had attributed the influence of N additions on P uptake by plants growing in soil to increased plant growth, changes in root morphology, chemical changes in the soil and changes in the rate of P absorption by the root. Ammonium is often superior to NO_3^- in stimulating P uptake and this has been attributed to its effect on root morphology and on soil P solubility.

2.6.1.4. Dry matter production

Roy and Wright (1974) reported that the rate of dry matter accumulation in fertilized sorghum plants was rapid early in the season and continued almost linearly until

maturity stage but in unfertilized plants, it began to drop after 70 days. The application of 50 kg N ha^{-1} significantly increased the dry matter of whole plant by 26.0 per cent over control and further the application of N at 120 kg ha^{-1} increased the dry matter by 35.2 per cent. Ramalingam (1975) observed that dry matter production of sorghum variety CSV-4 was the lowest at the seedling stage and it increased at subsequent stages. The effect of N levels on dry matter production was significant. Increasing levels of N increased the dry matter subsequently.

2.6.1.5. Content of nutrients

Herron et al. (1963) indicated that the N content of sorghum was 3.1 per cent at flowering stage and 1.14 to 1.56 per cent of N was found to be present in grain. Kamalam (1964) reported a sudden decline in the N content of straw at maturity stage due to translocation of accumulated N to the grain sorghum. Kaf Kafi (1967) reported that the N content of leaves of sorghum plants receiving 160 kg N ha^{-1} was consistently higher than those of plants from unfertilized plots. He also reported that all the nutrients decreased after the appearance of flower primordia.

Srivastava (1967) tried three levels of N (0, 50 and 100 kg N ha^{-1}) and three levels of P_2O_5 (0, 50 and $100 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1}$) in sorghum and concluded that application of 50 kg N ha^{-1}

did not influence the N content and uptake upto first 30 days and differences in N content was noticed only on 60th day. Muthusamy (1972) observed that increasing doses of N increased the N content of plant materials due to better absorption of the nutrients by the extensive rooting system caused by higher doses of N.

Ramalingam (1975) recorded high N, P and K concentrations at seedling stages in CSV-4 sorghum and the concentration of nutrients decreased towards maturity stage. Viswanathan (1976) reported that K was absorbed only at initial stages and got diluted as dry matter increased.

2.6.1.6. Uptake of nutrients

Herron et al. (1963) and Roy and Wright (1974) observed that the application of N had significant effect in increasing the uptake of N in sorghum. The effect of N in increasing the N uptake by plants was the highest at maturity stage. Ramalingam (1975) reported that the application of 280 kg N ha⁻¹ recorded the highest uptake value. But at maturity stage, treatment of 140 kg N ha⁻¹ produced highest quantity of grain which contained higher N content than straw in sorghum.

The N uptake increased progressively with the increasing levels of N upto 180 kg ha⁻¹ in sorghum.

..

Application of urea at the rate of 100 kg N ha^{-1} one as basal and another as split application to CSH-1 sorghum resulted in uptake values of 46.36 and 50.35 kg ha^{-1} respectively. They also tried in CSH-3 sorghum variety at Hissar experimental station four levels of N application viz., 0, 60, 90 and 120 kg N ha^{-1} and obtained uptake values of 16, 23, 29 and 30 kg N ha^{-1} respectively (Anon., 1972). Batley and Reynish (1976) stated that winter wheat fertilized with five levels of N in the range of 0 to 175 kg ha^{-1} showed increase in N content and uptake with increasing levels of N application. Singh et al. (1976) revealed that N uptake was enhanced with increasing rates of N application to rice.

2.6.1.7. Yield of sorghum

Thangavelu et al. (1968) reported that CSH-1 sorghum gave a grain yield of $2,310 \text{ kg ha}^{-1}$ and straw $15,880 \text{ kg ha}^{-1}$. Application of urea at the rate of 100 kg N ha^{-1} in two ways one as basal and another as split application to CSH-1 sorghum gave an yield of $5,116 \text{ kg ha}^{-1}$ and $4,569 \text{ kg ha}^{-1}$ respectively (Anon., 1972).

Ramalingam (1975) concluded that application of 140 kg N ha^{-1} increased the grain yield of CSV-4 and 130 kg N ha^{-1} was found to be the economic and optimum level. Rodge and Tok (1975) reported linear response of N upto 120 kg N ha^{-1}

which produced the highest grain yield of 5,183 kg ha⁻¹ and it was significantly superior to 0, 40 and 80 kg ha⁻¹ in sorghum. Similar observations were also recorded in CSH-5, CSH-6 by Bhalerao et al., (1976) and Surender Reddy and Reddy (1976).

2.6.2. Effect of sterilization on the N content in soil

Arunachalam (1975) reported that the organic carbon content increased in the rhizosphere with plant age, when compared to non-rhizosphere soils. It was higher in sterile soil than in non-sterile soil. The rhizosphere region of the black soil had higher organic carbon content than that of the red soil. He also observed that the rhizosphere samples obtained from sterile conditions had higher CEC than from non-sterile conditions. The CEC of soils increased with plant age. The total nitrogen content of rhizosphere samples from sterile soil was more than the non-sterile soil. The total nitrogen content in the black soil was more than the red soil and increased with plant age.

2.7. Availability and transformation of phosphorus in soils

A knowledge of phosphate adsorption characteristics is imperative for understanding the phosphorus availability and to suggest a proper P fertilizer dose. Transformation of

phosphorus in soil is believed to be a dynamic process, which is influenced by rhizosphere besides other soil and plant characteristics. The nature of initial reaction products resulting from the transformation of native and applied phosphorus under the influence of root exudates, the composition of which depends upon plant species, primarily determine the availability of phosphorus and hence its efficiency.

There are several mechanisms by which the plant root can modify the availability of phosphorus. Firstly, the release of phosphate from insoluble phosphates (Ca, Al, Fe) may be increased by the formation of soluble complexes between metal ions and metabolites either of microbial or plant origin (Barber, 1968). Secondly, organic acids found in root exudates that are capable of forming adsorption complexes and more particularly chelates are very effective competitors for phosphates adsorbed on kaolinite and aluminum oxides but less so on goethite (Nagarajah et al., 1970).

Lewis and Quirk (1967) concluded that over 94 per cent of the phosphate adsorbed by roots during four days had come from soil within 0.1 mm of it. The uptake of both phosphate and potassium can be restricted by the slow diffusion of these ions through the soil. Phosphorus is usually absorbed from a small cylinder of soil surrounding

the root, because P diffuses very slowly through the soil (Barber et al., 1963; Lewis and Quirk, 1967). If the form of N absorbed changes the pH of the rhizosphere soil, it will also change the availability of P (Miller et al., 1970).

Russel and Sanderson (1967) using photometers to treat portions of individual barley roots with ^{32}P phosphate showed that there was considerable leakage of ^{32}P from these portions of roots outside the photometers. They concluded that much of the leakage may have been due to diffusion along the cell-free space in the cortex rather than exudation of compounds incorporated into the vacuoles or cytoplasm.

Riley and Barber (1971) recognised that the rhizosphere microflora and exudates from the roots as factors influencing P availability (Nagarajah et al., 1968 and Taha et al., 1969). They also observed that extractable P values for the rhizoplane soil from the NO_3^- fertilized soybeans were not significantly different from those for the bulk soil due to leakage of P from damaged roots during separation of the rhizoplane soil.

Lewis and Quirk (1967) demonstrated that ~~phosphorus~~labelled with ^{32}P was rapidly removed by roots from within the root hair zone. Diffusion studies indicated that P

and K enter roots at a greater rate than could be explained by their diffusion in the bulk soil to the surface of the root itself. Boero and Thien (1978) reported that soil phosphatase was enriched upto 40 per cent by corn roots in the central core and to a lesser extent 5 mm away. No decrease in organic P levels in these zones was observed suggesting that enzyme activity was not limiting the mineralization of hydrolyzable phosphatase compounds.

Arunachalam (1975) reported that the available P of rhizosphere soil was higher than the non-rhizosphere soil and was more in non-sterile condition than under sterile condition. In general, the available P increased with plant age. Marschner (1983) reported that root induced pH changes of as much as 0.5 units were observed between the root core and the outer zones over the two week growing period. Available P levels increased as the root induced pH changes acidified the rhizosphere.

For phosphorus, clear evidence for a depletion zone around the roots has been postulated mainly by autoradiographic methods (Bhat and Nye, 1974). Claassen et al. (1981) and Hendricks et al. (1981) could demonstrate that plant roots decrease the concentration of the soil solution within the rhizosphere down to 1 μm phosphorus (Hendricks et al., 1981) 2-3 μm potassium (Jungk et al., 1982).

2.7.1. Effect of P fertilization on P availability and transformation

Large number of experiments have been conducted to study mainly the changes that occurred in respect of P availability when P was added alone or in combination with other fertilizers or manures. The effects of P application on P availability were studied earlier by Kothandaraman (1975) and Singaram (1988) and they found that direct application of P fertilizers increased the available P status. In red soils the residual effect was attributed to the resultant Fe-P and Ca-P formation in the course of time (Sherman, 1971). Phosphorus alone or along with N decreased the available K content of the soil as reported by Bhide and Motiramani (1964). Phosphorus added along with K also recorded an increase in the available P and organic carbon contents of the soil (Ramasamy and Raj, 1973).

Many investigations have been made on the changes in soil P during the conversion from dryness to submergence of soil (Patrick and Mahapatra, 1968; Mahapatra and Patrick, 1969; Islam, 1970; Kono and Kobo, 1970; Mandal and Khan, 1972; Ponnampereuma, 1972; Gupta and Kamal Nayan, 1975; Singh and Hariram, 1976 and Mandal, 1979). The transformation resulting from alternation of dryness and submergence induce an increased availability of soil P. Goswami and Banerjee (1978) considered the causes for this increase to be due to

of CO_2 in calcareous soil, (iii) reduction of $\text{FePO}_4 \cdot 2 \text{H}_2\text{O}$ to $\text{Fe}_3(\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}$ with higher solubility, (iv) higher solubilities of $\text{FePO}_4 \cdot 2 \text{H}_2\text{O}$ and $\text{AlPO}_4 \cdot 2 \text{H}_2\text{O}$, resulting from hydrolysis due to the increase of soil pH in acid and strongly acid soils, (v) release of phosphate ions from the exchange between organic anions and phosphate ions in Fe, Al, Phosphates, and (vi) increased diffusion of P under submerged conditions.

It is generally known that factors that may increase the availability of P disappear with the change in soil conditions from reduction to oxidation. However, some investigations have also found that this process can increase the availability of soil P (Savant et al., 1970). In this case the increase in available P may result from the mineralization of organic P in soil while the availability of iron and aluminium phosphate may be decreased.

Kumarasamy et al. (1973) reported that the abundant presence of CaCO_3 in calcareous soil of Coimbatore district coupled with high pH (8.2) would have rendered the P fraction unavailable to plants by converting the same into tricalcium phosphate. At this pH, the plants have preferred Fe-P and Al-P fractions to Ca-P fraction, since the former have remained in more available form than the latter. They also reported that in non-calcareous red soil (pH 7.0) all

the four fractions of P viz., Al-P, Fe-P, Ca-P and saloid-bound P were contributing significantly to the available phosphorus pool.

Kuo and Lotse (1973) studied the kinetics of P adsorption and found that the rate of P adsorption was rapid initially and decreased with prolonged time. Species and concentration of associated cations had greater effects on P sorption than pH, by minerals and soils over a pH range of 4 to 7. Higher P sorption was observed with Ca solutions and the increased sorption was greater when the pH and Ca concentrations were higher (Volkweiss et al., 1973). Singh and Hariram (1976) observed that the amount of added soluble P transformed into Ca-P was much less in laterite mar and alluvial soils in comparison to Al-P and Fe-P under both the moisture regimes. Sharma et al. (1980) reported that the conversion of added P into Al-P and Fe-P fractions in the acid soils of Himachala Pradesh is negatively associated with pH, indicating thereby an increase in Al-P and Fe-P fractions with decrease in pH from neutral to acidic range. They also reported that less amount of P transformed into Ca-P fraction in the soils of Himachala Pradesh can be ascribed to the absence of CaCO_3 in these soils.

Jain and Sarkar (1980) observed that a major portion of the applied phosphorus is transformed into Al-P and Fe-P

during the initial stages. They also reported that the transformation of Ca-P into Al-P and Fe-P in control plots seems to be brought about by the rhizosphere supplemented by the root exudates. A reverse mechanism i.e., conversion of Al-P and Fe-P into Ca-P seems to be operative between tillering and maturity stages. The plant feed initially on Al-P and Fe-P and subsequently on Ca-P.

Sharma and Saxena (1982) stated that phosphorus application @ 75 kg ha⁻¹ to pea (Pisum sativum) crop over control caused a significant increase in Olsen's P at maturity stage in both rhizosphere and non-rhizosphere regions. Olsen's P values were higher in rhizosphere as compared to those in non-rhizosphere regions and this is attributed to the solubilization of insoluble phosphate compounds because of organic acids as a result of increased microbial activity in the rhizosphere (Duff et al., 1963). Phosphate concentration in the rhizosphere is usually much lower than in soil solution (Lewis and Quirk, 1967).

Sharma and Saxena (1982) stated that the changes caused by inclusion of legume in a crop rotation have influence on the P availability in rhizosphere region because of the fact that P movement and absorption in soil occurs through diffusion and interception. Squalli and Nadir (1983) stated that conditions favouring the mobilisation of P are

almost the same as those favouring the mineralisation of N. At pH 6-7, rates of mineralisation of P increase more than that of N. Mineralization of both is favoured by alternate wetting and drying and by high temperature (40-60°C).

2.8. Availability and transformation of Potassium in soil

Potassium in readily available form in the soil exists in the soil solution in the ionic phase and in the exchangeable form. This availability is largely conditioned by pH of the soil, the total K content of soil and its colloidal content. The amount of readily available K depends upon the nature and concentration of competing cations and the nature of the exchange material.

Plants are able to utilize not only water soluble and exchangeable K, but also the non-exchangeable form of K. Schiffer and Schachtschabil (1967) called this form of K, the subsequently available one. Exchangeable K was the immediate source of K for plant uptake and the depletion was followed by replenishment from other sources of K in the soil preferably from non-exchangeable K. The non-exchangeable K content was higher in clay plus silt fraction rather than fine and coarse fractions (Jayaraj and Dhanapalan Mosi, 1973).

Selvaseelan et al. (1973) observed that black soil was significantly superior to red soil in the release of available K. About 2 per cent of the total K is in

exchangeable form. The highest amounts of exchangeable K was obtained in clay plus silt fractions of black soil followed by red, alluvial and laterite soils (Jayaraj and Dhanapalan Mosi, 1973). Generally, the K held at interlattice positions is K non-exchangeable and this form is not exchangeable by $\text{N.NH}_4\text{OAc}$ (Ramamurthy and Velayutham, 1976). The per cent utilization of fixed K decreased as the level of added K increased in rice crop (Ramanathan, 1977 and Nagarajan, 1980). The amount of water soluble K fraction in the major soil groups followed the order of alluvial < black < red < laterite (Ramanathan, 1977).

Though Barber et al. (1963) reported that diffusion is the major mechanism by which K reaches plant roots, Sekhon (1985) reported that root interception, mass flow and diffusion are the three mechanisms of movement of K to the plant roots.

The depletion zone around roots is also affected by the buffering capacity of a soil for nutrients and by the concentration gradient between the bulk soil solution and the soil solution at the root surface. For potassium with increasing clay content, the extension of the depletion zone decreases and the equilibrium concentration at the root surface increases (Jungk et al., 1982). In the same soil, increase in K concentration in the soil solution by

fertilizer application, for example, increases both the diffusion coefficient and the extension of the depletion zone around the roots.

The rate of diffusion is influenced by the content of soil moisture and the amount of exchangeable K. As the effective volume of soil moisture decreases, the cross sectional area for K diffusion becomes smaller, the diffusion path to the roots becomes more tortuous owing to increase in air space; both factors tend to decrease the rate of K diffusion (Sekhon, 1985).

2.9. Availability and transformation of micronutrients in soil

Total reserves and availability of micronutrients (B, Cl, Co, Cu, Fe, Mn, Mo, Zn) in soils are mostly inherited from parent materials and modified by weathering and leaching. Little was known of the ways in which these elements are held in soils (Cooke, 1962). Now the situation is better than in 1962.

2.9.1. Iron

Iron is one of the most abundant elements in soil. The available cations in soils are of two valencies Fe^{++} and Fe^{+++} . Their availability is largely controlled by oxidation-

reduction systems in the soil and higher concentration of heavy metals. The most readily available form of Fe taken by the plants from the soil is (Fe^{++}) ferrous iron (Kliman, 1937).

The available Fe content of soils have been reported to vary from 8.5 to 18.7 ppm in Gujarat alluvial soils (Rai et al., 1968); whereas it was 2.2 ppm in Himachal Pradesh soils (Takkar and Bhumbra, 1968); 2.7 to 17.3 ppm in Madhya Pradesh soils (Bansal et al., 1969); 0.6 to 8.7 ppm in deep black soils of Madhya Pradesh (Rai et al., 1970); 6 to 22 ppm in Tamil Nadu soils (Arunachalam and Dhanapalan Mosi, 1973); 0.30 to 32.0 ppm in soils of hilly tract of Tamil Nadu (Rajagopal et al., 1973); 0.02 to 2.4 ppm in Tamil Nadu soils (Rajagopal et al., 1975); traces to 1214 ppm in Indian soils (Randhawa and Takkar, 1975) and 4.8 to 23.4 ppm in Uttar Pradesh paddy soils (Singh and Patiram, 1975).

Sauchelli (1969) suggested that Fe was held as chelate by organic matter in soluble form and was easily available to crops. Mortvedt et al. (1977) stated that Fe is available to the plant in ferrous form and it is affected by oxidation-reduction processes in the soil such as pH, soil aeration (drainage) and CaCO_3 content. It is the free or active CaCO_3 which releases bicarbonate ion into the soil solution which decreases the solubility of iron (Hagen and

Tucker. 1982). Soil texture and organic matter content also affect iron availability (Silanpää, 1982),

Although total Fe content of Indian soils is fairly high, its availability to plants is very much restricted. On account of differences in the nature of soils and differential capacity of the plants to remove Fe from soil, its content in plants varies to a great deal. Chimanika (1969) reported the Fe content of IR 8 paddy grain as 26.6 to 35.4 ppm and straw and 429 to 722 ppm. In the case of Bajra, Karam Narain (1969) found the Fe content of grain and whole plant in both 'local' and 'Hybrid HB-1'umbu to vary from 114 to 149 ppm and 126 to 166 ppm respectively. Mann (1969) reported that the Fe content of maize grain and straw ranged from 15.8 to 18.7 ppm and from 134.5 to 160.4 ppm respectively.

2.9.2. Manganese

The available Mn content has been reported to vary from 0.5 to 10.5 ppm in Tanjore soils of Tamil Nadu (Lakshmanan et al., 1972); 0.7 to 8.76 ppm in Tamil Nadu soils (Balaguru and Dhanapalan Mosi, 1972); 0.6 to 26.0 ppm in Tamil Nadu soils (Arunachalam and Dhanapalan Mosi, 1973); 1 to 180 ppm in hilly tracts of Tamil Nadu (Rajagopal et al., 1973); 0.5 to 50 ppm in saline alkali and sodic soils (Velayutham, 1974).

Manganese found in the soil solution is taken up by plants in the divalent form or adsorbed on the exchange complex (Anderson and Okhi, 1977). Manganese availability is much affected by oxidation-reduction conditions in the soil. Hagen and Tucker (1982) concluded that Mn deficiency would occur in well aerated alkaline and calcareous soils. Soil texture, organic matter content and electrical conductivity also affect Mn availability (Anderson and Okhi, 1977 and Sillanpää, 1982).

2.9.2. Copper

The available Cu content of West Indian soils ranged from 0.3 to 13.0 ppm (Neelakandan and Mehta, 1961); 0.83 to 3.10 ppm in Vidharbha soils (Kavimandan et al., 1964); 0.45 to 12.34 ppm in Madhya Pradesh soil (Agarwal and Mothiramani, 1966); 1.2 to 10.66 ppm in Uttar Pradesh soils (Mishra et al., 1969); 0.25 to 1.00 ppm in Madhya Pradesh soils (Singh and Jain, 1971); 0.16 to 0.60 ppm in Tamil Nadu soils (Balasundaram et al., 1973); 0.01 to 12.0 ppm in Tamil Nadu soils (Rajagopal et al., 1973).

Lindsay and Norwell (1969) reported that the precipitation of Cu compounds in calcareous soils was observed to be responsible for the reduced availability of

Cu. Krauskopf (1972) stated that Cu was precipitated as Cu_2O under alkaline or reduced environment.

Appavu (1976) reported that the mean values of available Cu content were 0.54 ppm for black soils; 0.69 ppm for alluvial soils; 0.56 ppm for red soils and 0.39 ppm for laterite soils; 0.51 and 0.53 ppm for red calcareous and non-calcareous soils respectively. Available Cu occurs mainly in the clay fraction (Khan, 1979) and irrigated sandy soils are likely to be low in available Cu. High organic matter, texture index, CEC and electrical conductivity were found to increase the availability of Cu (Sillanpää, 1982).

2.9.4. Zinc

The available Zn content was found to vary from 0.5 to 6.05 ppm in Gujarat soils (Mehta et al., 1964). Balasundaram et al. (1973) reported the value of 0.7 to 2.6 ppm of available Zn in soils of Tamil Nadu. Similar observation was also reported by Rajagopal et al. (1975).

Lindsay (1972) suggested that organic matter could interact with Zn in two ways viz., Zn from soluble organic matter could be mineralized and released, Zn becomes bound to organic matter and was made immobile. It may then be released

slowly. In the presence of high available phosphate, zinc might be partly precipitated as $\text{Zn}_3(\text{PO}_4)_2 \cdot 6 \text{H}_2\text{O}$. Zinc availability is low in calcareous soils presumably due to precipitation of zinc carbonate (Kalbasi *et al.*, 1978), soil texture, organic matter content, electrical conductivity and to a lesser extent, CEC also affect its availability (Sillanpää, 1982).

Conveyance of Zn to plant roots principally occurs by diffusion (Wilkinson, 1972 and Elgawhary *et al.*, 1972). Diffusion theory offers an additional advantage that Fick's law of Diffusion coupled with equation of continuity when solved under various boundary conditions can be used to calculate concentration of the nutrients at the root surface, depletion zone around the roots and uptake by the plants. Such studies have been conducted so far with P (Olsen and Watanabe, 1970) and Iron (O'Connor *et al.*, 1975).

2.10. Movement of water and salts into the roots

The passive movement of water into the roots in response to the respiration demand of the foliage depletes the soil of water in the immediate individual rootlets and of the rhizosphere generally; it decreases the soil water potential. Entry of water into a root or evaporation from the soil surface sets up a gradient which causes water to move from soil particle to particle towards the denuded zone (Winter, 1980).

Fairly large molecules can be incorporated into the root in the normal process of uptake for example, the common antibiotics such as terramycin and streptomycin with molecular weights upto 60. It has been advocated that even much larger molecules can pass into the root. The protein lysozyme of a molecular weight of about 15,000 is taken up by the undamaged roots under some circumstances by the suggested mechanism of pinocytosis (Burstrom, 1945 a).

Riely and Barber (1969) showed an approximate doubling of soluble salts in the rhizosphere soil around soybean (1-4 mm distance from the root) and approximately six fold increase at the rhizoplane and confirmed by experiments that the total salt movement to the roots by mass flow was greater than salt uptake by plants.

QUESTION 3

1. (10 marks) Consider the function

$$f(x) = \begin{cases} x^2 \sin\left(\frac{1}{x}\right) & x \neq 0 \\ 0 & x = 0 \end{cases}$$

(a) Show that f is differentiable at $x = 0$.

(b) Find $f'(0)$.

CHAPTER 3

MATERIALS AND METHODS

To elicit information on the chemistry of rhizosphere soils in relation to root development pattern, root exudation pattern, nutrient availability, transformation, flow rate and effect of crop nutrition, the following laboratory studies and pot culture studies were conducted with the test crop sorghum Co.24. The experimental details, analytical procedures adopted for analysing materials and also the statistical techniques used for studying the treatment effects are briefly summarised in this chapter.

3.1. Studies on the root development pattern in sorghum

The study was carried out as per procedure described by Fåhreaus Slide Technique (1957). The techniques used for this study involved the use of two glass plates of size 10x3cm. A surface sterilized sorghum seed was placed in between the two glass plates separately. The two glass plates were held together by means of rubber band at the two ends of the plate in such a way that the seed was not damaged. This arrangement was placed in a 100 cm³ beaker individually and a little quantity of Hoagland's No.2 nutrient solution with the following composition was added to the beaker till the surface of the solution was just below the position of the seed in between the two glass plates.

Hoagland's No.2 nutrient solution

1 M Calcium nitrate	5 ml
1 M Potassium nitrate	5 ml
1 M Magnesium sulphate	2 ml
1 M Potassium dihydrogen phosphate	1 ml
5000 ppm iron EDTA	1 ml
*Trace elements solution	1 ml

***Composition of the trace elements solution**

Manganous chloride	1.87 g
Boric acid	2.86 g
Zinc sulphate	0.22 g
Copper sulphate	0.08 g
Molybdic acid	0.09 g
Redistilled water	1000 ml

The entire arrangement was covered with a bell jar. After 3-4 days, the seed developed root and plumule. The morphological studies on the root system were made and presented in Fig.2.

3.2. Determination of root exudation pattern

The root exudates of sorghum plant was collected from the root exudation apparatus designed by Kandasamy et al. (1973). The exudation apparatus (Fig. 3) is useful to grow

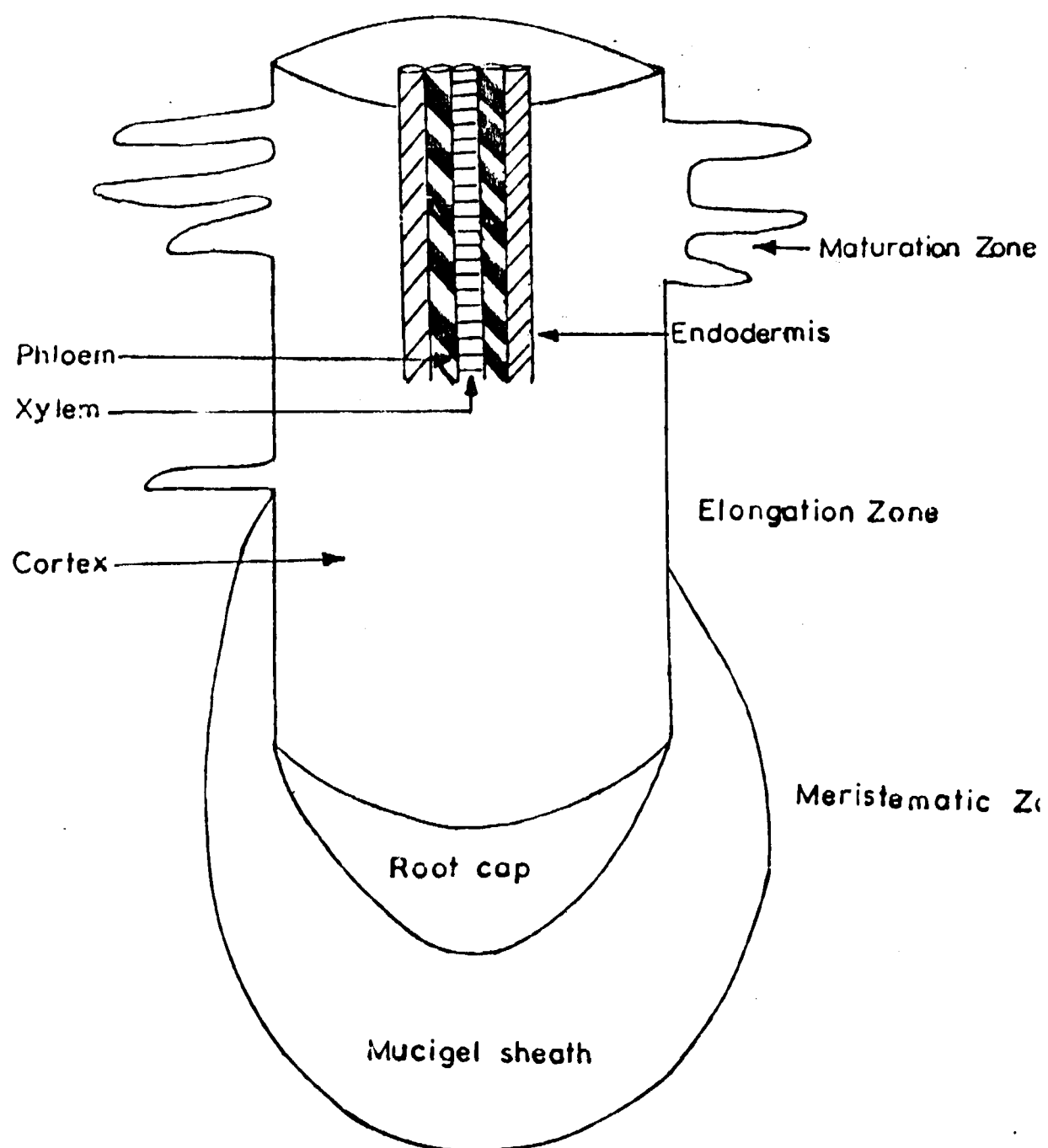


FIG. 2 LONGITUDINAL SECTION OF APICAL ZONE OF SORGHUM ROOT

plants over a period of 45 days with the root system under aseptic conditions at the same time exposing the shoot to the atmosphere and also useful to collect root exudates at periodical intervals without disturbing the root system.

The apparatus consists of an inverted 250 ml pyrex Erlenmeyer conical flask provided with stopcock at the bottom. One hole of 2.5 cm diameter at the centre and three holes of 0.5 cm diameter were made at the top. Through the central hole a glass tube of 7.0 cm in length was inserted so that about 4.0 cm length of the tube remained inside the flask thus forming a well. Through the other three holes, glass tubes of varying lengths were inserted for passing sterile air (T_1) for adding nutrient solution (T_2) and for the exit of the air (T_3). The flask was filled successively with acid washed quartz, quartz plus sand mixture and fine sand over a thin layer of glass wool each about 3 cm in depth and holes plugged with cotton wool. The apparatus was covered with a thick sheet of paper and sterilized at 20 psi for 30 minutes. Then the apparatus was taken out and covered with a black sheet of paper.

3.2.1. Techniques for the collection of root exudates

Sorghum Co.24 healthy seeds were surface sterilized with 0.1 per cent mercuric chloride solution and two seeds of sorghum were positioned aseptically on the sand in the

exudation apparatus. After addition of sterile nutrient solution of Hoagland and Arnon (1950) to the required level, the sand barrier was provided over the seeds. As the seedlings emerged out of the sand barrier, the microbial barrier was provided by placing a layer of 1 to 1.5 cm thickness of Dowex 50 x 12 (20-15 mesh) ion exchange resin which was previously washed with 0.1 N Hydrochloric acid followed by water and 0.2N mercuric chloride and sterile distilled water and dried at 50° C (Bradefute et al., 1962). Sterile cotton was also placed over the microbial barrier to ensure further aseptic conditions. All other openings were closed with sterile cotton. Air, freed from dust and microorganisms by passing through a trap containing cotton and bubbling through sterile water was injected through the opening continuously so that continuous bubbling of air in the nutrient solution was maintained. Nutrient solutions were changed at weekly intervals, utmost care being taken to prevent contamination during the process.

Darkness was provided to the root system during the experimental period by wrapping a thick black paper around the apparatus. The exudation apparatus was maintained at 23-25°C under artificial light (30,000 lux) during the period. Periodical checking of the exudation for any microbial contamination was done by plating 1 ml of the

exudate in appropriate medium. It was found possible to maintain complete sterility of the root system for not less than 45 days.

Exudates were collected from the plant at fortnightly intervals upto 45 days by opening the stop-cock and passed through ion exchange resin column for the separation of aminoacids and sugars.

3.2.2. Analysis of amino-acids and sugars in the root exudates

The amino acids and sugars contained in the root exudates were determined by following a modified procedure of Hussain and McKeen (1963). The root exudates were analysed by adsorption chromatography by passing through ion-exchange resin column and then eluting with a suitable solvent as detailed below:

For preparing the ion-exchange resin column, two glass tubes of 2.5 cm diameter and 15.0 cm long with a nozzle end were used. Glass wool occupying 1 cm of the bottom of the tube was passed with a blunt glass rod. In one of the tubes, the ion exchange resin, Dowex-50 $\times$ 8, 200-400 mesh in H^+ form was added to about 10 cm height and washed several times with distilled water. More glass wool was packed on top of the Dowex-50 column and was closed with a rubber stopper provided with a glass tubing for external

connection. In the other tube, Dowex 1 x 8, Cl^- form, 200-400 mesh was added in a similar manner. Both the columns were secured to a metal stand, keeping the Dowex column above the Dowex-50 column and were interconnected by plastic tubing. The resin column above was connected to a flask containing the exudates and the set up was arranged such that an automatic flow of the exudate would pass through the Dowex column and then through the Dowex-50 column. Uniform flow of the liquid was achieved by manipulating the screw type cock at the outlet. By this arrangement, it was possible to handle large volume of the exudation at a time. Such set was used for analysing exudates from the plant under test.

When the exudate was passed through the column, the anions in the exudate were adsorbed to the strongly basic Dowex-1 and the amino acids were adsorbed on Dowex-50 which is a strongly acidic, cation exchange resin. The effluent contained the sugars and were collected separately. When all the liquid had passed through the column, distilled water was added repeatedly to flush the resin column and Dowex-1 column was separated from the Dowex-50 column, which contained the adsorbed amino acids. Piperidine (0.1M) was used to elute amino acids from Dowex-50. The effluent containing sugars and piperidine amino acid solution were dried separately in vacuo at 40°C in a flash evaporator.

3.2.2.1. Chromatographic separation of amino acids

The dried material containing amino acids was dissolved in 0.2 ml of distilled water and this was used for the quantitative estimation of amino acids spectrophotometrically by the method of Block et al., (1958). One tenth ml of the concentrated solution was spotted on Whatman No.1 filter paper (25 cm x 25 cm) and developed ascendingly in n-butanol: acetic acid: water (9:1:2.2) for 20 hours. The chromatograms were air dried, sprayed with ninhydrin (0.5 g ninhydrin, 95 ml acetone and 5 ml water) and dried in an air oven at 60°C for 10 minutes. The amino acids were identified by their R_f values and estimated quantitatively after eluting in alcohol-buffer mixture for three hours. The concentrations were arrived at from a standard curve.

3.2.2.2. Chromatographic separation of sugars

One tenth ml of the concentrated root exudate was spotted on Whatman No.1 filter paper and ascendingly developed in n-butanol; acetic acid; water (4:1:5 organic phase) for 2 hours. After air drying, the chromatograms were sprayed with aniline hydrogen phthalate reagent as recommended by Partridge (1949) and dried in an oven at 100°C for 5-10 minutes, when the coloured spots appeared on white background. By comparing the colour of the spots and their R_f values with the spot developed by co-chromatography with standard sugar samples, the sugars in the root exudates of two plant species were identified.

The relative concentrations of the various sugars present on the chromatograms were estimated quantitatively after eluting the coloured spots in 4 ml of 3:2 mixture of alcohol and water and the colour intensity was read at 360 nm in a spectronic-20 spectrophotometer.

3.3. Details regarding soil samples

The soils used in the pot experiment represented typical black soil of Tamil Nadu collected from Eastern Block of Central Farm in Tamil Nadu Agricultural University campus, Coimbatore (Periyanaickenpalayam series). In this type of black soil, sorghum crop is mostly grown. The soil is classified, taxonomically as Typic ustivercept.

Red soil, which is one of the most important soil groups occupying the major portion of cultivated area in Tamil Nadu was collected from Millet Breeding Station in Tamil Nadu Agricultural University campus, Coimbatore (Palathurai series). The soil is classified taxonomically as Typic haplustalf. The details of the physico-chemical characteristics of the two soil types are given in Table 3.

3.3.1. Pot culture experiment

A pot culture experiment was conducted to study the nutrient availability, transformation, flow rate in the

rhizosphere region as compared to that of non-rhizosphere region as influenced by soil types, fertilization and sterilization. The details of treatments are given in Table 1.

Table 1. Details of the experiment

Crop: Sorghum Replication: 8 Design: CRBD Variety: Co.2

S.No.	Treatment combinations
1.	$S_1 N_0 P_0$
2.	$S_1 N_1 P_0$
3.	$S_1 N_2 P_0$
4.	$S_1 N_0 P_1$
5.	$S_1 N_1 P_1$
6.	$S_1 N_2 P_1$
7.	$S_2 N_0 P_0$
8.	$S_2 N_1 P_0$
9.	$S_2 N_2 P_0$
10.	$S_2 N_0 P_1$
11.	$S_2 N_1 P_1$
12.	$S_2 N_2 P_1$

S_1 : Black soil

S_2 : Red soil

N at 3 levels

N_0 : 0 kg N ha⁻¹
 N_1 : 50 kg N ha⁻¹ as urea
 N_2 : 100 kg N ha⁻¹

P at 2 levels

P_0 : 0 kg P₂O₅ ha⁻¹
 P_1 : 50 kg P₂O₅ ha⁻¹ as single super phosphate

K was uniformly added @ 50 kg K₂O ha⁻¹ as potassium chlori

Sets of soil: 2 (Sterilized and non-sterilized
i.e. normal condition)

Stages: 3 (30 days i.e., vegetative stage,
 60 days i.e., pre-flowering stage,
 90 days i.e., pre-harvest stage)

Site of collection of soil: 2 (Rhizosphere region and
 non-rhizosphere region).

The soil was processed, sieved in 6 mm sieve and
 filled in cleaned earthen pots of height 30 cm and dia.25 cm
 at the rate of 9 kg of soil per pot. The pot experiment
 consisted of 48 treatments viz., two types of soils (black
 and red), x two sets of soils (sterilized and non-sterilized).

i.e., normal condition) x three N levels (0, 50 and 100 kg N ha⁻¹) x two P levels (0, 50 kg P₂O₅ ha⁻¹) x two sampling zones (rhizosphere and non-rhizosphere soils).

For the purpose of sterilization, the required number of pots with the soil were sterilized in autoclave at 20 psi for 30 minutes, taking care that there is complete sterilization. Sorghum Co.24 seeds were sown in the pots at the rate of 3 seeds per pot and thinned later to maintain two plants per pot. The crop was fertilized at the dosage as indicated in Table 1 in the form of analytical grade chemicals as urea, single superphosphate and potassium chloride.

Out of eight replications maintained, two of the replications were utilized for collecting soil and plant samples representing vegetative stage; another set of two replications were utilized for collection of soil and plant samples representing preflowering stage; another set of two replications were utilized for collection of soil and plant samples representing pre-harvest stages and the remaining two replications were maintained upto harvest stage for recording the yield data and for other analyses.

At all stages of sampling, separate soil samples were collected to represent rhizosphere and non-rhizosphere soil samples. They were analysed for soil available nutrients and transformed forms of nutrients. The plant samples were analysed for nutrient contents apart from the routine biometric observations, viz., dry weight of root and shoot, diameter of root, number of roots per plant, total length of root and volume of root.

3.3.1.1. Method of collection of soil and plant samples

Rhizosphere and non-rhizosphere soil samples and plant samples were collected at three stages of crop growth i.e., at 30, 60 and 90 days after seeding (viz., vegetative, pre-flowering and heading, i.e., preharvest stages). At the particular stage of collecting the soil sample, the soil in the pot was depotted at field moisture capacity and the plants were carefully removed from the soil with the root system intact. The root was gently tapped to remove the loosely adhering soil. The strongly adhering soil to the root i.e., the particles of soil at the boundary of the outermost root tissue i.e., closest to the root tissues (0-5 mm distance from the root) were carefully removed and this was taken as rhizosphere soil (Riley and Barber, 1969 and 1971). The soil which lay outside the rhizosphere zone and is not directly influenced by growing

root except for the withdrawal of water and nutrients was collected as non-rhizosphere soil or arhizosphere soil. The root and shoot were separated. The root samples after the removal of rhizosphere soil were collected and the root growth measurements like root length, number of roots per plant, diameter of root, volume of root, weight of root and weight of shoot were recorded. Broken rootlets were recovered from the soil and added to the root sample. The root mass had been washed free of soil with tap water, distilled water, 0.5 N HCl and then with distilled water. The root and shoot were then dried under shade followed by oven drying at 70°C to a constant weight and the dry weight of the samples were recorded. The plant material samples and grain samples were ground to pass 20 mesh sieve and these were taken for chemical analysis.

3.4. Methods of chemical analysis of soil and plants

The laboratory analysis of rhizosphere and non-rhizosphere soil samples were conducted for the following determinations:

1. Analysis of soil samples for available nutrients viz., N, P, K, Fe, Mn, Cu and Zn.
2. Fractionation of soil samples for various forms of N, P and K.
3. Analysis of root, shoot and grain samples for N, P, K, Fe, Mn, Cu and Zn.

3.5. Preparation of soil samples

Excepting for certain determinations required under wet conditions, the collected rhizosphere and non-rhizosphere soil samples at the above said three stages were air dried under shade, gently pound with wooden mallet to pass through 2 mm sieve. The soil which passed through 2 mm sieve were stored in polythene bottles for further analysis. Specific soil preparations for individual chemical analyses were followed whenever necessary. Besides, the soil material passing through a 150 mesh plastic sieve was used for micronutrient analysis.

3.5.1. Estimation of available nutrients

3.5.1.1. Available nitrogen

This was done by alkaline permanganate method of Subbiah and Asija (1956).

3.5.1.2. Available phosphorus

0.5 N - NaHCO_3 (pH 8.5) was used as extractant (Olsen's P) for estimating the soil available P using Spectronic 2000 colorimeter as described by Jackson (1973).

3.5.1.3. Available potassium

This was estimated by the procedure outlined by Toth and Prince (1949) using Corning 400 Flame photometer.

3.5.1.4. Available micronutrients (Fe, Mn, Cu and Zn)

The available micronutrients were extracted with DTPA (Diethylene Triamine Penta Acetic Acid) extractant adjusted to pH 7.3 at 1:2 ratio after shaking for two hours, filtering and available Fe, Mn, Cu and Zn were estimated in the extract using Pye Unicam Atomic Absorption Spectrophotometer (Lindsay and Norvell, 1969).

3.6. Fractionation of soil samples for various forms of N, P and K

3.6.1. Fractionation of N

3.6.1.1. Exchangeable NH_4^+ nitrogen

Ammoniacal N was determined in 1 N KCl extractant of the soil with Kjeldahl's distillation apparatus (Bremner and Shaw, 1955).

3.6.1.2. Nitrate nitrogen

An aliquot of the above soil extract was distilled with ignited MgO and Devardas' alloy in Kjeldahl's apparatus as described by Bremner and Shaw (1955).

3.6.2. Fractionation of soil inorganic P

Inorganic phosphorus fractions of soil samples were estimated by the modified procedure of Chang and Jackson

(1957) and after Petersen and Corey (1966) as outlined by Hesse (1971). The following fractions were determined in rhizosphere and non-rhizosphere soil samples.

3.6.2.1. Saloid-bound P

One g of 0.15 mm soil was placed in a 100 cm³ polypropylene centrifuge tube 50 cm³ of 1 M.NH₄Cl solution was added and shaken for 30 minutes and centrifuged. Phosphorus was then estimated in the centrifugate by chloromolybdo-phosphoric blue colour method (Jackson, 1973) and expressed as saloid-P.

3.6.2.2. Aluminium-bound P (Al-P)

To the soil previously extracted with ammonium chloride, 50 cm³ of 0.5 M.NH₄F solution made to pH 8.2 with NH₄OH was added and shaken for one hour and centrifuged. Phosphorus in the solution after decolourizing with activated carbon was estimated as in Saloid-P in the presence of boric acid (0.5% level) to prevent the interference of fluoride ions and expressed as Aluminium-bound P (Jackson, 1973).

3.6.2.3. Iron-bound P (Fe-P)

The residue from the second step was washed twice with 25 ml portions of saturated NaCl solution and centrifuged each time ~~to~~ recover the soil. The soil was added

with 50 cm³ of 0.1 N.NaOH and shaken for 17 hours and centrifuged. Then five drops of concentrated H₂SO₄ were added to the solution and centrifuged. After flocculation of organic matter, the solution was decolourized by activated phosphorus free carbon and phosphorus was estimated by sulfomolybdo-phosphoric blue colour method (Jackson, 1973).

3.5.2.4. Calcium-bound P (Ca-P)

The residue from previous extraction was washed twice with 25 cm³ portion of saturated NaCl solution. The washed residue was suspended in 50 cm³ of 0.5 N H₂SO₄ and shaken for one hour and centrifuged. The residue was discarded. The phosphorus was estimated by sulfomolybdo-phosphoric blue colour method (Jackson, 1973).

3.6.3. Fractionation of soil potassium

Different forms of soil potassium were estimated in the soil samples using the following methods.

3.6.3.1. Water soluble-K

The method of Toth and Prince (1949) was followed.

Ten g of soil was shaken with 25 cm³ of distilled water for 10 minutes, centrifuged and the clear supernatant liquid filtered. The filtrate was collected in a 100 cm³

volumetric flask. Three additional extractions were made in the same manner and the combined extracts diluted to 100 cm³ with distilled water. The solution was mixed well and K determined using Corning 400 Flame photometer by comparing the emission intensity with that from standards made in distilled water and this gives the water soluble-K.

3.6.3.2. Exchangeable-K

The method of Pratt (1965) was followed.

Ten g of soil was shaken with 25 cm³ of N.N.NH₄OAc in a 50 cm³ centrifuge tube, centrifuged and the clear supernatant liquid filtered. The filtrate was collected in a 100 cm³ volumetric flask. Three additional extractions were made in the same manner and the combined extracts diluted to 100 cm³ with N.N.NH₄OAc. The solution was mixed well and K determined using Corning 400 flame photometer by comparing the emission intensity with that from standards made in N.N.NH₄OAc solution. The difference between this and the water soluble-K was taken as the exchangeable-K.

Since the water soluble K formed only a fraction of the exchangeable-K, the latter was considered as available K.

3.6.3.3. HNO₃ extractable -K (Non-exchangeable-K)

1 N.HNO₃ extractable K was determined by employing the method of Wood and De Turk (1941).

Two g of finely ground soil was boiled for 10 minutes with 25 cm³ of N.HNO₃ acid in 100 cm³ Erlenmeyer flask. The contents were filtered and the clear filtrate was collected in a 100 cm³ volumetric flask. The soil was washed four times with 15 cm³ portions of 0.1 N HNO₃ and the leachings were collected in the volumetric flask. After cooling, the solution was mixed well and K determined using Corning 400 flame photometer by comparing the emission intensity with that from standards made in N.HNO₃ acid. The difference between this and the water soluble plus exchangeable-K was taken as the non-exchangeable-K.

3.7. Determination of root growth characteristics

The root system of the above said sorghum plant, after the removal of rhizosphere soil, was separated. The volume of the root was measured by the method of displacement, when the root bunches were immersed in water contained in a measuring cylinder (Jena et al., 1980). The mass of the root was estimated by means of Metler top pan balance E 200. The diameter of the root samples was measured with the help of a microscope by taking cross sections at five different places in the root portion and the mean of these five diameters was taken into account (Patel and Ghildyal, 1980). The total root length was then calculated assuming the root to be cylindrical by using

the relationship $V = \pi r^2 L$ where V is the volume of root (cm^3), r the radius of the root (cm) and L the length of root (cm) (Patel and Ghildyal, 1980).

3.8. Analysis of plant samples

The root and shoot samples collected at different growth stages as well as the grain samples were separately analysed for N, P, K, Fe, Mn, Cu and Zn.

3.8.1. Preparation of the samples

The root and shoot were separated and washed successively in 0.1 N.HCl distilled water and redistilled deionized water. After recording their wet and dry weights, the samples were prepared for subsequent analysis. The cleaned samples were ground to fine powder mechanically to pass through 20 mesh sieve.

3.8.1.1. Nitrogen

Nitrogen in the root, shoot and grain samples was estimated in di-acid extract (sulphuric; perchloric acid 5:1) (Piper, 1966).

3.8.1.2. Phosphorus

Phosphorus in plant samples was extracted using triple acid mixture of HNO_3 , H_2SO_4 and HClO_4 in the proportion

of 9:1:3 and estimated by Vanadomolybdo-phosphoric method (Jackson, 1973) using Speetronic-2000 colorimeter.

3.8.1.3. Potassium

Potassium in the digested extract was determined using Corning 400 flame photometer, after neutralising with NH_4OH and after diluting it suitably.

3.8.1.4. Micronutrients (Fe, Mn, Cu and Zn)

The micronutrients, viz., Fe, Mn, Cu and Zn contents were estimated in the digested extracts using an Atomic Absorption Spectrophotometer (Pye Unicam Model) at the corresponding wavelengths of the element.

3.9. Determination of nutrient flow rate or uptake rate or flux

The rate of uptake of nutrients per meter of root was calculated using the following equation as used by Warncke and Barber (1974).

$$I = \frac{(U_2 - U_1) \left(\ln \frac{L_2}{L_1} \right)}{(t_2 - t_1) (L_2 - L_1)}$$

where I is the flux/meter of root or nutrient uptake rate, U is the amount of nutrient in the plant, t is the time and L is the root length. The subscripts 1 and 2 refer to the initial and final harvest respectively.

The equation reflects the exponential nature of root growth. Since root length reached a maximum at 80 days, this equation was used only upto 60 days. For the calculation of flux per meter of root for the 90 days, mean root length $\frac{L_1 + L_2}{2}$ was used as the root length value instead of $\frac{(\ln L_2 - \ln L_1)}{(L_2 - L_1)}$. The data reported based on this method of calculation, nutrient flux expressed as moles was calculated by dividing grams of nutrient uptake by the atomic weight of the concerned nutrient element.

3.10. Uptake of nutrients

This was worked out by multiplying the dry matter yield by the corresponding nutrient content.

3.11. Statistical analysis

The analytical data of the soil and plant samples and various other biometric characters such as grain yield, number of roots/plant, length of root, volume of root, diameter of root, weight of root and weight of shoot were subjected to statistical scrutiny as per the procedure given by Panse and Sukhatme (1978) to find out the influence of various treatments on the nutrient availability, transformation pattern and flow rate in the plant. Simple correlation as well as fitting up of regression equations were deduced as per the procedure described by Panse and Sukhatme (1978).

CHAPTER 4

RESULTS

The results obtained from the studies on the pattern of root development, root exudation and analysis of both soil and plant samples as well as the results of statistical analysis of the experimental data of the present investigation are presented in this chapter.

4.1. Root development pattern in sorghum

As already indicated, the root development of any plant assumes considerable significance in the utilization pattern of the nutrients available in the soil. Therefore, the root development pattern studies in sorghum were carried out as per procedure described by Fahreaus Slide Technique (1957). The root pattern was similar to that of already established for this crop.

4.2. Root exudation pattern of sorghum

The pattern of root exudation in the sorghum crop was thought to be of interest and root exudation studies were carried out as per details already furnished in Chapter 3.

The root exudates were collected at 15, 30 and 45 days growth stages of sorghum and studied for the nature of

root exudate. The qualitative and quantitative nature of the root exudate of sorghum crop at three different stages of plant growth are summarized in Tables 2(a) to 2(c).

4.2.1. Exudation pattern of sorghum plant at different stages of plant growth

In all, 16 amino acids were identified from the root exudate of sorghum plant. Seven amino acids on 15th day, 11 amino acids on 30th day and 10 amino acids on 45th day were detected from sorghum root exudate. Aspartic acid, glutamic acid, leucine and serine were found to be exuded by the plant irrespective of the stage of plant growth. In general, the number of amino acids exuded increased upto 30 days of plant growth after which it declined. In all, three sugars and two organic acids were identified from the exudate. Glucose and fructose were invariably present in the exudate at three stages, but declined at 45th day. Xylose was detected in the exudate in the later stages of plant growth viz., from the 30th day onwards. The organic acids were found to be present at 15 and 30 days of plant growth.

4.3. Influence of soil types, sterilization and fertilizer application on nutrient environment in the rhizosphere and non-rhizosphere region soils

Representative black and red soil (Periyanaickenpalayam series and Palathurai series respectively) collected

TABLE 2(a). EXUDATION PATTERN OF AMINO ACIDS THROUGH ROOT OF
SORGHUM PLANT ($\mu\text{g/plant}$)

S.No.	Amino acid	Age of the plant in days		
		15	30	45
1.	Alanine	-	+	-
2.	Asparagine	+++	-	-
3.	Aspartic acid	+++	+++	+++
4.	Cystine	++	-	+
5.	Glutamic acid	+++++	+++++	++++
6.	Glycine	-	+	-
7.	Histidine	-	-	-
8.	Leucine	+	+	T
9.	Lysine	-	-	-
10.	Methionine	-	T	T
11.	Phenylalanine	-	+	T
12.	Proline	-	+	++
13.	Serine	++	++	+
14.	Threonine	++	+	-
15.	Tryptophan	-	+	T
16.	Tyrosine	-	-	+
17.	Unidentified	1	-	1

+ : 0.1 to 0.2 $\mu\text{g/plant}$
 ++ : 0.2 to 0.3 "
 +++ : 0.3 to 0.4 "
 ++++ : 0.4 to 0.5 "
 +++++ : 0.5 to 0.6 "
 - : Not detectable
 T : Present in traces

TABLE 2(b). EXUDATION PATTERN OF SUGARS THROUGH ROOT OF
SORGHUM PLANT ($\mu\text{g/plant}$)

Sugars	Age of the plant in days		
	15	30	45
Glucose	++++	++++	+++
Fructose	+++	+++	+
Xylose	-	+	+
Sucrose	-	-	-

+ : 10 to 20 $\mu\text{g/plant}$
 ++ : 20 to 30 "
 +++ : 30 to 40 "
 ++++ : 40 to 50 "
 - : Not detectable

TABLE 2(c). EXDUATION PATTERN OF ORGANIC ACIDS THROUGH ROOT
OF SORGHUM PLANT ($\mu\text{g/plant}$)

Organic acids	Age of the plant in days		
	15	30	45
Tartaric acid	++	++	-
Oxalic acid	+++	++	-

++ : 20 to 30 $\mu\text{g/plant}$

+++ : 30 to 40 "

- : Not detectable

from Tamil Nadu Agricultural University Campus (Coimbatore) were used for the pot experiment. There were considerable differences in the physico-chemical properties of these two soils and as such helped to study the effect of treatments under varied soil situations (Table 3). As already indicated, this experiment carried 48 treatments (two soils, sterilized and unsterilized, three levels of N and two levels of P and rhizosphere region and non-rhizosphere region). Eight sets of such treatments were maintained to represent two replications per stage of collection viz., 30, 60 and 90 days. The final two sets of replications were used for recording grain and straw yield.

4.4. Studies of the effect on soil properties

4.4.1. Effect on availability of N, P and K in soils (Fig.4)

4.4.1.1. Effect on available N (Table 4)

Individual effects

i) Rhizosphere: The mean value for this main effect ranged from 83.2 to 108.9 ppm. At all the three stages of crop growth, the rhizosphere soil recorded higher available N content than non-rhizosphere soil.

ii) Sterilization: The mean value for this main effect ranged from 77.8 to 105.9 ppm. Under sterilized condition higher available N content was recorded at 30th day

TABLE 3. PHYSICO-CHEMICAL CHARACTERISTICS OF THE INITIAL SOIL SAMPLES COLLECTED FROM THE TNAU FARM, COIMBATORE (Pot Study)

A: BLACK SOIL COLLECTED FROM EASTERN BLOCK OF TNAU FARM, COIMBATORE
PERIANAYAKKANPALAYAM SERIES

Taxonomic classification: Typic ustivertept

B: RED SOIL, COLLECTED FROM MILLET BREEDING STATION, COIMBATORE
PALATHURAI SERIES

Taxonomic classification : Typic haplustalf

Heads of analysis	Values	
	A	B
<u>A. Textural composition</u>		
Clay (per cent)	43.7	7.7
Silt (per cent)	9.2	25.5
Fine sand (per cent)	19.2	42.5
Coarse sand (per cent)	27.5	23.7
Textural class	Clay loam	Sandy loam
<u>B. Chemical properties</u>		
a. Moisture (per cent)	5.32	4.12
b. Total N (ppm)	1050	720.0
c. Available N (ppm)	97.60	85.60
d. Ammoniacal nitrogen (ppm)	24.25	20.15
e. NO_3 - N (ppm)	19.75	15.82
f. Total P (ppm)	765.0	875.0
g. Available P (ppm)	1.25	2.32
h. Saloid - P (ppm)	4.15	8.67
i. Al-P (ppm)	5.67	4.72
j. Fe-P (ppm)	41.6	52.25
k. Ca-P (ppm)	7.67	6.56
l. Total K (ppm)	2765	2325
m. Available K (ppm)	235.0	168.0
n. Water soluble K (ppm)	57.0	43.0
o. HNO_3 extractable-K (ppm)	325.0	265.0
p. Total Fe (ppm)	1280	1300.0
q. Available Fe (ppm)	4.60	6.30
r. Total Mn (ppm)	490.0	380.0
s. Available Mn (ppm)	16.50	20.6
t. Total Cu (ppm)	20.0	19.0
u. Available Cu (ppm)	0.75	1.27
v. Total Zn (ppm)	40.0	150.0
w. Available Zn (ppm)	0.30	0.42
<u>C. Physico-chemical properties</u>		
i) pH	8.10	7.65
ii) EC (m.mhos cm^{-1})	0.62	0.45
iii) Cation exchange capacity (m.e 100^{-1} g soil)	36.60	16.50

than under non-sterilized condition and decreased with advancement of crop growth.

iii) Soil type: The mean value for this main effect ranged from 82.6 to 110.4 ppm. In the case of black soil, the available N content increased upto 60th day and thereafter declined. In the case of red soil, the available N content decreased with stage and the decrease in the third stage was insignificant when compared to the second stage. However in the third stage, the red soil registered more of available N content than the black soil.

iv) P levels: The mean value for this main effect ranged from 80.0 to 108.2 ppm. Phosphorus application did not increase the available N status at the earlier stages but increased at near about harvest.

v) N levels: The mean value for this main effect ranged from 83.3 to 104.8 ppm. Nitrogen application at all levels did not increase the available N status of the soil.

Interaction effects

At 30th day, the interactions viz., Rh x S, Rh x N, S x P, S x N and P x N were significant. The salient inferences drawn from the interaction effects are: (i) in both the rhizosphere and non-rhizosphere soils, the black soil

TABLE 4. EFFECT OF TREATMENTS ON AVAILABLE N IN RHIZOSPHERE AND
NON-RHIZOSPHERE REGIONS OF SORGHUM IN BLACK AND RED SOILS (ppm)

Treatments (1)	30 days (2)	60 days (3)	90 days (4)
Rh	108.9	110.0	86.0
NRh	95.7	90.7	83.2
St	105.9	104.2	91.4
NSt	98.7	96.5	77.8
S ₁	110.4	112.8	82.6
S ₂	94.2	87.9	86.6
P ₀	108.2	104.0	80.0
P ₅₀	96.4	96.7	89.3
SE	1.9	1.6	1.4
CD	5.5	4.5	3.9
N ₀	104.4	104.8	85.1
N ₅₀	102.7	100.0	85.3
N ₁₀₀	100.0	96.3	83.3
SE	2.4	2.0	1.7
CD	6.7	5.5	4.8
Rh x St	110.8	115.6	97.1
Rh x NSt	107.1	104.4	75.0
NRh x St	101.1	92.8	85.8
NRh x NSt	90.3	88.6	80.6
Rh x S ₁	120.4	133.0	82.3
Rh x S ₂	97.5	86.9	89.8
NRh x S ₁	100.4	92.6	82.9
NRh x S ₂	91.0	88.9	83.5
Rh x P ₀	115.9	118.0	80.6
Rh x P ₅₀	102.0	102.0	91.5
NRh x P ₀	100.5	90.1	79.4
NRh x P ₅₀	90.8	91.4	87.0
St x S ₁	109.3	117.6	86.3
St x S ₂	88.1	90.8	96.6
NSt x S ₁	111.5	108.0	78.9
NSt x S ₂	100.4	85.0	76.6

Contd.,

(1)	(2)	(3)	(4)
St x P ₀	112.4	110.2	83.5
St x P ₅₀	99.4	98.3	99.4
NSt x P ₀	104.0	97.9	76.4
NSt x P ₅₀	93.4	95.1	79.2
S ₁ x P ₀	113.4	119.6	81.3
S ₁ x P ₅₀	107.4	106.0	84.0
S ₂ x P ₀	103.0	88.5	78.7
S ₂ x P ₅₀	85.5	87.4	94.6
SE	2.7	2.3	2.0
CD	7.7	6.4	5.6
Rh x N ₀	119.1	113.3	85.9
Rh x N ₅₀	104.0	109.4	88.1
Rh x N ₁₀₀	104.8	107.4	84.0
NRh x N ₀	89.7	96.3	84.2
NRh x N ₅₀	101.3	90.6	82.4
NRh x N ₁₀₀	96.1	85.3	83.0
St x N ₀	106.0	104.8	92.9
St x N ₅₀	108.6	110.0	91.2
St x N ₁₀₀	103.2	98.0	90.3
NSt x N ₀	102.8	104.9	77.3
NSt x N ₅₀	96.7	90.0	79.3
NSt x N ₁₀₀	96.7	94.7	76.8
S ₁ x N ₀	104.1	119.4	84.0
S ₁ x N ₅₀	114.4	109.3	81.5
S ₁ x N ₁₀₀	112.7	109.7	82.3
S ₂ x N ₀	104.7	90.2	86.1
S ₂ x N ₅₀	90.9	90.6	89.0
S ₂ x N ₁₀₀	87.1	82.9	84.8
N ₀ x P ₀	106.7	104.7	81.8
N ₀ x P ₅₀	102.1	104.5	88.4
N ₅₀ x P ₀	113.5	104.5	79.4
N ₅₀ x P ₅₀	91.8	95.5	91.0
N ₁₀₀ x P ₀	104.4	102.9	78.8
N ₁₀₀ x P ₅₀	95.4	89.7	88.3
SE	3.3	2.8	2.4
CD	9.5	7.8	6.8

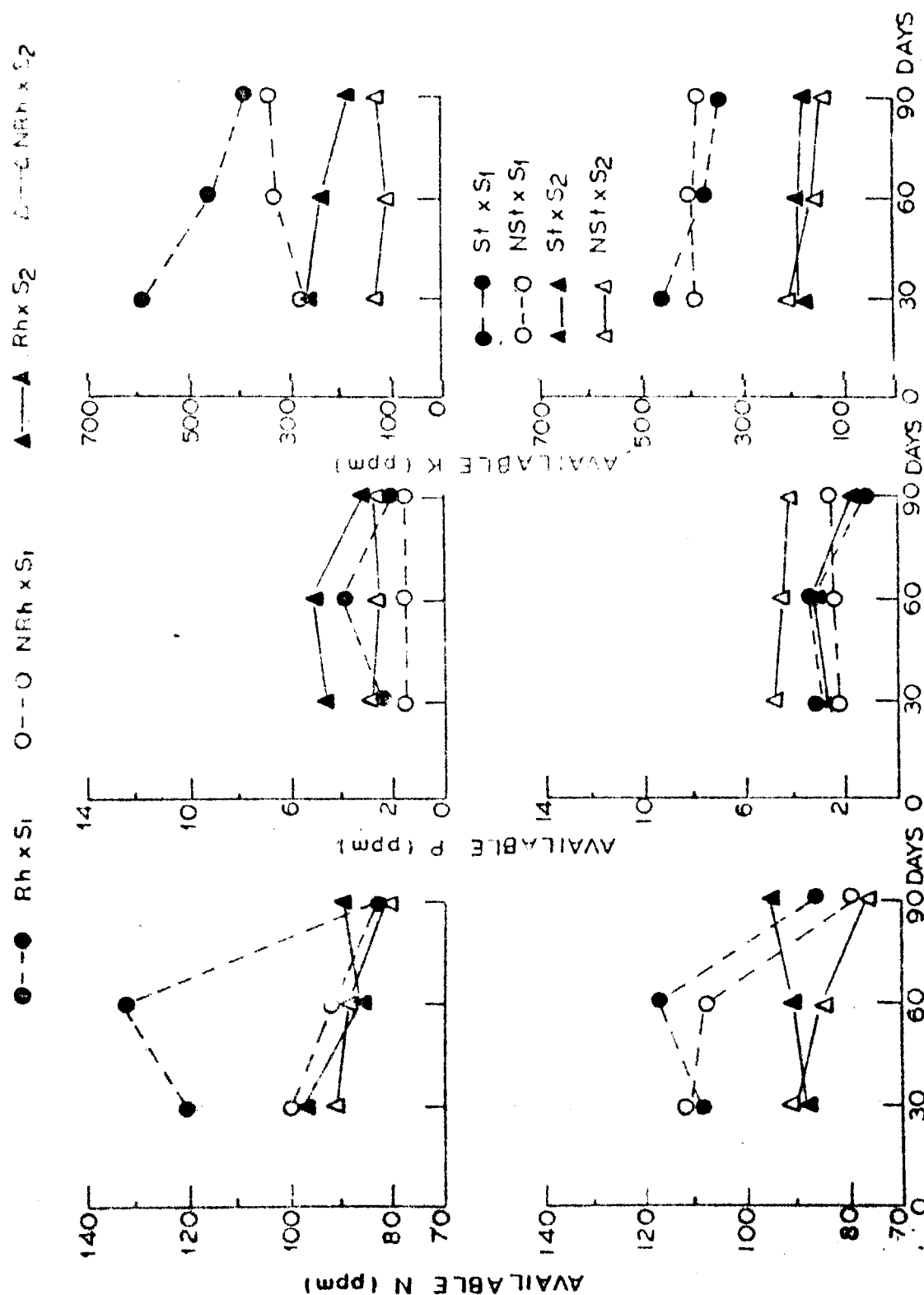


FIG-4 AVAILABILITY OF MAJOR NUTRIENTS AS INFLUENCED BY RHIZOSPHERE, SOIL TYPES AND STERILIZATION AT DIFFERENT STAGES OF CROP GROWTH

recorded significantly higher available N content than the red soil and the available N content in the rhizosphere soil was more in both the soils than in the non-rhizosphere soils;; (ii) the available N content was more in the rhizosphere soil irrespective of the levels of N tried; (iii) irrespective of P application, the black soil registered higher available N content than the red soil and in both the soils, P application did not enhance the available N content; (iv) the available N content in the black soil was influenced by the N application, but that was on par with control and in the red soil, levels of N did not have any influence in increasing the available N content; and (v) the combined application of $N_{50}P_0$ and N_0P_{50} recorded higher available N content, but on par with other combined applications.

At 60th day, the interactions viz., St x P, St x N, Rh x S, Rh x P and S x P were found to be significant. The salient inferences drawn are: (i) the levels of N and P tried did not increase the available N content under both the sterilized and unsterilized conditions; (ii) at N_0 level, the unsterilized i.e., normal soil, was on par with sterilized soil; (iii) at N_{50} and N_{100} levels, under sterilized condition of the soil higher available N content was recorded than the normal soil and that attained the level

of significance only at N_{50} level; (iv) irrespective of P application the available N content was more under unsterilized condition and at P_0 level, the differences were significant; (v) in the black soil, the available N content was significantly superior in the rhizosphere region than the red soil, while in the red soil in both the rhizosphere and non-rhizosphere soils, the available N content was more or less the same; and (vi) irrespective of P application, the rhizosphere soil recorded significantly higher available N content.

At 90th day, the interactions viz., St x Rh, St x S, St x P and S x P were significant. The important inferences are (i) under sterilized condition, the available N content was higher in the rhizosphere soil than that in the non-rhizosphere soil, in the red soil than in the black soil and at P_{50} level than at P_0 level. The above trend was completely reversed under non-sterilized condition; (ii) the content of available N was not increased in both the soil types and at both the levels of P application; (iii) within the soil types, generally P_{50} level registered higher available N content than P_0 level but the significance was observed only in the red soil; and iv) at P_0 level the black soil was on par with the red soil whereas at P_{50} level, the red soil recorded higher available N content than the black soil.

4.4.1.2. Effect on available phosphorus (Table 5)

Individual effects

i) Rhizosphere: The mean value for the main effect ranged from 2.12 to 4.81 ppm and at all stages of crop growth, the rhizosphere soil contained significantly higher available P content than the non-rhizosphere soil.

ii) Sterilization: The mean value ranged from 1.60 to 3.48 ppm and the sterilized condition brought about a significant depression in the available P content at all stages of crop growth.

iii) Soil types: The mean available P content for the soil types ranged from 1.83 to 3.91 ppm. For any given growth stage, the red soil was found to contain more available P than the black soil.

iv) P levels: The status of available P was higher in P applied treatments during all the three stages than in no P treatment.

v) N levels: At 30th day, the effect due to addition of N at all levels remained on par. With advancement in crop growth period, the added N levels caused depression of available P. But this effect was reversed at 90th day.

TABLE 5. EFFECT OF TREATMENTS ON AVAILABLE P IN RHIZOSPHERE AND NON-RHIZOSPHERE REGIONS OF SORGHUM IN BLACK AND RED SOILS (ppm)

Treatments (1)	30 days (2)	60 days (3)	90 days (4)
Rh	4.08	4.81	2.57
NRh	2.12	2.12	2.37
St	2.78	3.44	1.60
NSt	3.43	3.48	3.34
S ₁	2.56	3.01	1.83
S ₂	3.65	3.91	3.10
P ₀	2.24	2.90	1.84
P ₅₀	3.97	4.03	3.09
SE	0.12	0.15	0.08
CD	0.35	0.42	0.24
N ₀	3.17	3.85	2.24
N ₅₀	3.08	3.31	2.59
N ₁₀₀	3.07	3.23	2.57
SE	0.15	0.18	0.10
CD	0.43	0.51	0.29
Rh x St	3.69	5.17	1.97
Rh x NSt	4.48	4.44	3.17
NRh x St	1.97	1.72	1.22
NRh x NSt	2.38	2.53	3.51
Rh x S ₁	3.47	4.37	1.78
Rh x S ₂	4.69	5.24	3.36
NRh x S ₁	1.64	1.66	1.89
NRh x S ₂	2.61	2.59	2.85
Rh x P ₀	2.94	4.30	2.02
Rh x P ₅₀	5.22	5.31	3.12
NRh x P ₀	1.54	1.50	1.66
NRh x P ₅₀	2.70	2.74	3.07
St x S ₁	2.89	3.42	1.16
St x S ₂	2.67	3.47	2.04
NSt x S ₁	2.22	2.61	2.51
NSt x S ₂	1.63	4.35	4.16

Contd.

(1)	(2)	(3)	(4)
St x P ₀	1.77	2.75	1.16
St x P ₅₀	3.70	4.14	2.04
NSt x P ₀	2.70	3.05	2.53
NSt x P ₅₀	4.15	3.92	4.15
S ₁ x P ₀	1.71	2.34	1.50
S ₁ x P ₅₀	3.40	3.69	2.17
S ₂ x P ₀	3.77	3.45	2.19
S ₂ x P ₅₀	4.53	4.37	4.02
SE	0.17	0.21	0.12
CD	0.49	0.59	0.33
Rh x N ₀	4.49	5.20	2.25
Rh x N ₅₀	3.72	4.87	2.84
Rh x N ₁₀₀	4.04	4.34	2.62
NRh x N ₀	1.84	2.51	2.24
NRh x N ₅₀	2.43	1.74	2.35
NRh x N ₁₀₀	2.11	2.11	2.52
St x N ₀	2.38	3.73	1.48
St x N ₅₀	3.08	3.49	1.69
St x N ₁₀₀	2.89	3.11	1.63
NSt x N ₀	3.95	3.98	3.01
NSt x N ₅₀	3.07	3.12	3.50
NSt x N ₁₀₀	3.26	3.34	3.51
S ₁ x N ₀	2.20	3.62	1.47
S ₁ x N ₅₀	2.78	2.36	2.04
S ₁ x N ₁₀₀	2.69	3.07	1.99
S ₂ x N ₀	4.13	4.09	3.01
S ₂ x N ₅₀	3.37	4.26	3.15
S ₂ x N ₁₀₀	3.46	3.38	3.15
N ₀ x P ₀	2.67	3.24	1.46
N ₀ x P ₅₀	3.67	4.47	3.03
N ₅₀ x P ₀	2.10	2.82	2.12
N ₅₀ x P ₅₀	4.05	3.79	3.07
N ₁₀₀ x P ₀	1.96	2.63	1.95
N ₁₀₀ x P ₅₀	4.19	3.82	3.19
SE	0.21	0.26	0.14
CD	0.60	0.73	0.41

Interaction effects

At 30th day, the various interactions viz., St x N, St x S, Rh x P, Rh x N, S x N and P x N indicated statistical significance. For any given level of N, the application of P favoured, greater accumulation of available P and irrespective of P application, the rhizosphere soil recorded higher accumulation of available P content than the non-rhizosphere soil.

At 60th day, the interactions viz., St x Rh, St x S and S x N indicated statistical significance. The salient inferences from the above are: (i) sterilization caused greater accumulation of P in the rhizosphere soil (ii) in the black soil, sterilization favoured greater accumulation of available P as against a reverse effect associated with the red soil; and (iii) in the red soil, higher level of N tended to depress the available P status.

At 90th day, the interactions viz., St x Rh, St x S, St x P, Rh x S and S x P attained statistical significance. The important inferences drawn are: (i) the sterilized condition tended to enhance available P in the rhizosphere soil; (ii) the sterilized condition had similar effect in both the soil types; (iii) irrespective of sterilization, addition of P enhanced the available P status in the soils; in both rhizosphere and non-rhizosphere soils the red soil

contained more available P as compared to the black soil; and (iv) the effect P addition in enhancing the available P status was observed in both the soil types.

4.4.1.3. Effect of available K (Table 17)

The exchangeable-K is taken as available-K since the water soluble K recorded only very little fraction. The exchangeable K is dealt in detail under effect on K transformation.

4.4.2. Effect on availability of micronutrients in soils (Fig.5)

4.4.2.1. Effect on available Fe (Table 6)

Individual effects

i) Rhizosphere: The mean value for this main effect ranged from 5.15 to 20.58 ppm. The rhizosphere soil recorded higher values of available Fe content at all the three stages of crop growth than the non-rhizosphere soil.

ii) Sterilization: The mean value for this main effect ranged from 5.36 to 18.85 ppm. Under sterilized condition the available Fe content decreased at all the three stages of crop growth.

iii) Soil types: The mean values for this main effect ranged from 5.48 to 18.68 ppm. The black soil recorded

TABLE 6. EFFECT OF TREATMENTS ON AVAILABLE Fe IN RHIZOSPHERE AND
NON-RHIZOSPHERE REGIONS OF SORGHUM IN BLACK AND RED SOILS (ppm)

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Treatments (1)	30 days (2)	60 days (3)	90 days (4)
Rh	6.43	20.58	20.30
NRh	5.15	9.94	15.26
St	5.36	11.67	16.91
NSt	6.22	18.85	18.64
S ₁	5.48	16.11	18.68
S ₂	6.10	14.41	16.87
P ₀	5.57	14.70	18.00
P ₅₀	6.01	15.82	17.55
SE	0.08	0.42	0.40
CD	0.24	1.19	1.12
N ₀	5.95	16.05	18.47
N ₅₀	5.92	14.55	17.15
N ₁₀₀	5.50	15.17	17.71
SE	0.10	0.51	0.48
CD	0.29	1.46	1.38
Rh x St	6.07	17.92	18.73
Rh x NSt	6.78	23.24	21.88
NRh x St	4.64	5.42	15.10
NRh x NSt	5.67	14.47	15.41
Rh x S ₁	6.17	21.64	21.70
Rh x S ₂	6.69	19.51	18.90
NRh x S ₁	4.80	10.57	15.67
NRh x S ₂	5.51	9.31	14.85
Rh x P ₀	6.14	20.52	21.29
Rh x P ₅₀	6.71	20.64	17.31
NRh x P ₀	5.01	8.87	14.72
NRh x P ₅₀	5.30	11.01	15.79
St x S ₁	4.97	13.36	19.12
St x S ₂	5.73	9.98	14.71
NSt x S ₁	6.00	18.86	18.24
NSt x S ₂	6.46	18.85	19.04

Contd.,

(1)	(2)	(3)	(4)
St x P ₀	4.92	11.97	16.79
St x P ₅₀	6.22	11.37	17.04
NSt x P ₀	6.23	17.42	19.22
NSt x P ₅₀	6.21	20.28	18.06
S ₁ x P ₀	5.34	14.21	19.05
S ₁ x P ₅₀	5.62	18.01	18.31
S ₂ x P ₀	5.81	15.19	16.96
S ₂ x P ₅₀	6.39	13.64	16.80
SE	0.12	0.59	0.56
CD	0.34	1.68	1.59
Rh x N ₀	6.81	22.12	21.69
Rh x N ₅₀	6.40	19.60	19.13
Rh x N ₁₀₀	6.06	20.01	20.08
NRh x N ₀	5.09	9.98	15.26
NRh x N ₅₀	5.42	9.51	15.17
NRh x N ₁₀₀	4.94	10.34	15.34
St x N ₀	5.43	12.05	17.87
St x N ₅₀	5.50	10.51	14.78
St x N ₁₀₀	5.14	12.44	18.09
NSt x N ₀	6.47	20.05	19.08
NSt x N ₅₀	6.33	18.60	19.52
NSt x N ₁₀₀	5.87	17.90	17.33
S ₁ x N ₀	5.42	17.52	19.40
S ₁ x N ₅₀	5.83	15.29	17.06
S ₁ x N ₁₀₀	5.20	15.51	19.59
S ₂ x N ₀	6.48	14.58	17.55
S ₂ x N ₅₀	6.00	13.81	17.24
S ₂ x N ₁₀₀	5.81	14.84	15.83
N ₀ x P ₀	5.46	14.76	17.89
N ₀ x P ₅₀	6.45	17.35	19.06
N ₅₀ x P ₀	5.59	12.68	17.40
N ₅₀ x P ₅₀	6.24	16.42	16.90
N ₁₀₀ x P ₀	5.68	16.65	18.73
N ₁₀₀ x P ₅₀	5.33	13.70	16.69
SE	0.15	0.72	0.68
CD	0.42	2.06	1.95

higher amount of available Fe at 60 and 90 days of crop growth while the reverse was the case at 30 days.

iv) P levels: The mean value for this main effect ranged from 5.57 to 18.0 ppm. Phosphorus application increased the available Fe content.

v) N levels: The mean value for this main effect ranged from 5.50 to 18.47 ppm. Application of N at both the levels did not influence the available Fe content. The available Fe content decreased with N levels at 30 and 90 days of crop growth, while at 60 days, N_0 and N_{100} levels and N_{100} and N_{50} levels were on par.

Interaction effects

At 30th day, the interactions viz., St x P, Rh x N, S x N and P x N showed significance. The salient points of the inferences draw are; (i) P fertilization interacted significantly with sterilization and levels of N; (ii) P fertilization had positive effect of Fe availability under sterilized condition; (iii) Further, N application at higher level decreased Fe availability with P fertilization; and (iv) a stepwise reduction in Fe availability took place for each N addition in the rhizosphere soil as well as in the red soil.

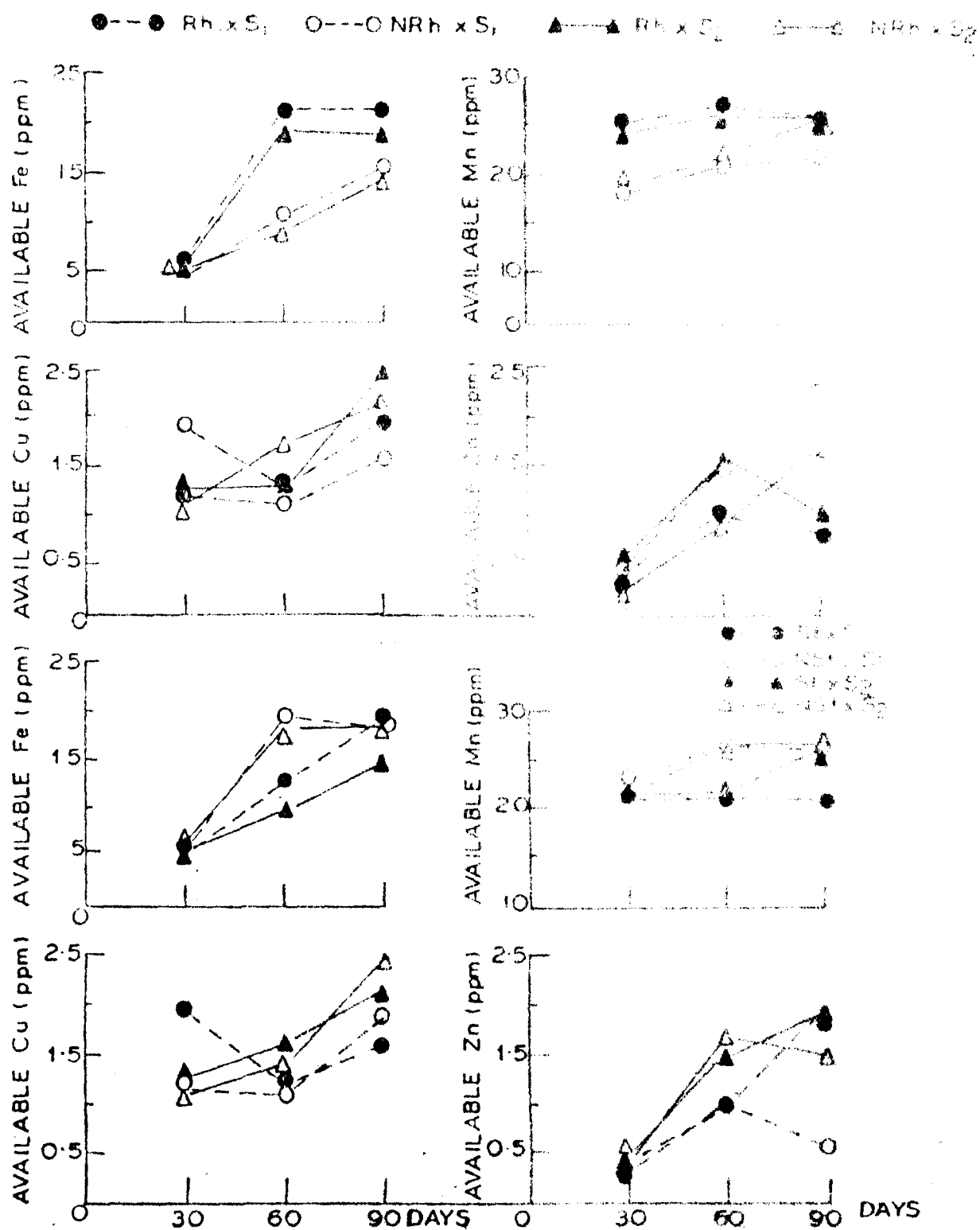


FIG.5 AVAILABILITY OF MICRONUTRIENTS AS INFLUENCED BY RHIZOSPHERE, SOIL TYPES AND STERILIZATION AT DIFFERENT STAGES OF CROP GROWTH

At 60th day, the interactions viz., St x Rh, St x S, St x P, S x P and P x N showed statistical significance. The salient inferences are: (i) in contrast to 30th day, P application helped to increase Fe availability only under non-sterilized condition; (ii) increased Fe availability for P addition was observed only in the black soil, while it was reduced for the same in the red soil; and (iii) similar to that of results obtained at 30th day, Fe availability was reduced at higher levels of N in the presence of P application.

At 90th day, the interaction involving soil with sterilization and soil with nitrogen attained significance. The salient inferences drawn are: (i) in the black soil, under sterilized condition of the soil Fe availability was not increased but in the red soil, it had a positive effect; (ii) differences were not conspicuous for Fe availability in the two soil types due to N addition at 50 kg level, but at 100 kg level the black soil had more Fe availability than its counterpart.

4.4.2.2. Effect on available Mn (Table 7)

Individual effects

i) Rhizosphere: The mean values for this main effect ranged from 18.58 to 26.80 ppm. The rhizosphere **soil**

showed higher accumulation of available Mn than the non-rhizosphere soil.

ii) Sterilization: The mean value for this main effect fell within the range of 21.24 to 26.63 ppm. The sterilized condition of the soil significantly decreased the available Mn content at all the three stages of crop growth.

iii) Soil types: The mean value for this main effect ranged from 21.66 to 26.19 ppm. The red soil enhanced the available Mn content only at 90 days of crop growth.

iv) P levels: The mean values for this main effect ranged from 21.03 to 25.24 ppm. Application of P increased the availability of Mn only at 30 and 60 days of crop growth period.

v) N levels: The mean values for this main effect ranged from 21.37 to 25.58 ppm. At 60 days of crop growth period, N at 100 kg level increased the available Mn content, while at 90 days N at 50 kg level increased the available Mn content. There was no significant difference among the N levels tried at 30 days of growth period.

TABLE 7. EFFECT OF TREATMENTS ON AVAILABLE Mn IN RHIZOSPHERE AND NON-RHIZOSPHERE REGIONS OF SORGHUM IN BLACK AND RED SOILS (ppm)

Treatments (1)	30 days (2)	60 days (3)	90 days (4)
Rh	24.92	26.80	25.84
NRh	18.58	21.66	24.15
St	21.24	21.83	23.53
NSt	22.26	26.63	26.47
S ₁	21.84	24.24	23.81
S ₂	21.66	24.21	26.19
P ₀	21.03	24.12	24.76
P ₅₀	22.48	24.34	25.24
SE	0.29	0.32	0.07
CD	0.83	0.92	0.21
N ₀	21.68	23.69	24.85
N ₅₀	22.20	23.42	25.00
N ₁₀₀	21.37	25.58	25.14
SE	0.36	0.32	0.09
CD	1.01	0.92	0.25
Rh x St	24.74	25.68	25.29
Rh x NSt	25.10	27.91	26.40
NRh x St	17.74	17.98	21.77
NRh x NSt	19.43	25.34	26.53
Rh x S ₁	25.58	27.19	25.42
Rh x S ₂	24.27	26.40	26.27
NRh x S ₁	18.11	21.30	22.20
NRh x S ₂	19.06	22.03	26.10
Rh x P ₀	23.94	27.12	25.40
Rh x P ₅₀	25.90	26.47	26.29
NRh x P ₀	18.11	21.13	24.11
NRh x P ₅₀	19.05	22.20	24.19
St x S ₁	20.88	21.60	21.18
St x S ₂	21.60	22.05	25.89
NSt x S ₁	22.80	26.89	26.45
NSt x S ₂	21.73	26.38	26.48

Contd.,

(1)	(2)	(3)	(4)
St x P ₀	20.09	21.45	23.03
St x P ₅₀	22.39	22.21	24.03
NSt x P ₀	21.96	26.80	26.48
NSt x P ₅₀	22.56	26.46	26.45
S ₁ x P ₀	20.96	24.07	23.30
S ₁ x P ₅₀	22.72	24.42	24.32
S ₂ x P ₀	21.09	24.17	26.22
S ₂ x P ₅₀	22.23	24.25	26.16
SE	0.41	0.46	0.10
CD	1.17	1.30	0.29
Rh x N ₀	22.50	26.11	25.92
Rh x N ₅₀	25.30	26.03	25.76
Rh x N ₁₀₀	23.97	28.24	25.85
NRh x N ₀	17.87	21.26	23.79
NRh x N ₅₀	19.10	20.80	24.24
NRh x N ₁₀₀	18.78	22.92	24.43
St x N ₀	22.43	21.77	23.25
St x N ₅₀	21.36	21.21	23.55
St x N ₁₀₀	19.94	22.49	23.79
NSt x N ₀	20.93	25.60	26.45
NSt x N ₅₀	23.05	25.62	26.45
NSt x N ₁₀₀	22.81	28.67	26.49
S ₁ x N ₀	22.04	22.90	23.51
S ₁ x N ₅₀	22.23	22.70	23.76
S ₁ x N ₁₀₀	21.25	27.13	24.17
S ₂ x N ₀	21.32	24.47	26.20
S ₂ x N ₅₀	22.17	24.13	26.25
S ₂ x N ₁₀₀	21.50	24.03	26.11
N ₀ x P ₀	19.68	23.12	24.52
N ₀ x P ₅₀	23.68	23.20	25.19
N ₅₀ x P ₀	22.02	26.04	24.66
N ₅₀ x P ₅₀	22.39	24.25	25.35
N ₁₀₀ x P ₀	21.39	23.64	25.10
N ₁₀₀ x P ₅₀	21.36	25.12	25.18
SE	0.50	0.56	0.13
CD	1.44	1.59	0.36

Interaction effects

At 30th day, the interactions viz., St x S, St x P, St x N, Rh x S and P x N showed statistical significance. The important inferences drawn are: (i) availability of Mn in soil was increased by the combined effect of P under sterilized condition and was decreased due to combined effect of N application under sterilized condition; and (ii) similar positive influences on Mn availability observed for P application was confined under sterilized condition and also without N application.

At 60th day, among the different interactions, the effect of N fertilization on Mn availability differed for soils, since at N_0 and N_{50} levels, Mn availability was more in the red soil, but at N_{100} kg level, the black soil showed higher value of Mn availability.

At 90th day, all the interactions excepting Rh x P were significant. The important inferences drawn are: (i) available Mn was observed to a higher extent in the rhizosphere soil in the black soil than that in the red soil and also due to P addition in the black soil and the red soil contained more Fe availability under sterilized condition; (ii) while N application had not significantly altered the Mn availability in the rhizosphere soil in the

black soil and without P application, the same got increased in the non-rhizosphere soil due to N fertilization; and (iii) the red soil was associated with significantly higher available Mn content irrespective of P application.

4.4.2.3. Effect on available Cu (Table 8)

Individual effects

i) Rhizosphere: The mean value for this main effect ranged from 1.17 to 2.21 ppm. The rhizosphere soil showed higher accumulation of available Cu content at 30 and 90 days of crop growth than the non-rhizosphere soil and the trend got reversed at 60 days of crop growth.

ii) Sterilization: The mean value for this main effect ranged from 1.13 to 2.19 ppm. Under sterilized condition of the soil available Cu content was enhanced at all the three stages of crop growth.

iii) Soil types: The mean value for this main effect ranged from 1.16 to 2.30 ppm. The black soil showed higher available Cu content at 30 days and 90 days of crop growth than the red soil and the trend got reversed at 60 days of crop growth.

iv) P levels: The mean value for this main effect ranged from 1.33 to 2.17 ppm. On par concentrations of

TABLE 8. EFFECT OF TREATMENTS ON AVAILABLE Cu IN RHIZOSPHERE AND
NON-RHIZOSPHERE REGIONS OF SORGHUM IN BLACK AND RED SOILS (ppm)

Treatments (1)	30 days (2)	60 days (3)	90 days (4)
Rh	1.58	1.30	2.21
NRh	1.17	1.38	1.89
St	1.62	1.40	1.90
NSt	1.13	1.27	2.19
S ₁	1.56	1.16	1.80
S ₂	1.20	1.52	2.30
P ₀	1.37	1.33	2.17
P ₅₀	1.38	1.35	1.92
SE	0.04	0.03	0.03
CD	0.10	0.09	0.09
N ₀	1.40	1.25	2.06
N ₅₀	1.36	1.46	2.13
N ₁₀₀	1.37	1.30	1.95
SE	0.04	0.04	0.04
CD	0.12	0.11	0.11
Rh x St	1.97	1.56	2.13
Rh x NSt	1.19	1.04	2.28
NRh x St	1.27	1.25	1.67
NRh x NSt	1.08	1.50	2.11
Rh x S ₁	1.89	1.26	1.96
Rh x S ₂	1.27	1.34	2.45
NRh x S ₁	1.23	1.06	1.63
NRh x S ₂	1.12	1.69	2.14
Rh x P ₀	1.58	1.26	2.33
Rh x P ₅₀	1.58	1.33	2.08
NRh x P ₀	1.17	1.40	2.01
NRh x P ₅₀	1.18	1.36	1.77
St x S ₁	1.95	1.20	1.66
St x S ₂	1.29	1.61	2.14
NSt x S ₁	1.17	1.12	1.93
NSt x S ₂	1.10	1.43	2.45

Contd.,

(1)	(2)	(3)	(4)
St x P ₀	1.62	1.31	1.97
St x P ₅₀	1.62	1.49	1.84
NSt x P ₀	1.13	1.35	2.37
NSt x P ₅₀	1.14	1.20	2.01
S ₁ x P ₀	1.51	1.14	1.97
S ₁ x P ₅₀	1.61	1.18	1.62
S ₂ x P ₀	1.24	1.52	2.37
S ₂ x P ₅₀	1.15	1.51	2.23
SE	0.05	0.04	0.04
CD	0.14	0.12	0.12
Rh x N ₀	1.68	1.19	2.10
Rh x N ₅₀	1.58	1.45	2.20
Rh x N ₁₀₀	1.48	1.25	2.32
NRh x N ₀	1.13	1.31	2.01
NRh x N ₅₀	1.14	1.48	2.06
NRh x N ₁₀₀	1.25	1.35	1.59
St x N ₀	1.67	1.29	1.93
St x N ₅₀	1.59	1.53	1.95
St x N ₁₀₀	1.60	1.39	1.82
NSt x N ₀	1.14	1.39	2.18
NSt x N ₅₀	1.13	1.40	2.31
NSt x N ₁₀₀	1.13	1.21	2.08
S ₁ x N ₀	1.50	1.06	1.89
S ₁ x N ₅₀	1.55	1.25	1.82
S ₁ x N ₁₀₀	1.62	1.17	1.68
S ₂ x N ₀	1.31	1.44	2.23
S ₂ x N ₅₀	1.18	1.68	2.44
S ₂ x N ₁₀₀	1.11	1.43	2.22
N ₀ x P ₀	1.27	1.33	2.14
N ₀ x P ₅₀	1.54	1.17	1.98
N ₅₀ x P ₀	1.40	1.49	2.16
N ₅₀ x P ₅₀	1.32	1.43	2.10
N ₁₀₀ x P ₀	1.45	1.17	2.21
N ₁₀₀ x P ₅₀	1.28	1.43	1.69
SE	0.06	0.05	0.05
CD	0.17	0.15	0.15

available Cu content were recorded for added P level at all the three stages of crop growth.

v) N levels: The mean value for this main effect ranged from 1.25 to 2.13 ppm. The N application at 50 kg level increased the available copper content at 60 days and 90 days of crop growth and there was no significant difference at 30 days of crop growth.

Interaction effects

At 30th day, the interactions viz., Rh x N and S x N showed statistical significance wherein availability of Cu was reduced due to N application in the rhizosphere soil while N application in the black soil increased the same.

At 60th day, the interactions viz., St x Rh, St x P, Rh x S and P x N showed statistical significance. The salient points of inferences drawn are: (i) the availability of Cu was more in the rhizosphere soil than that in the non-rhizosphere soil due to sterilized condition while under non-sterilized condition, it was distinctly more in the non-rhizosphere soil than that in the rhizosphere soil (ii) availability of Cu was increased only under sterilized condition due to P addition; (iii) availability of Cu was more in the rhizosphere soil and in the black soil while in

the red soil similar trend as that of main effect was observed; and (iv) at added P level, availability of Cu was more due to N addition at two levels than at N_0 level.

At 90th day, the interactions viz., St x Rh, St x P, Rh x N, S x P and P x N were significant. The salient inferences drawn are: i) as against the main effect, availability of Cu was decreased under the sterilized condition of the soil, irrespective of rhizosphere or non-rhizosphere soil and P application; ii) N application particularly at 100 kg level increased Cu availability in the rhizosphere soil; iii) due to P addition available Cu was reduced in both the soils; and iv) Cu availability was reduced by the combined application of P with N at higher level.

4.4.2.4. Effect on available Zn (Table 9)

Individual effects

i) Rhizosphere: The mean value for this main effect ranged from 0.31 to 2.06 ppm. The rhizosphere soil showed significantly higher accumulation of available Zn at 30 days of crop growth and the trend got reversed at 90 days stages. At 60 days of crop growth, there was no significant differences between rhizosphere and non-rhizosphere soils.

ii) Sterilization: The mean value for this main effect ranged from 0.37 to 1.94 ppm. Under sterilized condition of the soil enhanced concentration of available Zn was recorded at 30 and 90 days, but at 60 days stage, there was no significant difference between sterilized and normal soils.

iii) Soil types: The mean value for this main effect ranged from 0.35 to 1.70 ppm. The red soil registered higher accumulation of available Zn at all the three stages of crop growth.

iv) P levels: The mean value for the main effect fell within the range of 0.39 to 1.52 ppm. The beneficial effect of P application in enhancing the available zinc content was significantly visible only at 60 days of crop growth and the effect of P application was not observed at 30 and 90 days of crop growth.

v) N levels: The mean value for this main effect ranged from 0.38 to 1.58 ppm. N₅₀ level enhanced the available Zn content only at 90 days of crop growth, but significant differences were not observed due to N application at two levels at 30 and 60 days of crop growth. The effect of N in increasing the availability of Zn was observed only at later stages of crop growth.

TABLE 9. EFFECT OF TREATMENTS ON AVAILABLE Zn IN RHIZOSPHERE AND
NON-RHIZOSPHERE REGIONS OF SORGHUM IN BLACK AND RED SOILS (ppm)

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Treatments (1)	30 days (2)	60 days (3)	90 days (4)
Rh	0.50	1.30	0.90
NRh	0.31	1.27	2.06
St	0.44	1.22	1.94
NSt	0.37	1.34	1.02
S ₁	0.35	0.97	1.26
S ₂	0.46	1.60	1.70
P ₀	0.39	1.20	1.44
P ₅₀	0.42	1.37	1.52
SE	0.02	0.05	0.06
CD	0.05	0.13	0.18
N ₀	0.42	1.28	1.38
N ₅₀	0.42	1.38	1.58
N ₁₀₀	0.38	1.20	1.48
SE	0.02	0.06	0.08
CD	0.06	0.16	0.22
Rh x St	0.58	1.51	1.42
Rh x NSt	0.43	1.08	0.38
NRh x St	0.31	0.94	2.46
NRh x NSt	0.30	1.61	1.67
Rh x S ₁	0.45	1.03	0.81
Rh x S ₂	0.55	1.57	1.00
NRh x S ₁	0.25	0.92	1.71
NRh x S ₂	0.36	1.62	2.41
Rh x P ₀	0.49	1.21	0.90
Rh x P ₅₀	0.52	1.38	0.90
NRh x P ₀	0.30	1.19	1.97
NRh x P ₅₀	0.31	1.35	2.15
St x S ₁	0.41	0.96	1.98
St x S ₂	0.48	1.49	1.90
NSt x S ₁	0.30	0.98	0.54
NSt x S ₂	0.43	1.71	1.51

Contd.,

(1)	(2)	(3)	(4)
St x P ₀	0.38	0.94	1.97
St x P ₅₀	0.51	1.51	1.91
NSt x P ₀	0.41	1.47	0.90
NSt x P ₅₀	0.32	1.22	1.14
S ₁ x P ₀	0.34	0.79	1.26
S ₁ x P ₅₀	0.45	1.16	1.25
S ₂ x P ₀	0.37	1.62	1.61
S ₂ x P ₅₀	0.46	1.58	1.79
SE	0.02	0.07	0.09
CD	0.06	0.19	0.25
Rh x N ₀	0.44	1.29	0.81
Rh x N ₅₀	0.58	1.45	1.08
Rh x N ₁₀₀	0.49	1.16	0.80
NRh x N ₀	0.40	1.27	1.96
NRh x N ₅₀	0.26	1.30	2.08
NRh x N ₁₀₀	0.26	1.24	2.15
St x N ₀	0.51	1.56	1.88
St x N ₅₀	0.48	1.12	2.10
St x N ₁₀₀	0.34	1.00	1.83
NSt x N ₀	0.33	1.00	0.89
NSt x N ₅₀	0.36	1.63	1.06
NSt x N ₁₀₀	0.41	1.41	1.12
S ₁ x N ₀	0.30	0.82	1.31
S ₁ x N ₅₀	0.41	1.12	1.36
S ₁ x N ₁₀₀	0.35	0.98	1.11
S ₂ x N ₀	0.54	1.74	1.45
S ₂ x N ₅₀	0.43	1.63	1.81
S ₂ x N ₁₀₀	0.40	1.42	1.84
N ₀ x P ₀	0.43	1.23	1.57
N ₀ x P ₅₀	0.41	1.32	1.19
N ₅₀ x P ₀	0.40	1.25	1.54
N ₅₀ x P ₅₀	0.44	1.50	1.63
N ₁₀₀ x P ₀	0.36	1.13	1.20
N ₁₀₀ x P ₅₀	0.39	1.28	1.75
SE	0.03	0.08	0.11
CD	0.08	0.23	0.31

Interaction effects

At 30th day, the interactions viz., St x P, St x N, Rh x N and S x N were significant. The important inferences drawn are: (i) P addition had a positive effect on Zn availability only under sterilized condition and it caused reduction under non-sterilized condition and the sterilized condition of the soil proved to be beneficial on Zn availability only at N_0 and N_{50} levels; (ii) Zn availability was more in the rhizosphere soil than that in the non-rhizosphere soil under all levels of added N; and (iii) the differences in Zn availability that existed between the red and black soils in the absence of added N, got nullified due to N addition.

At 60th day, among the different interactions, the interactions viz., St x P, St x N, S x P and S x N showed marked variations similar to that of the trend observed at 30th day. The salient inferences drawn are: (i) Zn availability was increased due to P fertilization under sterilized condition, but it was more under non-sterilized condition at N_{50} level; (ii) P application had a positive influence only in the black soil; and (iii) similarly N application at 50 kg level exhibited a positive effect on Zn availability in the black soil while the trend got reversed in the red soil.

At 90th day, the important inferences from the interactions include are: (i) Zn availability was more in the red soil than that in the black soil due to N addition at both the levels; and (ii) the beneficial effect of P addition on Zn availability was felt at N_{100} level, but at N_0 level P application reduced Zn availability.

4.5. Effect on transformation of N, P and K in soils

4.5.1. Effect on N transformation (Fig.6)

4.5.1.1. Ammoniacal-N (NH_4 -N) (Table 10)

Individual effects

i) Rhizosphere: The mean value of NH_4 -N content ranged from 6.9 to 59.9 ppm. At 30th day, the rhizosphere soil was found to contain significantly higher amount of NH_4 -N (33.0 ppm) than the non-rhizosphere soil (14.9 ppm). At 60th day, more NH_4 -N accumulation was observed in the non-rhizosphere soil (59.6 ppm) than that in the rhizosphere soil (33.8 ppm). However with advancement in time i.e., at 90th day the trend was reversed with considerable reduction in either case.

ii) Sterilization: The mean NH_4 -N content ranged from 7.3 to 51.2 ppm during different growth stages. For any stage, the effect of sterilization resulted in reduced

TABLE 10. EFFECT OF TREATMENTS ON $\text{NH}_4\text{-N}$ IN RHIZOSPHERE AND NON-RHIZOSPHERE
REGIONS OF SORGHUM IN BLACK AND RED SOILS (ppm)

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Treatments (1)	30 days (2)	60 days (3)	90 days (4)
Rh	33.0	33.8	10.4
NRh	14.9	59.6	6.9
St	21.3	42.2	7.3
NSt	26.6	51.2	10.0
S ₁	25.7	42.9	7.1
S ₂	22.2	50.5	10.2
P ₀	26.5	53.5	9.3
P ₅₀	21.4	39.9	8.0
SE	1.3	2.0	0.5
CD	3.6	5.6	1.5
N ₀	24.1	44.7	7.7
N ₅₀	23.9	45.1	9.0
N ₁₀₀	23.8	50.3	9.3
SE	1.6	2.4	0.6
CD	4.4	6.8	1.8
Rh x St	36.1	36.5	7.1
Rh x NSt	29.9	31.2	13.7
NRh x St	6.4	65.8	7.6
NRh x NSt	23.4	53.3	6.2
Rh x S ₁	35.5	27.5	7.7
Rh x S ₂	30.6	40.2	13.1
NRh x S ₁	16.0	58.4	6.5
NRh x S ₂	15.7	60.7	7.3
Rh x P ₀	37.7	41.8	12.4
Rh x P ₅₀	28.4	25.9	8.4
NRh x P ₀	15.4	65.2	6.1
NRh x P ₅₀	14.4	53.9	7.6
St x S ₁	22.0	42.3	6.3
St x S ₂	20.5	60.0	8.3
NSt x S ₁	29.4	43.6	7.8
NSt x S ₂	23.9	40.9	12.1

Contd.,

(1)	(2)	(3)	(4)
St x P ₀	24.5	57.0	6.4
St x P ₅₀	17.9	45.3	8.2
NSt x P ₀	28.5	50.0	12.2
NSt x P ₅₀	24.8	34.5	7.8
S ₁ x P ₀	28.4	45.7	6.6
S ₁ x P ₅₀	23.1	40.2	7.6
S ₂ x P ₀	24.7	61.3	12.0
S ₂ x P ₅₀	19.6	39.6	8.4
SE	1.8	2.8	0.7
CD	5.1	7.9	2.1
Rh x N ₀	34.3	31.5	9.9
Rh x N ₅₀	33.5	35.2	10.5
Rh x N ₁₀₀	31.2	34.8	10.8
NRh x N ₀	13.9	57.8	5.5
NRh x N ₅₀	14.3	55.0	7.4
NRh x N ₁₀₀	16.4	65.8	7.7
St x N ₀	25.7	47.4	6.6
St x N ₅₀	19.6	49.0	7.4
St x N ₁₀₀	18.4	57.0	7.9
NSt x N ₀	22.4	41.9	8.8
NSt x N ₅₀	28.2	41.2	10.5
NSt x N ₁₀₀	29.3	43.6	10.6
S ₁ x N ₀	22.3	44.6	6.3
S ₁ x N ₅₀	25.5	43.8	7.8
S ₁ x N ₁₀₀	29.4	40.5	7.1
S ₂ x N ₀	25.9	44.8	9.1
S ₂ x N ₅₀	22.3	46.4	10.1
S ₂ x N ₁₀₀	18.2	60.2	11.4
N ₀ x P ₀	27.2	48.9	9.7
N ₀ x P ₅₀	21.0	40.5	5.7
N ₅₀ x P ₀	26.7	50.7	8.3
N ₅₀ x P ₅₀	26.7	39.5	9.6
N ₁₀₀ x P ₀	25.7	60.9	9.8
N ₁₀₀ x P ₅₀	21.9	39.8	8.7
SE	2.2	3.4	0.9
CD	6.2	9.7	2.6

accumulation of $\text{NH}_4\text{-N}$ content. But at 60th day, there was greater accumulation of $\text{NH}_4\text{-N}$ content under non-sterilized condition than that at two other stages.

iii) Soil types: Soil types had no significant differential influence on $\text{NH}_4\text{-N}$ content during the 30th day of crop growth. However, significant differences were noticed during later stages. In either case in the red soil, accumulation of $\text{NH}_4\text{-N}$ was high, when compared to the black soil. The mean value for the main effect observed were 25.7 and 22.2 ppm during 30th day, 42.9 and 50.5 ppm during 60th day; and 7.1 and 10.2 ppm for 90th day for the black and the red soil respectively. It is appropriate to mention here that there was enhanced accumulation of $\text{NH}_4\text{-N}$ with progress in growth in both the soil types at 60 days. With further progress in growth, the status of $\text{NH}_4\text{-N}$ showed a pronounced decrease.

iv) P levels: The status of $\text{NH}_4\text{-N}$ was found to be significantly influenced by the P levels. At all stages of crop growth, the addition of P was associated with significantly reduced accumulation of $\text{NH}_4\text{-N}$ in the soil.

v) N levels: The status of $\text{NH}_4\text{-N}$ concentration was found to be not appreciably influenced by N levels as

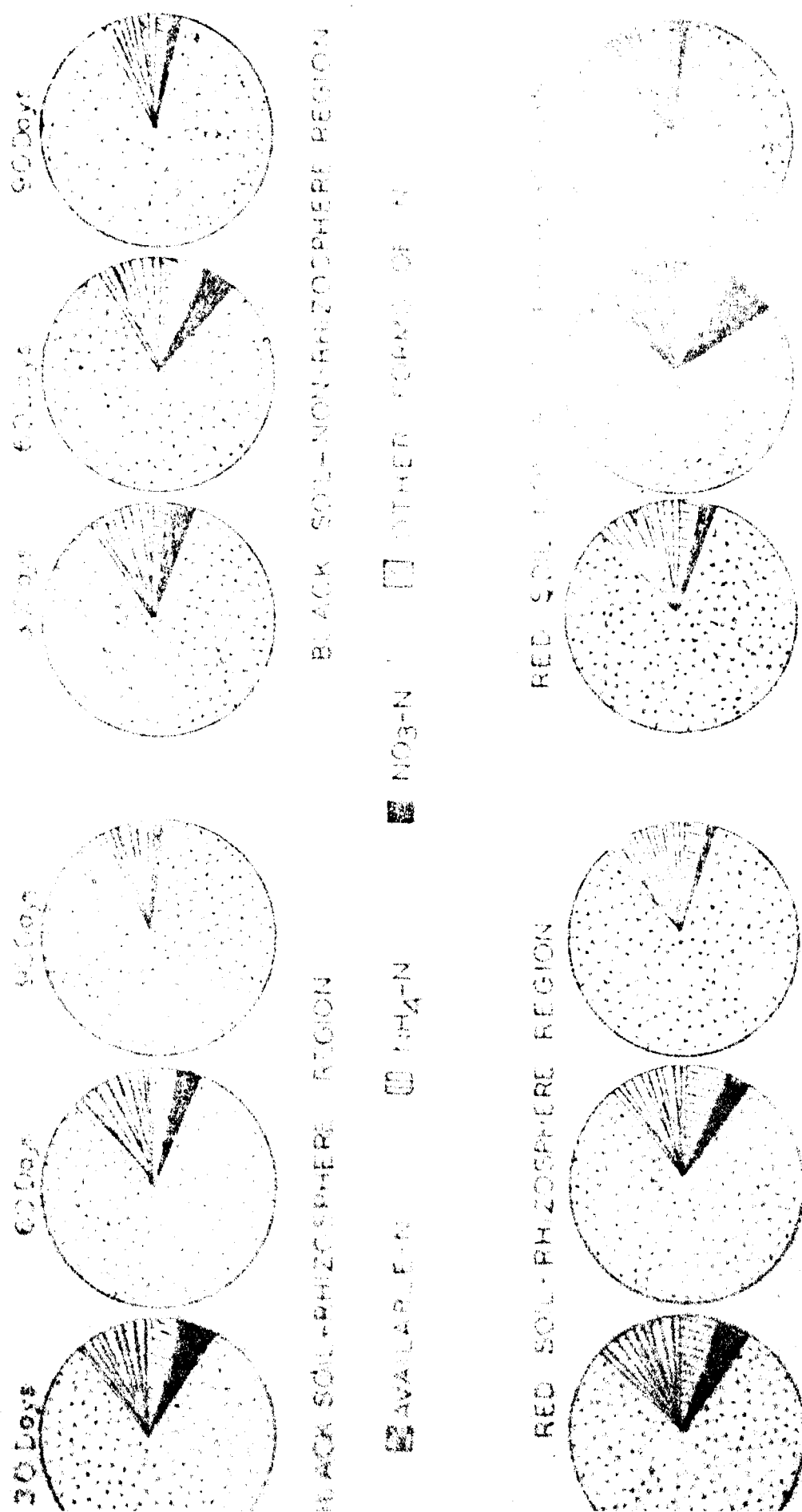


FIG. 6 DIFFERENT FORMS OF N AS INFLUENCED BY RHIZOSPHERE AND SOIL TYPES AT DIFFERENT STAGES OF CROP GROWTH

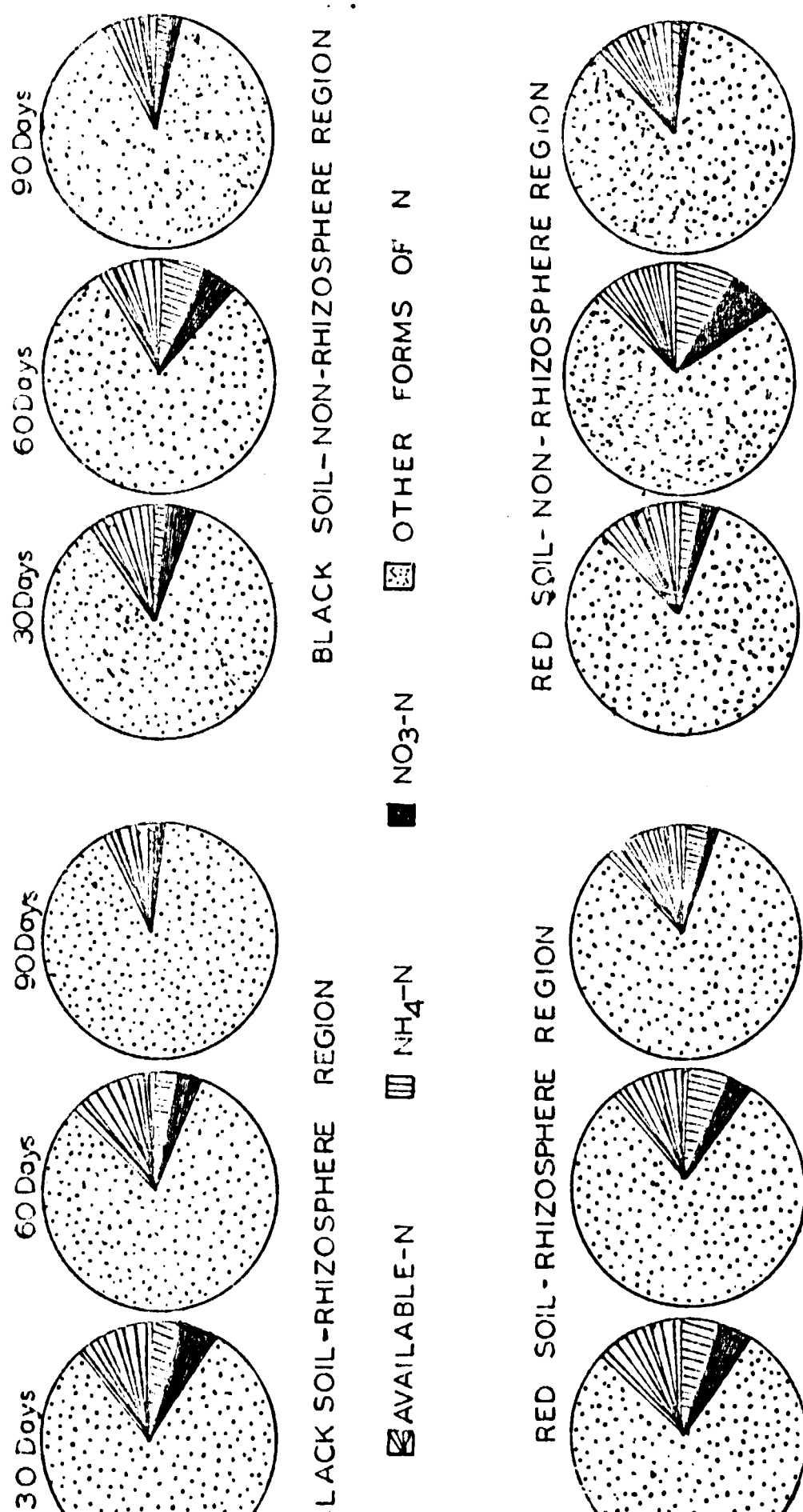


FIG.6 DIFFERENT FORMS OF N AS INFLUENCED BY RHIZOSPHERE AND SOIL TYPES AT DIFFERENT STAGES OF CROP GROWTH

evidenced by the mean values ranging from 23.8 to 24.1 ppm at 30th day; 44.7 to 50.3 ppm at 60th day and 7.7 to 9.3 ppm at 90th day. However, under all levels of N, there was enhanced accumulation of $\text{NH}_4\text{-N}$ at 60th day as compared to other stages.

Interaction effects

At 30th day, the interaction effects viz., St x Rh, St x N, Rh x P and S x N showed statistical significance. The important inferences drawn are: (i) in the rhizosphere soil under sterilized condition of the soil more $\text{NH}_4\text{-N}$ content was exhibited than that under non-sterilized condition and this effect was found to be reversed in the non-rhizosphere soil; (ii) N_{100} level registered increased values of $\text{NH}_4\text{-N}$ content whereas N_{50} and N_0 levels were on par; under sterilized condition, N_0 level recorded higher values of $\text{NH}_4\text{-N}$ content than N_{50} and N_{100} levels in both the soil types; (iii) at N_0 level, $\text{NH}_4\text{-N}$ contents under sterilized and non-sterilized conditions were on par while at N_{50} at N_{100} levels under non-sterilized condition of the soil higher amount of $\text{NH}_4\text{-N}$ content was recorded than that under sterilized condition; (iv) in the presence of P application, the rhizosphere soil had greater accumulation of $\text{NH}_4\text{-N}$ content than the non-rhizosphere soil and (v) $\text{NH}_4\text{-N}$ content increased with the levels of N in the black soil though all the levels were on par; and at N_{50} and N_{100} levels, the black soil registered higher amount of $\text{NH}_4\text{-N}$ content than the red soil.

At 60th day stage, the interactions viz., S x P and S x N showed statistical significance. The S x N interaction showed the same trend as that observed at 30th day; at P_0 level, the red soil recorded higher NH_4 -N content than at P_{50} level.

At 90th day, the interactions viz., St x P, Rh x S, Rh x P, S x P and P x N revealed statistical significance. The salient inferences drawn are: (i) at P_0 level more NH_4 -N content got accumulated under non-sterilized condition than at P_{50} level; (ii) in the absence of added P, the rhizosphere soil contained more NH_4 -N than non-rhizosphere soil and this effect vanished with added P; (iii) the differential accumulation of NH_4 -N content was confined to no P application; and (iv) the NH_4 -N content was not influenced due to N application at P_0 level whereas at P_{50} level, N_{50} and N_{100} levels resulted in higher NH_4 -N content than N_0 level; at N_0 level, P_0 level resulted in higher NH_4 -N content than at P_{50} level whereas the other two N levels did not increase the NH_4 -N content.

4.5.1.2. Nitrate -N (NO_3 -N) (Table 11)

Individual effects

i) Rhizosphere: The mean value for the main effect ranged from 2.9 to 47.3 ppm. The amount of NO_3 -N accumulation

in the rhizosphere soil was considerably more at 30 and 60 days stage but such effect was not obtained at 90 days stage.

ii) Sterilization: The mean value for this main effect ranged from 2.7 to 47.5 ppm. The sterilized condition accounted for significantly low $\text{NO}_3\text{-N}$ accumulation during the earlier stages of crop growth, but near about the harvest, such a difference was not observed. This implied that the effect of sterilization was only temporary and very soon the soil behaved as that of normal soil. In other words, the soil provided a medium very conducive for microbial growth and any attempt to sterilize could cause only a temporary cessation and the microflora build up occurred soon. This was reflected in $\text{NO}_3\text{-N}$ accumulation and in the present study irrespective of sterilization on par concentrations of $\text{NO}_3\text{-N}$ were noticed at harvest stage.

iii) Soil types: The $\text{NO}_3\text{-N}$ content was significantly higher in the black soil at 60 days stage, but this trend got reversed at 90 days stage. The mean value observed were 2.2 to 47.3 ppm. The $\text{NO}_3\text{-N}$ content got enhanced markedly at 60 days stage, but at 90th day, it was reduced to very low values of 2 to 3 ppm.

iv) P levels: During the initial stages of crop growth, the application of P significantly depressed the $\text{NO}_3\text{-N}$ content but at advanced growth stages i.e., at 60 and 90 days stages, the presence of P was more conducive for $\text{NO}_3\text{-N}$ accumulation.

TABLE 11. EFFECT OF TREATMENTS ON $\text{NO}_3\text{-N}$ IN RHIZOSPHERE AND NON-RHIZOSPHERE REGIONS OF SORGHUM IN BLACK AND RED SOILS (ppm)

Treatments (1)	30 days (2)	60 days (3)	90 days (4)
Rh	41.8	47.3	2.9
NRh	25.1	26.9	3.1
St	29.6	26.7	2.7
NSt	37.3	47.5	3.3
S_1	42.2	42.4	2.2
S_2	24.7	47.3	3.7
P_0	39.9	41.9	2.7
P_{50}	27.0	32.3	3.3
SE	1.4	1.0	0.2
CD	4.0	2.8	0.7
N_0	34.7	36.9	2.7
N_{50}	32.1	38.5	4.0
N_{100}	33.5	35.8	2.3
SE	1.7	1.2	0.3
CD	4.9	3.4	0.8
Rh x St	54.1	33.1	2.4
Rh x NSt	29.6	20.7	3.3
NRh x St	5.1	61.8	2.9
NRh x NSt	45.0	32.8	3.3
Rh x S_1	49.4	31.8	2.1
Rh x S_2	34.3	22.0	3.6
NRh x S_1	35.1	53.1	2.3
NRh x S_2	15.0	41.4	3.9
Rh x P_0	50.2	31.3	2.4
Rh x P_{50}	33.5	22.5	3.3
NRh x P_0	29.6	52.4	3.0
NRh x P_{50}	20.6	42.1	3.2
St x S_1	33.3	48.6	1.6
St x S_2	25.9	46.3	3.7
NSt x S_1	51.1	36.3	2.8
NSt x S_2	23.4	17.1	3.8

Contd.,

(1)	(2)	(3)	(4)
St x P ₀	36.2	51.4	2.2
St x P ₅₀	23.0	43.5	3.1
NSt x P ₀	43.6	32.3	3.2
NSt x P ₅₀	31.0	21.2	3.5
S ₁ x P ₀	46.9	51.4	2.1
S ₁ x P ₅₀	37.6	43.5	2.3
S ₂ x P ₀	32.9	32.3	3.2
S ₂ x P ₅₀	16.5	21.2	4.2
SE	2.0	1.0	0.3
CD	5.6	2.8	0.9
Rh x N ₀	49.8	28.5	2.6
Rh x N ₅₀	33.2	24.8	3.8
Rh x N ₁₀₀	42.4	27.4	2.2
NRh x N ₀	19.6	45.3	2.7
NRh x N ₅₀	31.0	52.2	4.2
NRh x N ₁₀₀	24.6	44.3	2.4
St x N ₀	36.8	44.5	2.7
St x N ₅₀	20.4	50.2	2.8
St x N ₁₀₀	31.5	47.7	2.5
NSt x N ₀	32.6	29.4	2.6
NSt x N ₅₀	43.9	26.8	5.3
NSt x N ₁₀₀	35.4	24.0	2.1
S ₁ x N ₀	37.2	36.9	1.9
S ₁ x N ₅₀	45.7	45.7	2.7
S ₁ x N ₁₀₀	43.8	44.7	2.0
S ₂ x N ₀	32.2	36.9	2.4
S ₂ x N ₅₀	18.6	31.2	5.3
S ₂ x N ₁₀₀	23.1	27.0	2.5
N ₀ x P ₀	46.2	42.2	2.1
N ₀ x P ₅₀	23.2	31.5	3.2
N ₅₀ x P ₀	35.0	44.2	3.6
N ₅₀ x P ₅₀	29.3	32.8	4.4
N ₁₀₀ x P ₀	38.4	39.1	2.3
N ₁₀₀ x P ₅₀	28.5	32.5	2.2
SE	2.4	1.7	0.4
CD	6.9	4.8	1.12

v) N levels: The N levels brought about an appreciable difference in the $\text{NO}_3\text{-N}$ content for any given stage of crop growth. However it may be noted that the amount of $\text{NO}_3\text{-N}$ content of 34.7 ppm at 30 days got reduced to 2.7 ppm at 90th day indicating the unstable nature and greater losses associated with nitrate form of nitrogen.

Interaction effects

At 30th day, the interactions viz., St x S, St x N, St x Rh, S x N and P x N showed statistical significance. The important inferences emanating from the above interactions are: (i) sterilized condition made no difference in the red soil; (ii) in the absence of any added N, again the sterilized condition showed no differential influence; (iii) the sterilized condition caused enhanced $\text{NO}_3\text{-N}$ accumulation in the rhizosphere soil; (iv) in the absence of any added N, P addition diminished the $\text{NO}_3\text{-N}$ content; and (v) in the absence of any added N, both the soils recorded on par concentration of $\text{NO}_3\text{-N}$.

At 60th day, the various interaction viz., St x Rh, St x S, St x N, Rh x N and S x N revealed statistical significance. The salient points from the above interactions are: (i) irrespective of sterilized condition, the rhizosphere soil contained more $\text{NO}_3\text{-N}$ content than the non-

rhizosphere soil; (ii) under sterilized condition greater accumulation of $\text{NO}_3\text{-N}$ content was favoured in both the soil types; (iii) whether N was added or not, the sterilized condition caused greater accumulation; (iv) for any level of N, the rhizosphere soil carried higher amounts of $\text{NO}_3\text{-N}$ content; and (v) in the absence of any added N, the red soil was associated with more $\text{NO}_3\text{-N}$ and the effect was found to be reversed with the addition of N.

At 90th day, S x N interaction alone revealed statistical significance. At N_0 and N_{50} levels, more $\text{NO}_3\text{-N}$ accumulated in the red soil and the difference got nullified at N_{100} level between the two soil types.

4.5.2. Effect on P transformation (Fig. 7)

4.5.2.1. Saloid-bound P (Table 12)

Individual effects

i) Rhizosphere: The mean values for this main effect ranged from 3.13 to 4.84 ppm for rhizosphere soil and from 2.59 to 9.65 ppm for non-rhizosphere region. The non rhizosphere soil relatively contained more saloid-bound P than the rhizosphere soil the trend was reversed at 90th day.

TABLE 12. EFFECT OF TREATMENTS ON SALOID-BOUND P IN RHIZOSPHERE AND NON-RHIZOSPHERE REGIONS OF SORGHUM IN BLACK AND RED SOILS (ppm)

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Treatments (1)	30 days (2)	60 days (3)	90 days (4)
Rh	4.84	4.34	3.13
NRh	9.65	4.06	2.59
St	7.95	4.58	2.60
NSt	6.54	3.82	3.12
S ₁	5.20	3.17	2.19
S ₂	9.28	5.23	3.53
P ₀	6.80	3.61	2.83
P ₅₀	7.69	4.79	2.89
SE	0.34	0.04	0.017
CD	0.97	0.11	0.049
N ₀	7.93	3.98	2.68
N ₅₀	7.22	4.42	2.88
N ₁₀₀	6.58	4.20	3.01
SE	0.42	0.048	0.021
CD	1.19	0.14	0.060
Rh x St	4.98	4.72	2.63
Rh x NSt	4.69	3.96	3.62
NRh x St	10.92	3.67	2.56
NRh x NSt	8.38	4.45	2.62
Rh x S ₁	3.94	3.29	2.47
Rh x S ₂	5.74	5.39	3.79
NRh x S ₁	6.47	3.04	1.91
NRh x S ₂	12.83	5.08	3.27
Rh x P ₀	4.27	3.77	3.09
Rh x P ₅₀	5.40	4.91	3.17
NRh x P ₀	9.33	3.45	2.58
NRh x P ₅₀	9.97	4.66	2.60
St x S ₁	3.82	2.41	1.92
St x S ₂	12.08	5.25	3.27
NSt x S ₁	6.59	3.92	2.45
NSt x S ₂	6.49	5.25	3.79

(1)	(2)	(3)	(4)
St x P ₀	6.08	2.64	2.52
St x P ₅₀	9.82	4.99	2.67
NSt x P ₀	7.51	4.58	3.14
NSt x P ₅₀	5.56	4.58	3.10
S ₁ x P ₀	4.63	2.47	1.76
S ₁ x P ₅₀	5.78	3.86	2.62
S ₂ x P ₀	8.97	4.75	3.91
S ₂ x P ₅₀	9.60	5.72	3.15
SE	0.48	0.056	0.024
CD	0.37	0.14	0.069
Rh x N ₀	5.43	4.16	2.91
Rh x N ₅₀	4.49	4.60	3.17
Rh x N ₁₀₀	4.59	4.27	3.31
NRh x N ₀	10.43	3.80	2.45
NRh x N ₅₀	9.94	4.25	2.60
NRh x N ₁₀₀	8.57	4.12	2.71
St x N ₀	8.51	3.59	2.39
St x N ₅₀	8.45	4.22	2.64
St x N ₁₀₀	6.89	3.64	2.76
NSt x N ₀	7.35	4.37	2.98
NSt x N ₅₀	5.98	4.62	3.13
NSt x N ₁₀₀	6.28	4.76	3.26
S ₁ x N ₀	5.42	3.09	2.02
S ₁ x N ₅₀	5.41	3.32	2.25
S ₁ x N ₁₀₀	4.78	3.09	2.30
S ₂ x N ₀	10.44	4.88	3.35
S ₂ x N ₅₀	9.03	5.52	3.52
S ₂ x N ₁₀₀	8.39	5.30	3.72
N ₀ x P ₀	7.00	3.23	2.66
N ₀ x P ₅₀	8.86	4.73	2.71
N ₅₀ x P ₀	6.47	3.90	2.88
N ₅₀ x P ₅₀	7.97	4.95	2.89
N ₁₀₀ x P ₀	6.92	3.71	2.96
N ₁₀₀ x P ₅₀	6.24	4.68	3.06
SE	0.59	0.074	0.03
CD	1.68	0.19	0.08

ii) Sterilization: The mean value for the main effect ranged from 2.60 to 7.95 ppm. The sterilization process tended to enhance saloid-bound P. At 90th day, the non-sterilized condition showed higher amounts of saloid-bound P.

iii) Soil types: The amount of saloid-bound P ranged from 2.19 to 9.28 ppm and during all the three stages, the red soil was associated with significantly higher amounts of saloid-bound P.

iv) P levels: The mean value for this main effect ranged from 2.83 ppm to 7.69 ppm. Phosphrous application enhanced the saloid-P contnt in the soil at 60 days of crop growth period.

v) N levels: During the initial stages, much of the phosphorus remained in solution as evidenced by the control recording more saloid-bound P over those which received P application. But this effect was reversed during the subsequent stages owing to better opportunities for the reactions involving P. At 90th day, increasing N addition was associated with increased saloid-bound P.

Interaction effects

At 30th day, the interactions St x Rh, St x S and St x P were found to be statistically significant. The

important inferences deduced are: (i) the sterilization effect in increasing the saloid-bound P was confined to the non-rhizosphere soil; (ii) the sterilized condition enhanced the saloid-bound P in the red soil while the reverse was true in the black soil; and (iii) the effect of sterilization was more pronounced in the presence of added P.

At 60th day, St x S, St x P, S x P, S x N and P x N interactions were associated with statistical significance indicating the following important inferences: (i) the effect of sterilization in diminishing the saloid-bound P was confined to black soil; (ii) under non-sterilized condition both the P levels recorded on par content of saloid-bound P; (iii) whether it be red soil or black soil, the addition of P enhanced the saloid-bound P; (iv) in both the soil types, N₅₀ level was associated with enhanced saloid-bound P over other N levels; and (v) for any given level of N, added P favoured greater accumulation of saloid-bound P.

At 90th day, the interactions viz., St x Rh, St x P, S x P and S x N were associated with statistical significance. These interactions revealed the following inferences: (i) both under sterilized and non-sterilized conditions of the soil, the rhizosphere soil carried more saloid-bound P; (ii) the addition of P in enhancing the saloid-bound P was confined to the sterilized condition;

(iii) the tendency of P addition to enhance the saloid-bound P was more pronounced in the black soil and the effect was reversed in the red soil; and (iv) for any given level of N, the red soil was associated with more saloid-bound P over the black soil.

4.5.2.2. Aluminium phosphate (Al-P); (Table 13)

Individual effects

i) Rhizosphere: The mean value of Al-P for this effect ranged from 3.50 to 4.63 ppm. At all the three stages of crop growth, the rhizosphere soil accounted for more Al-P than non-rhizosphere soil.

ii) Sterilization: The mean value of Al-P for this main effect fell within the range of 3.40 to 4.49 ppm and at all the three stages of crop growth, the sterilized condition favoured more Al-P content than the normal soil.

iii) Soil types: The mean value of Al-P for this main effect remained within the range of 3.15 to 4.93 ppm. During all the three stages, the black soil was associated with greater amounts of Al-P than the red soil.

iv) P levels: The mean value showed a range of 3.49 to 4.31 ppm. Though the added P had no effect at 30 days of crop growth, at 90 days of crop growth P application increased the Al-P content in the soil. At 60 days, P_{50} and P_{100} levels were on par.

TABLE 13. EFFECT OF TREATMENTS ON Al-P IN RHIZOSPHERE AND NON-RHIZOSPHERE REGIONS OF SORGHUM IN BLACK AND RED SOILS (ppm)

Treatments (1)	30 days (2)	60 days (3)	90 days (4)
Rh	4.63	4.38	3.67
NRh	3.90	4.14	3.50
St	4.49	4.31	3.76
NSt	4.03	4.21	3.40
S ₁	4.85	4.93	4.01
S ₂	3.67	3.59	3.15
P ₀	4.31	4.24	3.49
P ₅₀	4.21	4.28	3.68
SE	0.06	0.04	0.02
CD	0.17	0.11	0.05
N ₀	4.67	4.31	3.70
N ₅₀	4.22	4.17	3.47
N ₁₀₀	3.89	4.30	3.57
SE	0.07	0.05	0.02
CD	0.20	0.14	0.06
Rh x St	4.69	4.45	3.84
Rh x NSt	4.57	4.30	3.50
NRh x St	4.30	4.16	3.69
NRh x NSt	3.49	4.12	3.30
Rh x S ₁	5.23	5.06	4.08
Rh x S ₂	4.02	3.69	3.25
NRh x S ₁	4.48	4.80	3.94
NRh x S ₂	3.31	3.48	3.06
Rh x P ₀	4.62	4.38	3.58
Rh x P ₅₀	4.63	4.38	3.76
NRh x P ₀	4.00	4.10	3.40
NRh x P ₅₀	3.79	4.18	3.60
St x S ₁	5.13	4.92	3.99
St x S ₂	3.85	3.69	3.54
NSt x S ₁	4.57	4.94	4.04
NSt x S ₂	3.49	3.48	2.77

Contd.,

(1)	(2)	(3)	(4)
St x P ₀	4.47	4.25	3.79
St x P ₅₀	4.52	4.36	3.74
NSt x P ₀	4.15	4.22	3.19
NSt x P ₅₀	3.91	4.21	3.61
S ₁ x P ₀	5.11	4.96	3.88
S ₁ x P ₅₀	4.60	4.90	4.14
S ₂ x P ₀	3.51	3.52	3.09
S ₂ x P ₅₀	3.82	3.66	3.22
SE	0.08	0.04	0.03
CD	0.23	0.11	0.07
Rh x N ₀	5.04	4.40	3.76
Rh x N ₅₀	4.61	4.32	3.58
Rh x N ₁₀₀	4.23	4.42	3.66
NRh x N ₀	4.31	4.21	3.64
NRh x N ₅₀	3.82	4.03	3.37
NRh x N ₁₀₀	3.55	4.17	3.49
St x N ₀	4.92	4.64	4.15
St x N ₅₀	4.30	4.18	3.65
St x N ₁₀₀	4.25	4.09	3.49
NSt x N ₀	4.43	3.97	3.25
NSt x N ₅₀	4.13	4.17	3.30
NSt x N ₁₀₀	3.53	4.50	3.65
S ₁ x N ₀	5.82	5.29	4.33
S ₁ x N ₅₀	4.64	4.65	3.76
S ₁ x N ₁₀₀	4.10	4.85	3.94
S ₂ x N ₀	3.53	3.32	3.07
S ₂ x N ₅₀	3.79	3.70	3.18
S ₂ x N ₁₀₀	3.68	3.74	3.21
N ₀ x P ₀	4.74	4.43	3.53
N ₀ x P ₅₀	4.61	4.18	3.88
N ₅₀ x P ₀	4.14	4.08	3.41
N ₅₀ x P ₅₀	4.30	4.27	3.53
N ₁₀₀ x P ₀	4.06	4.20	3.52
N ₁₀₀ x P ₅₀	3.72	4.39	3.63
SE	0.10	0.07	0.03
CD	0.29	0.19	0.09

v) N levels: The mean value ranged from 3.47 to 4.67 ppm and nitrogen additions tended to diminish the Al-P content at 30 and 90 days of crop growth stage while at 60 days N_0 and N_{100} levels and N_{100} and N_{50} levels were on par.

Interaction effects

At 30th day, St x Rh, St x N, and S x N interactions indicated statistical significance. The salient points deduced are: (i) the sterilized condition enhanced Al-P only in the non-rhizosphere soil; (ii) the effect of sterilization in enhancing Al-P was observed under all levels of N; and (iii) the effect of N in diminishing the Al-P content was confined to the black soil.

At 60th day, several interactions such as St x S, S x N and P x N were associated with statistical significance. The salient points of inferences are: (i) under sterilized condition enhancement of Al-P was confined to the red soil; (ii) at all levels of N, the red soil registered more Al-P than the black soil; (iii) in the absence of any added N, addition of P favoured enhanced accumulation of Al-P fraction but this effect got vanished on the application of N.

At 90th day again, several interactions were significant and the following important inferences were drawn:

(i) while the sterilized condition made no difference in respect of the black soil, it caused a significant enhancement in the red soil; (ii) the influence of P addition in enhancing Al-P content occurred only under non-sterilized condition; (iii) the effect of sterilization enhanced Al-P content only under N_0 and N_{50} levels (iv) the influence of P addition on Al-P occurred irrespective of soil types; (v) under all levels of N, the black soil contained more Al-P content than the red soil; and (vi) the P addition enhanced Al-P content under all levels of N.

4.5.2.3. Iron phosphate (Fe-P) (Table 14)

Individual effects

i) Rhizosphere: The mean value of Fe-P ranged from 32.3 to 43.5 ppm. The concentration of Fe-P during the earlier stages in rhizosphere and non-rhizosphere soils were on par but at 90th day, the accumulation of Fe-P in the rhizosphere soil was significantly higher than in the non-rhizosphere soil.

ii) Sterilization: The mean value of Fe-P was found to range from 30.0 to 46.7 ppm. The process of sterilization enhanced the Fe-P content and this effect continued to remain during the subsequent stages as well.

iii) Soil types: The mean value of Fe-P ranged from 29.2 to 51.1 ppm for this main effect and the red soil contained more Fe-P during all the three stages of crop growth.

iv) P levels: The mean value for this main effect ranged from 31.6 to 43.7 ppm. The addition of P reflected in enhancement of Fe-P content in the soil during 60 and 90 days of crop growth but at 30th day, such a significant difference was not observed.

v) N levels: The mean value fell within the range of 28.6 to 44.3 ppm. N_{100} level decreased the Fe-P content at 30 and 60 days of crop growth but at 90th day N_{100} and N_0 levels were on par.

Interaction effects

At 30th day, the interactions viz., St x S, St x P, St x N, S x P, S x N and P x N were associated with significant effects. The important inferences drawn from the above interaction effects are; (i) while the sterilized condition could account for enhanced Fe-P content in the red soil, the reverse was the case in the black soil; (ii) the addition of P in enhancing Fe-P was confined to the sterilized condition; (iii) At all levels of N, the

TABLE 14. EFFECT OF TREATMENTS ON Fe-P IN RHIZOSPHERE AND NON-RHIZOSPHERE REGIONS OF GORGNUM IN BLACK AND RED SOILS (ppm)

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Treatments (1)	30 days (2)	60 days (3)	90 days (4)
Rh	43.5	40.7	34.2
NRh	42.4	39.5	32.3
St	46.7	43.9	30.0
NSt	39.2	36.3	36.5
S ₁	34.8	32.6	29.2
S ₂	51.1	47.6	37.2
P ₀	42.1	38.7	31.6
P ₅₀	43.7	41.5	34.8
SE	0.7	0.6	0.4
CD	2.0	1.8	1.3
N ₀	44.1	40.5	35.1
N ₅₀	44.3	41.6	28.6
N ₁₀₀	40.3	38.1	35.9
SE	0.8	0.8	0.5
CD	2.4	2.2	1.5
Rh x St	47.2	44.6	37.0
Rh x NSt	39.7	36.7	31.4
NRh x St	46.2	43.1	36.0
NRh x NSt	38.6	35.9	28.6
Rh x S ₁	35.4	33.1	30.2
Rh x S ₂	51.6	48.2	38.1
NRh x S ₁	34.2	32.0	28.2
NRh x S ₂	50.6	47.1	36.3
Rh x P ₀	42.7	39.6	32.5
Rh x P ₅₀	44.2	41.7	35.8
NRh x P ₀	41.6	37.8	30.8
NRh x P ₅₀	43.2	41.3	33.8
St x S ₁	32.8	30.3	34.4
St x S ₂	60.6	57.4	38.5
NSt x S ₁	36.8	34.8	28.9
NSt x S ₂	41.6	37.8	31.1

Contd.,

(1)	(2)	(3)	(4)
St x P ₀	44.5	41.8	34.4
St x P ₅₀	48.9	45.9	38.5
NSt x P ₀	39.8	35.6	28.9
NSt x P ₅₀	38.5	37.1	31.1
S ₁ x P ₀	37.6	34.7	29.2
S ₁ x P ₅₀	31.9	30.4	29.2
S ₂ x P ₀	46.6	42.7	34.1
S ₂ x P ₅₀	55.5	52.6	40.4
SE	0.97	0.9	0.6
CD	2.8	2.5	1.8
Rh x N ₀	44.9	41.4	36.2
Rh x N ₅₀	45.1	42.4	29.4
Rh x N ₁₀₀	40.4	38.2	36.9
NRh x N ₀	43.4	39.6	34.0
NRh x N ₅₀	43.6	40.9	27.9
NRh x N ₁₀₀	40.3	38.1	34.9
St x N ₀	44.2	41.3	36.4
St x N ₅₀	49.4	46.7	33.4
St x N ₁₀₀	46.4	43.5	39.6
NSt x N ₀	44.0	39.7	33.8
NSt x N ₅₀	39.2	36.6	23.8
NSt x N ₁₀₀	34.3	32.7	32.2
S ₁ x N ₀	42.6	39.9	33.8
S ₁ x N ₅₀	34.2	32.2	22.9
S ₁ x N ₁₀₀	27.5	25.6	30.9
S ₂ x N ₀	45.7	41.2	36.4
S ₂ x N ₅₀	54.4	51.1	34.4
S ₂ x N ₁₀₀	53.1	50.6	40.9
N ₀ x P ₀	45.0	40.1	32.5
N ₀ x P ₅₀	43.3	40.9	37.7
N ₅₀ x P ₀	38.5	35.4	27.2
N ₅₀ x P ₅₀	50.2	47.9	30.0
N ₁₀₀ x P ₀	42.9	40.7	35.2
N ₁₀₀ x P ₅₀	37.7	35.6	36.6
SE	1.2	1.1	0.8
CD	3.4	3.1	2.2

sterilized condition favoured greater accumulation of Fe-P content than the non-sterilized condition; (iv) at both the P levels and at all levels of N, the red soil had more Fe-P than the black soil; and (v) in the absence of N addition, P application produced no appreciable effect on Fe-P content in the soil; but at N_{50} level P_{50} level had a significant effect; however at N_{100} level, absence of P recorded more Fe-P content than P application.

At 60th day, the interactions viz., St x S, St x N, S x P, S x N and P x N revealed statistical significance. The important inferences drawn are: (i) the sterilized condition increased Fe-P content in the red soil and decreased the same in the black soil; (ii) under sterilized condition enhancement of Fe-P content occurred at all levels of N; (iii) at P_{50} level and at N_{50} and N_{100} levels more Fe-P content was observed in the red soil than in the black soil and (iv) N and P combined addition was found to be less conducive for Fe-P accumulation.

At 90th day, the interactions viz., St x S, St x N, S x P, S x N and P x N were significant. The important inferences drawn are: (i) the sterilized condition brought about significant difference in Fe-P content in the red soil; (ii) under all levels of N the sterilized condition was better than non-sterilized condition; (iii) the effect of P

addition in enhancing Fe-P content was observed only in the red soil; (iv) at all levels of N, the red soil recorded more Fe-P content than the black soil; and v) irrespective of N level, P addition favoured accumulation of Fe-P content in the soil.

4.5.2.4. Calcium phosphate (Ca-P) (Table 15)

Individual effects

i) Rhizosphere: The mean value for the main effect fell within the range of 4.16 to 6.39 ppm at all stages of crop growth. The rhizosphere soil contained significantly higher amount of Ca-P than the non-rhizosphere soil.

ii) Sterilization: The mean value for this main effect ranged from 3.87 to 6.90 ppm. At all the three stages of crop growth, the sterilized condition brought about a significant depression on Ca-P content in the soil.

iii) Soil types: The mean value remained within the range of 2.93 to 7.56 ppm. During all the three stages, the black soil was associated with greater amount of Ca-P content than the red soil.

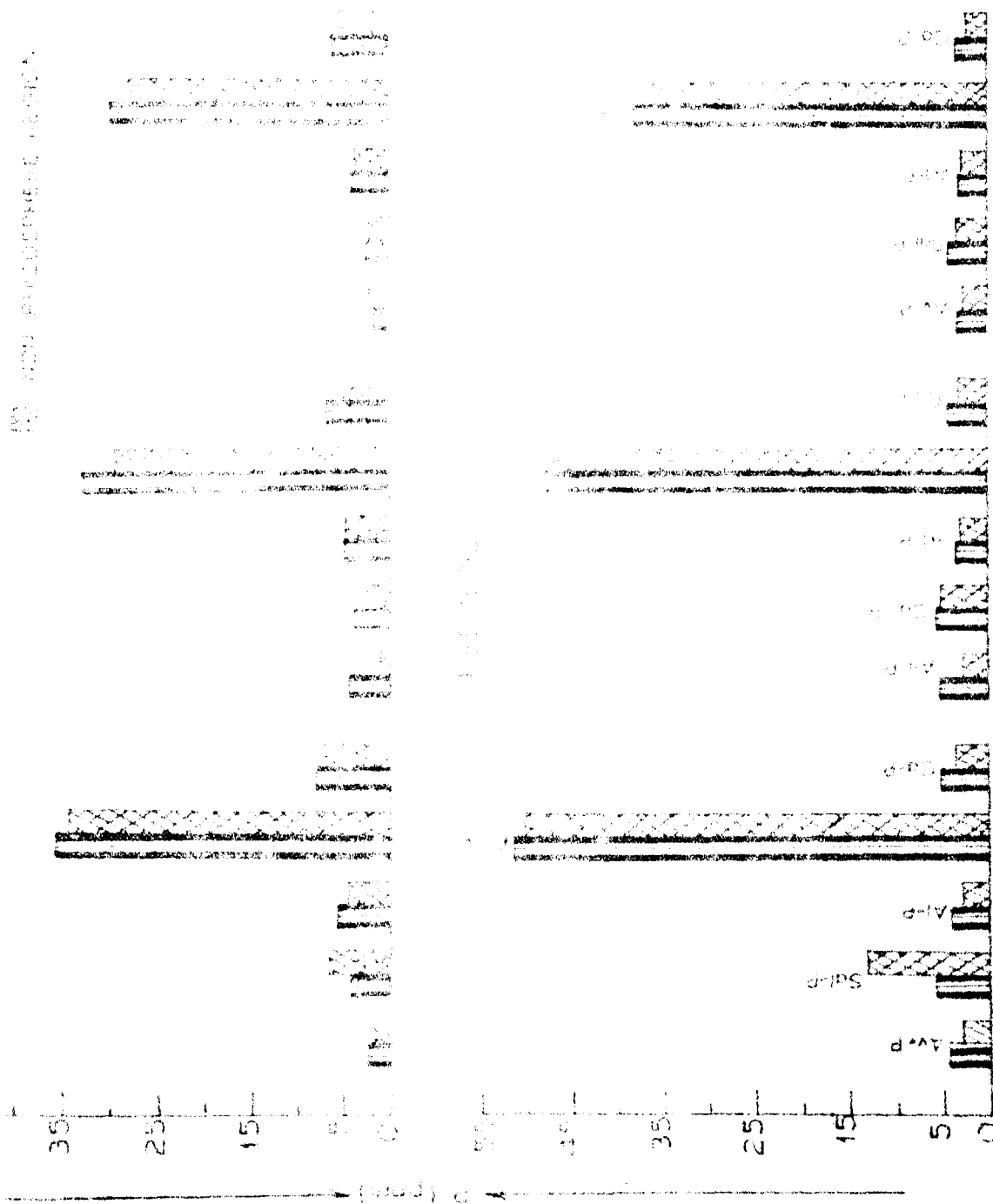
iv) P levels: The mean values ranged from 3.77 to 6.37 ppm. P application enhanced the Ca-P content at all the three stages of crop growth.

TABLE 15. EFFECT OF TREATMENTS ON Ca-P IN RHIZOSPHERE AND NON-RHIZOSPHERE REGIONS OF SORGHUM IN BLACK AND RED SOILS (ppm)

Treatments (1)	30 days (2)	60 days (3)	90 days (4)
Rh	6.39	5.24	4.38
NRh	5.46	5.00	4.16
St	4.94	4.40	3.87
NSt	6.90	5.81	4.68
S ₁	7.56	6.58	5.61
S ₂	4.28	3.63	2.93
P ₀	5.47	4.73	3.77
P ₅₀	6.37	5.48	4.77
SE	0.06	0.04	0.04
CD	0.16	0.11	0.11
N ₀	6.15	5.15	4.43
N ₅₀	5.49	4.95	4.14
N ₁₀₀	6.13	5.22	4.25
SE	0.07	0.05	0.05
CD	0.20	0.15	0.14
Rh x St	5.24	4.53	4.00
Rh x NSt	7.54	5.95	4.78
NRh x St	4.65	4.27	3.75
NRh x NSt	6.27	5.67	4.57
Rh x S ₁	7.93	6.75	5.73
Rh x S ₂	4.85	3.72	3.03
NRh x S ₁	7.20	6.40	5.49
NRh x S ₂	3.71	3.54	2.84
Rh x P ₀	5.90	4.83	3.91
Rh x P ₅₀	6.88	5.64	4.85
NRh x P ₀	5.05	4.63	3.63
NRh x P ₅₀	5.87	5.32	4.69
St x S ₁	7.04	6.22	5.52
St x S ₂	2.84	2.57	2.21
NSt x S ₁	8.09	6.93	5.70
NSt x S ₂	5.72	4.69	3.65

Contd.,

(1)	(2)	(3)	(4)
St x P ₀	4.09	3.66	2.98
St x P ₅₀	5.79	5.14	4.76
NSSt x P ₀	6.85	5.81	4.57
NSSt x P ₅₀	6.95	5.82	4.78
S ₁ x P ₀	6.32	5.69	4.57
S ₁ x P ₅₀	8.81	7.47	6.65
S ₂ x P ₀	4.62	3.78	2.97
S ₂ x P ₅₀	3.94	3.49	2.89
SE	0.08	0.06	0.06
CD	0.16	0.17	0.16
Rh x N ₀	6.58	5.28	4.54
Rh x N ₅₀	5.95	5.02	4.30
Rh x N ₁₀₀	6.63	5.41	4.30
NRh x N ₀	5.72	5.01	4.32
NRh x N ₅₀	5.02	4.89	3.98
NRh x N ₁₀₀	5.63	5.02	4.19
St x N ₀	5.09	4.63	4.18
St x N ₅₀	5.11	4.71	4.98
St x N ₁₀₀	4.62	3.86	3.35
NSSt x N ₀	7.20	5.67	4.68
NSSt x N ₅₀	5.86	5.20	4.21
NSSt x N ₁₀₀	7.65	6.57	5.15
S ₁ x N ₀	7.50	6.51	5.38
S ₁ x N ₅₀	7.21	6.51	5.49
S ₁ x N ₁₀₀	7.98	6.72	5.96
S ₂ x N ₀	4.79	3.79	3.47
S ₂ x N ₅₀	3.76	3.40	2.80
S ₂ x N ₁₀₀	4.28	3.71	2.53
N ₀ x P ₀	5.82	4.73	3.85
N ₀ x P ₅₀	6.47	5.57	5.00
N ₅₀ x P ₀	5.06	4.67	3.85
N ₅₀ x P ₅₀	5.92	5.23	4.42
N ₁₀₀ x P ₀	5.54	4.79	3.61
N ₁₀₀ x P ₅₀	6.73	5.64	4.88
SE	0.10	0.07	0.07
CD	0.28	0.21	0.20



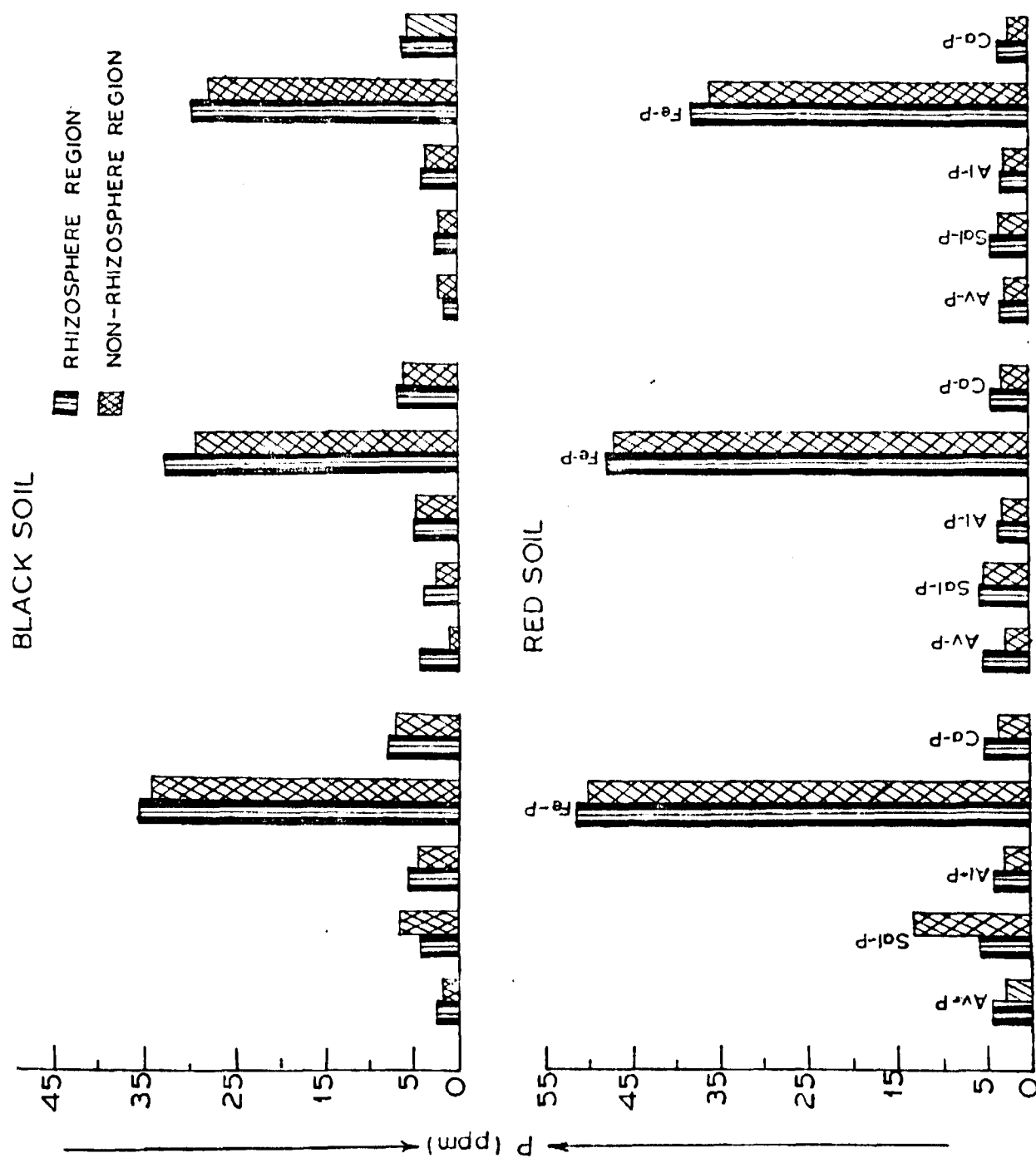


FIG.7 DIFFERENT FORMS OF P AS INFLUENCED BY RHIZOSPHERE AND SOIL TYPES AT DIFFERENT STAGES OF CROP GROWTH

v) N levels: The mean value ranged from 4.14 to 6.15 ppm. At all the three stages of crop growth N_{50} level significantly caused depression of Ca-P content in the soil at 30 and 60 days of crop growth while at 90 days N_{100} and N_{50} levels were on par.

Interaction effects

At 30th day, the interactions viz., St x Rh, St x S, St x P, St x N, R x S, S x P, S x N and P x N showed statistical significance. The salient inferences deduced are: (i) the sterilized condition caused depression in Ca-P content both in rhizosphere and non-rhizosphere soils; (ii) only under sterilized condition, P fertilization had positive effect on Ca-P content; and (iii) with no P application, N addition at 50 and 100 kg level resulted in the reduction of Ca-P content in the soil.

At 60th day, the interactions viz., St x S, St x P, St x N, S x P and S x N attained statistical significance. The important inferences deduced are: (i) addition of P enhanced Ca-P content only under sterilized condition; and (ii) addition of P enhanced the Ca-P content only in the black soil.

At 90th day, the interactions viz., St x S, St x P, St x N, S x P, S x N and P x N showed statistical significance. The salient inferences deduced are: (i) without addition of P, the sterilized condition caused a marked decrease in Ca-P content, but at added levels of P, the difference was meagre; and (ii) as regards the effect of N fertilization on Ca-P content in two types of soils, the black soil had positive effect while the red soil had opposite effect on Ca-P content.

4.5.3. Effect on K transformation (Fig. 8)

4.5.3.1. Water soluble-K (Table 16)

Individual effects

i) Rhizosphere: The mean value for the main effect ranged from 20.1 to 67.6 ppm. The rhizosphere soil contained higher concentration of water soluble-K than the non-rhizosphere soil at all the three stages of crop growth.

ii) Sterilization: The mean value of water soluble K content remained within the range of 27.3 to 62.7 ppm. Under sterilized condition of the soil the water soluble-K content was increased upto 30 days of crop growth, but at 90 days stage, the trend got reversed. At 60th day of crop growth, the effect of sterilization was on par with the non-sterilized condition.

TABLE 16. EFFECT OF TREATMENTS ON WATER SOLUBLE - K IN RHIZOSPHERE AND NON-RHIZOSPHERE REGIONS OF SORGHUM IN BLACK AND RED SOILS (ppm)

Treatments (1)	30 days (2)	60 days (3)	90 days (4)
Rh	67.6	48.1	49.2
NRh	44.3	26.4	20.1
St	62.7	38.2	27.3
NSt	49.2	36.4	42.0
S ₁	50.4	30.2	29.2
S ₂	61.5	44.3	40.1
P ₀	58.7	37.3	35.1
P ₅₀	53.2	37.2	34.2
SE	1.7	1.2	2.7
CD	4.8	3.4	7.5
N ₀	56.7	39.0	34.3
N ₅₀	51.0	39.7	36.3
N ₁₀₀	60.2	33.0	33.3
SE	2.1	1.5	3.2
CD	5.8	4.2	9.2
Rh x St	66.6	50.8	36.1
Rh x NSt	66.6	45.3	62.3
NRh x St	56.8	25.5	18.5
NRh x NSt	31.8	27.4	21.8
Rh x S ₁	63.2	38.0	41.6
Rh x S ₂	72.0	58.2	56.8
NRh x S ₁	37.7	22.5	16.8
NRh x S ₂	51.0	30.4	23.5
Rh x P ₀	68.6	47.3	50.4
Rh x P ₅₀	66.5	48.9	48.0
NRh x P ₀	48.8	27.3	19.9
NRh x P ₅₀	39.8	25.6	20.4
St x S ₁	49.9	29.3	21.7
St x S ₂	75.5	47.0	32.9
NSt x S ₁	51.0	31.2	36.7
NSt x S ₂	47.5	41.5	47.3

Contd.,

(1)	(2)	(3)	(4)
St x P ₀	61.4	33.9	26.0
St x P ₅₀	64.0	42.5	28.5
NSt x P ₀	56.1	40.7	44.3
NSt x P ₅₀	42.3	32.0	39.8
S ₁ x P ₀	49.8	34.2	30.7
S ₁ x P ₅₀	51.1	26.3	27.8
S ₂ x P ₀	67.7	40.4	39.6
S ₂ x P ₅₀	55.3	48.2	40.6
SE	2.4	1.7	3.7
CD	6.7	4.8	10.7
Rh x N ₀	69.4	46.1	47.4
Rh x N ₅₀	61.3	52.6	51.4
Rh x N ₁₀₀	72.0	45.5	48.8
NRh x N ₀	43.9	31.9	21.3
NRh x N ₅₀	40.8	26.8	21.2
NRh x N ₁₀₀	48.3	20.6	17.9
St x N ₀	62.6	37.7	26.0
St x N ₅₀	56.4	45.6	31.8
St x N ₁₀₀	69.1	31.2	24.1
NSt x N ₀	50.8	40.4	42.7
NSt x N ₅₀	45.7	33.8	40.9
NSt x N ₁₀₀	51.2	34.9	42.5
S ₁ x N ₀	45.1	31.9	27.8
S ₁ x N ₅₀	48.2	29.1	30.1
S ₁ x N ₁₀₀	58.0	29.6	29.8
S ₂ x N ₀	68.3	46.1	40.9
S ₂ x N ₅₀	53.9	50.3	42.5
S ₂ x N ₁₀₀	62.3	36.4	36.9
N ₀ x P ₀	62.0	40.1	34.4
N ₀ x P ₅₀	51.4	37.9	34.3
N ₅₀ x P ₀	55.1	38.1	38.3
N ₅₀ x P ₅₀	46.9	41.4	34.4
N ₁₀₀ x P ₀	59.1	33.7	32.8
N ₁₀₀ x P ₅₀	61.3	32.4	33.9
SE	2.9	2.1	4.6
CD	8.2	5.9	13.1

iii) Soil types: The mean water soluble K content ranged from 29.2 to 61.5 ppm. During all the three stages of crop growth, the red soil was associated with greater amount of water soluble-K content than the black soil.

iv) P levels: The mean value for the main effect ranged from 36.2 ppm to 58.7 ppm. Application of P at 50 kg level reduced water soluble-K content at 30 days of crop growth while at 60 and 90 days of crop growth, P_0 and P_{50} levels were on par.

v) N levels: The mean value for the main effect ranged from 33.0 to 60.2 ppm. N application either at 50 or 100 kg level showed no beneficial effect in enhancing water soluble-K content at all the three stages of crop growth.

Interaction effects

At 30th day, the interactions viz., St x Rh, St x S, St x P, S x P and S x N were found to be significant. The salient points deduced are: (i) increased water soluble-K content was observed in the non-rhizosphere soil under sterilized condition; (ii) only under sterilized condition, the red soil had more water soluble-K content; (iii) P addition had no effect under sterilized condition; (iv) P application exhibited no difference in accumulating water soluble-K content but with no P application, the red soil recorded more water soluble-K content than the black soil.

At 60th day, the interactions viz., St x Rh, St x S, St x P, St x N, Rh x S, Rh x N, S x P and S x N showed statistical significance. The important conclusions drawn are: (i) under sterilized condition of the soil positive influence on water soluble-K content was recorded in the rhizosphere soil; (ii) in the red soil also, P addition tended to increase the water soluble-K content in the soil; (iii) the reduction of water soluble-K content due to N addition was confined to the non-rhizosphere region; and (iv) in the red soil positive effect was observed due to P application and negative effect in the black soil.

At 90th day, the interaction St x Rh showed significance. The conclusion drawn is that under sterilized condition of the soil marked decrease in water soluble-K content occurred in the rhizosphere soil.

4.5.3.2. $N.N.NH_4OAc$ extractable-K or exchangeable-K content (Table 17)

Individual effects

i) Rhizosphere: The mean value for this effect ranged from 206 to 432 ppm. At all the three stages of crop growth, the rhizosphere soil showed higher amount of exchangeable-K content than the non-rhizosphere soil.

ii) Sterilization: The mean value for this main effect ranged from 245 to 340 ppm. Under sterilized condition of the soil exchangeable-K content was increased at 60 and 90 days of crop growth, while at 30 days reverse was the case.

iii) Soil types: The mean value remained within the range of 163 to 434 ppm. The red soil showed higher amount of exchangeable-K than the black soil at 30 days of crop growth, while at later stages, the trend was reversed.

iv) P levels: The mean value for this main effect ranged from 264 to 326 ppm. P application decreased the exchangeable-K content at 90 days of crop growth while at 30 and 60 days of crop growth P_0 and P_{50} levels were on par.

v) N levels: The mean value for this main effect ranged from 247 to 327 ppm. Application of N at two levels did not increase the exchangeable-K content at all the three stages of crop growth.

Interaction effects

At 30th day, the interactions viz., St x Rh, St x S, St x P, Rh x S and S x N showed statistical significance. The salient points of inferences drawn are: (i) the sterilized

TABLE 17. EFFECT OF TREATMENTS ON EXCHANGEABLE-K IN RHIZOSPHERE
AND NON-RHIZOSPHERE REGIONS OF SORGHUM IN BLACK AND RED
SOILS (ppm)

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Treatments (1)	30 days (2)	60 days (3)	90 days (4)
Rh	432	350	297
NRh	206	223	235
St	299	298	287
NSt	340	276	245
S ₁	434	394	370
S ₂	204	180	163
P ₀	313	291	269
P ₅₀	326	282	264
SE	6.0	6.0	5.4
CD	17.0	17.0	15.3
N ₀	314	297	268
N ₅₀	316	278	247
N ₁₀₀	327	286	284
SE	7.3	7.3	6.6
CD	21.0	21.0	18.8
Rh x St	397	369	311
Rh x NSt	467	332	283
NRh x St	201	226	263
NRh x NSt	211	220	207
Rh x S ₁	593	459	398
Rh x S ₂	271	241	197
NRh x S ₁	276	328	343
NRh x S ₂	137	119	128
Rh x P ₀	420	367	310
Rh x P ₅₀	444	334	285
NRh x P ₀	206	216	228
NRh x P ₅₀	207	231	243
St x S ₁	403	406	391
St x S ₂	195	189	183
NSt x S ₁	466	381	349
NSt x S ₂	213	171	142

Contd.,

(1)	(2)	(3)	(4)
St x P ₀	281	298	289
St x P ₅₀	316	297	285
NSSt x P ₀	344	284	248
NSSt x P ₅₀	335	268	242
S ₁ x P ₀	425	416	386
S ₁ x P ₅₀	443	371	354
S ₂ x P ₀	200	166	151
S ₂ x P ₅₀	208	194	174
SE	8.4	8.4	7.6
CD	24.0	24.0	21.7
Rh x N ₀	432	371	308
Rh x N ₅₀	422	333	274
Rh x N ₁₀₀	442	347	311
NRh x N ₀	196	223	227
NRh x N ₅₀	211	223	221
NRh x N ₁₀₀	212	225	258
St x N ₀	286	318	285
St x N ₅₀	302	278	258
St x N ₁₀₀	308	296	319
NSSt x N ₀	342	275	250
NSSt x N ₅₀	331	277	237
NSSt x N ₁₀₀	346	275	250
S ₁ x N ₀	390	409	361
S ₁ x N ₅₀	440	363	338
S ₁ x N ₁₀₀	473	408	412
S ₂ x N ₀	238	185	174
S ₂ x N ₅₀	193	192	157
S ₂ x N ₁₀₀	182	163	157
N ₀ x P ₀	311	314	284
N ₀ x P ₅₀	317	280	251
N ₅₀ x P ₀	316	260	242
N ₅₀ x P ₅₀	317	296	253
N ₁₀₀ x P ₀	311	300	281
N ₁₀₀ x P ₅₀	343	271	288
SE	10.3	10.3	9.3
CD	29.4	29.4	26.5

condition caused reduction in exchangeable K content in the rhizosphere soil and also in the black soil; (ii) P application recorded higher exchangeable-K content in the soil under sterilized condition than under non-sterilized condition; and (iii) N fertilization at 50 and 100 kg level increased the exchangeable-K content in the black soil.

At 60th day, the interactions viz., Rh x P, S x P, S x N and P x N showed statistical significancen. The important inferences drawn are: (i) P fertilization reduced the exchangeable-K in both the rhizosphere and non-rhizosphere soils; but the reduction was conspicuous in the rhizosphere soil; (ii) significantly lower exchangeable K content was associated with P fertilization in the black soil than that in the red soil; and (iii) higher exchangeable K content in the red soil than that in the black soil was observed due to P fertilization.

At 90th day, the interactions viz., St x N, Rh x P, S x P, S x N and P x N showed statistical significance. The salient inferences drawnare: (i) P fertilization reduced the exchangeable-K content in the rhizosphere soil; (ii) P fertilization reduced the exchangeable-K content in the black soil; (iii) N fertilization at higher level had positive effect in the black soil; (iv) though P application caused reduction in exchangeable-K content in the absence of N addition, it showed positive effect for N addition at the two

levels; and (v) an inconsistent trend for N fertilization was observed since the sterilized condition increased exchangeable K content in the soil at N_0 and N_{100} levels markedly, but it was meagre at N_{50} level.

4.5.3.3. HNO_3 extractable-K (Table 18)

Individual effects

i) Rhizosphere: The mean value for this main effect fell within the range of 217 to 415 ppm. The rhizosphere soil registered higher value of HNO_3 extractable-K content at all the three stages of crop period than the non-rhizosphere soil.

ii) Sterilization: The mean value for this main effect remained within the range of 262 to 370 ppm. The process of sterilization decreased the HNO_3 extractable-K content at 30 and 90 days, but showed a reverse effect at 60 days of crop growth.

iii) Soil types: The mean value for this main effect ranged from 242 to 377 ppm. At all the three stages, the black soil registered higher amounts of HNO_3 extractable-K content than the red soil.

TABLE 18. EFFECT OF TREATMENTS ON HNO_3 EXTRACTABLE-K IN RHIZOSPHERE AND NON-RHIZOSPHERE REGIONS OF SORGHUM IN BLACK AND RED SOILS (ppm)

Treatments (1)	30 days (2)	60 days (3)	90 days (4)
Rh	415	317	296
NRh	258	232	217
St	370	286	252
NSt	302	263	262
S ₁	377	302	271
S ₂	296	247	242
P ₀	336	283	256
P ₅₀	337	266	257
SE	4.7	4.7	4.7
CD	13.3	13.3	13.3
N ₀	349	285	259
N ₅₀	319	265	245
N ₁₀₀	341	274	266
SE	5.7	5.7	5.7
CD	16.3	16.3	16.3
Rh x St	368	336	239
Rh x NSt	461	298	310
NRh x St	237	236	221
NRh x NSt	279	228	213
Rh x S ₁	474	353	308
Rh x S ₂	355	281	283
NRh x S ₁	279	251	234
NRh x S ₂	236	214	200
Rh x P ₀	409	323	291
Rh x P ₅₀	253	311	300
NRh x P ₀	262	243	220
NRh x P ₅₀	253	222	214
St x S ₁	330	316	264
St x S ₂	275	257	239
NSt x S ₁	424	288	278
NSt x S ₂	316	278	245

Contd.,

(1)	(2)	(3)	(4)
St x P ₀	267	288	253
St x P ₅₀	338	284	250
NSt x P ₀	404	278	258
NSt x P ₅₀	336	249	265
S ₁ x P ₀	366	324	287
S ₁ x P ₅₀	388	280	255
S ₂ x P ₀	306	242	225
S ₂ x P ₅₀	285	253	259
SE	6.6	6.6	6.6
CD	18.8	18.8	18.8
Rh x N ₀	423	323	288
Rh x N ₅₀	383	306	278
Rh x N ₁₀₀	439	322	322
NRh x N ₀	276	247	230
NRh x N ₅₀	255	225	211
NRh x N ₁₀₀	243	226	211
St x N ₀	318	308	257
St x N ₅₀	285	275	238
St x N ₁₀₀	305	276	260
NSt x N ₀	381	262	261
NSt x N ₅₀	353	255	251
NSt x N ₁₀₀	377	273	273
S ₁ x N ₀	382	327	279
S ₁ x N ₅₀	365	270	253
S ₁ x N ₁₀₀	384	308	282
S ₂ x N ₀	316	243	239
S ₂ x N ₅₀	272	260	236
S ₂ x N ₁₀₀	298	240	251
N ₀ x P ₀	357	305	273
N ₀ x P ₅₀	341	264	245
N ₅₀ x P ₀	321	252	236
N ₅₀ x P ₅₀	316	278	253
N ₁₀₀ x P ₀	329	291	259
N ₁₀₀ x P ₅₀	352	257	274
SE	8.0	8.0	8.0
CD	23.0	23.0	23.0

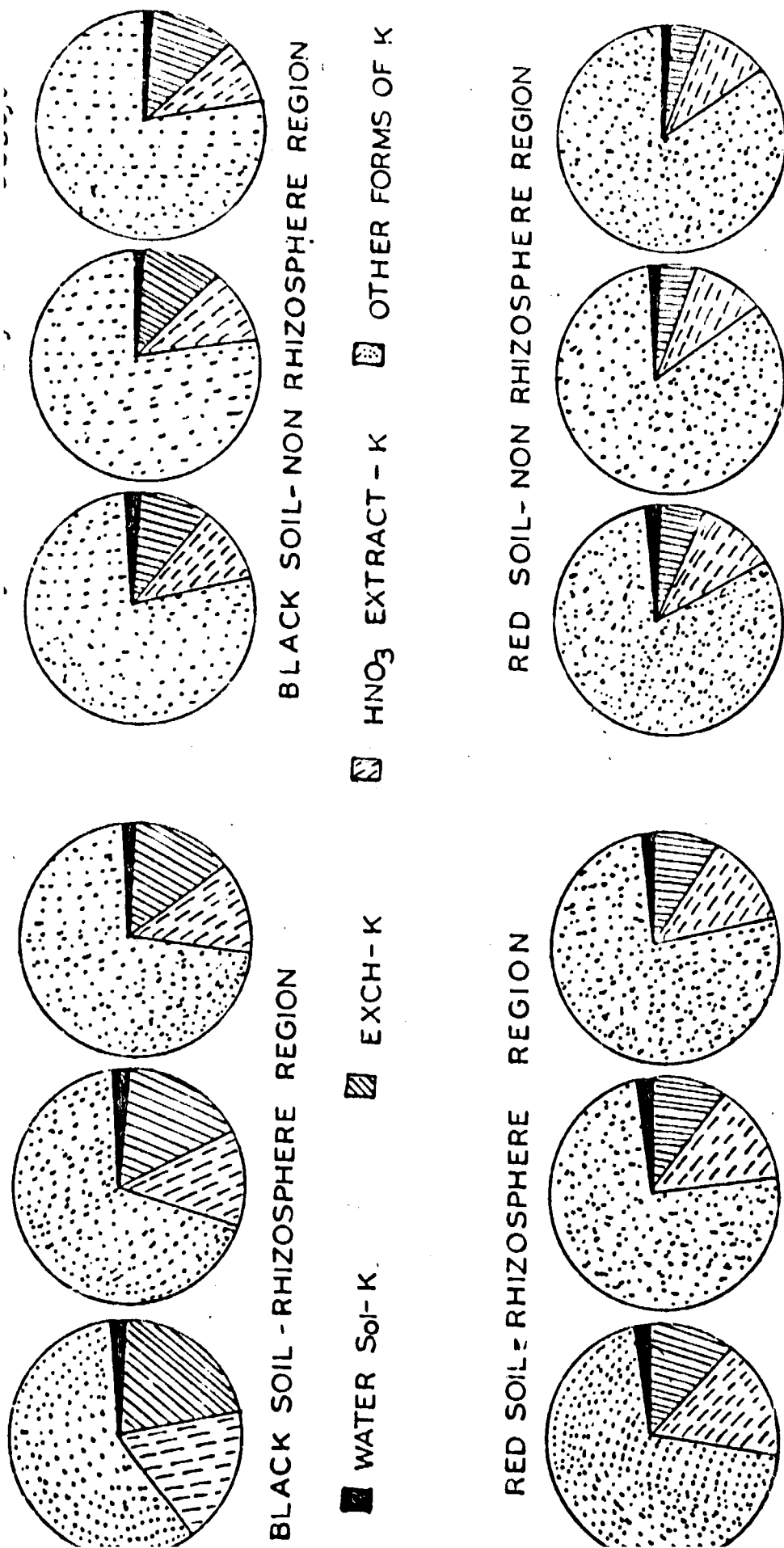


FIG.8 DIFFERENT FORMS OF K AS INFLUENCED BY RHIZOSPHERE AND SOIL TYPES AT DIFFERENT STAGES OF CROP GROWTH

iv) P levels: The mean value for this main effect ranged from 256 to 337 ppm. P application at 30 and 90 days had no effect on HNO_3 extractable-K content, while at 60 days stage, it recorded lowest value of HNO_3 extractable-K content.

v) N levels: The mean value for this main effect ranged from 245 to 349 ppm. Application of N at 50 kg level decreased the HNO_3 extractable-K content at all the three stages of crop growth generally.

Interaction effects

At 30th day, the interactions viz., St x Rh, St x S, St x P, Rh x S, Rh x N and S x P showed statistical significance. The important inferences drawn are: (i) In the P fertilization, the HNO_3 extractable-K content differed in both, sterilized and non-sterilized conditions since HNO_3 extractable-K was significantly higher due to P addition under sterilized condition, while under non-sterilized condition P addition caused marked decrease; (ii) N addition at 100 kg level caused marked reduction of HNO_3 extractable-K in non-rhizosphere region; and (iii) P fertilization on HNO_3 extractable-K content had positive and negative effects in black and red soils respectively.

At 60th day, the interactions viz., St x Rh, St x N, Rh x S, S x P, S x N and P x N showed statistical significance. The inferences drawn are: (i) under sterilized condition, N fertilization caused reduction in HNO_3 extractable-K content and (ii) P fertilization decreased HNO_3 extractable -K content in the black soil.

At 90th day, the interactions viz., St x Rh, Rh x N, S x P and P x N showed statistical significance. The inferences drawn are: (i) the sterilized condition increased the HNO_3 extractable-K content in the non-rhizosphere soil and decreased the same in the rhizosphere soil and also N application at 100 kg level increased the HNO_3 extractable-K content in the rhizosphere soil; (ii) P application interacted differently with soils, since the lowest value was associated with P addition in the black soil and the reverse was the case for the red soil; and (iii) the synergistic effect of P x N was observed for HNO_3 extractable-K content as revealed by the trend of mean values for P x N interaction.

4.6. Effect on nutrient flow rate or flux or uptake rate in the plant

4.6.1. Effect on N, P and K flow rate in the plant (Table 19)

(Fig. 9)

4.6.1.1. Effect on N flow rate

Individual effects

i) Sterilization: The differential trend in N flow rate for both the conditions of the soil was not marked.

ii) Soil types: The N flow rate was significantly high in the black soil ($146.4 \mu \text{ moles/cm/day} \times 10^{-4}$) than the red soil ($87.0 \mu \text{ moles/cm/day} \times 10^{-4}$).

iii) P levels: Difference in N flow rate due to P application was not significant.

iv) N levels: The N application at 100 kg level recorded significantly higher value for N flow rate ($136.3 \mu \text{ moles/cm/day} \times 10^{-4}$) but it was on par with N_0 level. Nitrogen flow rate at N_{50} level was recorded as $92.0 \mu \text{ moles/cm/day} \times 10^{-4}$.

v) Stages: Nitrogen flow rate at 30 days stage was found to be high registering $296.8 \mu \text{ moles/cm/day} \times 10^{-4}$. The rate was high at the early growth phase, more or less 8 to 16 times more than that at 90 and 60 days stages respectively.

Interaction effects

The interactions viz., Stages x St, S x Stages, S x P, S x N, Stages x P and Stages x N attained statistical

significance. The main inferences drawn are: (i) on an overall basis under sterilized condition of the soil N flow rate at 30 days stage of crop growth was enhanced; (ii) N flow rate was more in the black soil than that in the red soil at 30 days stage, while the difference in flow rate was marginal between two soil types at later stages of crop growth, but was marked at 30 days stage; (iii) P application caused reduction in N flow rate in the black soil but showed marginal increase in the red soil; (iv) N_{100} level recorded higher N flow rate in the red soil than that in the black soil; while N_{50} level was on par with N_0 level; and (v) the negative effect of P application on N flow rate was observed at 30 days vegetative stage, while at later stages the differences were only numerical.

4.6.1.2. Effect on P flow rate

Individual effects

i) Sterilization: Differential trend in P flow rate for both the conditions of the soil was insignificant.

ii) Soil types: Similar to that of N flow rate, P flow rate was observed to be higher in the black soil ($33.2 \mu \text{ moles/cm/day} \times 10^{-4}$) than that in the red soil ($16.8 \mu \text{ moles/cm/day} \times 10^{-4}$).

iii) P levels: P application significantly reduced P flow rate from 31.0 to 19.0 μ moles/cm/day $\times 10^{-4}$.

iv) N levels: N application had no significant effect on P flow rate.

v) Stages: P flow rate at 30 days stage was found to be remarkably high registering 67.30 μ moles/cm/day $\times 10^{-4}$.

Interaction effects

The interactions viz., St $\times$ P, S $\times$ Stages, S $\times$ P, S $\times$ N, Stages $\times$ P, Stages $\times$ N and P $\times$ N attained statistical significance. The salient inferences are: (i) under normal condition of the soil higher P flow rate was recorded than that under sterilized condition; (ii) at 30 days stage P flow rate was more in the black soil than that in the red soil but with advancement of crop growth, this trend was not observed; (iii) P application recorded significantly lower P flow rate in the black soil while it recorded marginal difference in the red soil; (iv) N application which was able to cause a stepwise reduction in P flow rate in the black soil showed a reverse trend in the red soil; (v) the negative effect of P application on P flow rate was observed only at 30 days stage, while at later stages the effect of P application was on par with no P application; and (vi) the combined application of N_{100} P_{50} showed a complimentary effect.

4.6.1.3. Effect on K flow rate

Individual effects

i) Sterilization: Differential trend in K flow rate for both the conditions of the soil was insignificant though under normal condition of the soil a numerically higher value of K flow rate was recorded than that under sterilized condition of the soil.

ii) Soil types: Similar to that of N flow rate, K flow rate was found to be higher in the black soil ($82.7 \mu \text{ moles/cm/day} \times 10^{-4}$) than that in the red soil ($54.0 \mu \text{ moles/cm/day} \times 10^{-4}$).

iii) P levels: P application significantly reduced K flow rate from 77.6 to $59.1 \mu \text{ moles/cm/day} \times 10^{-4}$.

iv) N levels: N application had no significant effect on K flow rate.

v) Stages: K flow rate at 30 days stage was significantly higher registering $82.7 \mu \text{ moles/cm/day} \times 10^{-4}$ than that at 60 and 90 days stages.

Interaction effects

The interactions viz., St x S, St x Stages, S x Stages, S x P, Stages x P and P x N attained statistical significance.

TABLE 19. EFFECT OF TREATMENTS ON N, P AND K UPTAKE RATE IN SORGHUM PLANT IN
BLACK AND RED SOILS (μ moles/cm/day $\times 10^{-4}$)

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Treatments	N uptake rate	P uptake rate	K uptake rate
St	129.1	22.8	69.5
NSt	104.3	27.3	67.2
S ₁	146.4	33.2	82.7
S ₂	87.0	16.8	54.0
P ₀	131.5	31.0	77.6
P ₅₀	102.5	19.0	59.1
SE	10.2	1.6	4.8
CD	28.7	4.5	13.6
N ₀	122.0	27.2	74.9
N ₁	92.0	22.2	58.2
N ₂	136.3	25.6	72.0
St ₁	296.8	67.3	165.8
St ₂	17.8	1.4	12.0
St ₃	35.5	6.3	27.3
SE	12.5	2.0	5.9
CD	35.2	5.5	16.7
St $\times$ S ₁	157.9	30.5	73.5
St $\times$ S ₂	100.2	15.0	65.5
NSt $\times$ S ₁	135.0	36.0	92.0
NSt $\times$ S ₂	73.7	18.6	42.6
St $\times$ P ₀	139.6	26.5	76.4
St $\times$ P ₅₀	118.5	19.1	62.6
NSt $\times$ P ₀	123.4	35.6	78.9
NSt $\times$ P ₅₀	85.2	18.9	55.6
S ₁ $\times$ P ₀	185.0	44.8	109.4
S ₁ $\times$ P ₅₀	108.0	21.6	56.0
S ₂ $\times$ P ₀	78.1	17.3	45.9
S ₂ $\times$ P ₅₀	95.9	16.4	62.2
SE	14.4	2.3	6.9
CD	40.6	6.4	19.2
St $\times$ St ₁	361.6	65.1	187.8
St $\times$ St ₂	10.8	1.3	8.3
St $\times$ St ₃	15.0	1.9	12.4
NSt $\times$ St ₁	232.0	69.5	143.7
NSt $\times$ St ₂	24.8	1.6	15.7
NSt $\times$ St ₃	56.1	10.6	42.3
St $\times$ N ₀	142.5	27.5	74.7
St $\times$ N ₅₀	101.4	18.6	54.6
St $\times$ N ₁₀₀	143.3	22.2	79.2
NSt $\times$ N ₀	101.4	26.9	75.2
NSt $\times$ N ₅₀	82.3	25.9	61.9
NSt $\times$ N ₁₀₀	129.2	28.9	64.6

Contd.,

(1)	(2)	(3)	(4)
$S_1 \times St_1$	377.5	9.3	207.0
$S_1 \times St_2$	20.0	1.1	11.8
$S_1 \times St_3$	41.9	6.2	29.4
$S_2 \times St_1$	216.1	42.3	124.6
$S_2 \times St_2$	15.6	1.8	12.2
$S_2 \times St_3$	35.5	6.4	25.3
$S_1 \times N_0$	173.8	41.7	106.7
$S_1 \times N_{50}$	122.8	32.1	76.3
$S_1 \times N_{100}$	142.7	25.8	65.0
$S_2 \times N_0$	70.1	12.7	43.2
$S_2 \times N_{50}$	61.0	12.3	40.1
$S_2 \times N_{100}$	129.8	25.4	78.8
$N_0 \times P_0$	158.8	42.0	96.1
$N_0 \times P_{50}$	85.1	12.4	53.8
$N_1 \times P_0$	101.8	26.6	57.9
$N_1 \times P_{50}$	82.0	17.9	58.6
$N_2 \times P_0$	134.0	24.5	79.0
$N_2 \times P_{50}$	138.5	26.7	64.9
$St_1 \times P_0$	352.3	87.5	203.0
$St_1 \times P_{50}$	241.3	47.2	128.6
$St_2 \times P_0$	18.1	1.4	10.2
$St_2 \times P_{50}$	17.4	1.4	13.8
$St_3 \times P_0$	24.1	4.2	19.8
$St_3 \times P_{50}$	47.0	8.4	34.9
SE	17.7	2.8	8.4
CD	49.7	7.8	23.6
$St_1 \times N_0$	299.8	73.5	173.0
$St_1 \times N_{50}$	232.8	57.4	143.0
$St_1 \times N_{100}$	358.4	71.0	181.5
$St_2 \times N_0$	18.8	1.5	11.5
$St_2 \times N_{50}$	14.2	1.5	12.6
$St_2 \times N_{100}$	18.4	1.3	11.0
$St_3 \times N_0$	47.3	6.5	40.4
$St_3 \times N_{50}$	27.2	7.8	18.3
$St_3 \times N_{100}$	32.0	4.5	23.4
SE	21.6	3.4	10.3
CD	60.9	9.6	28.9

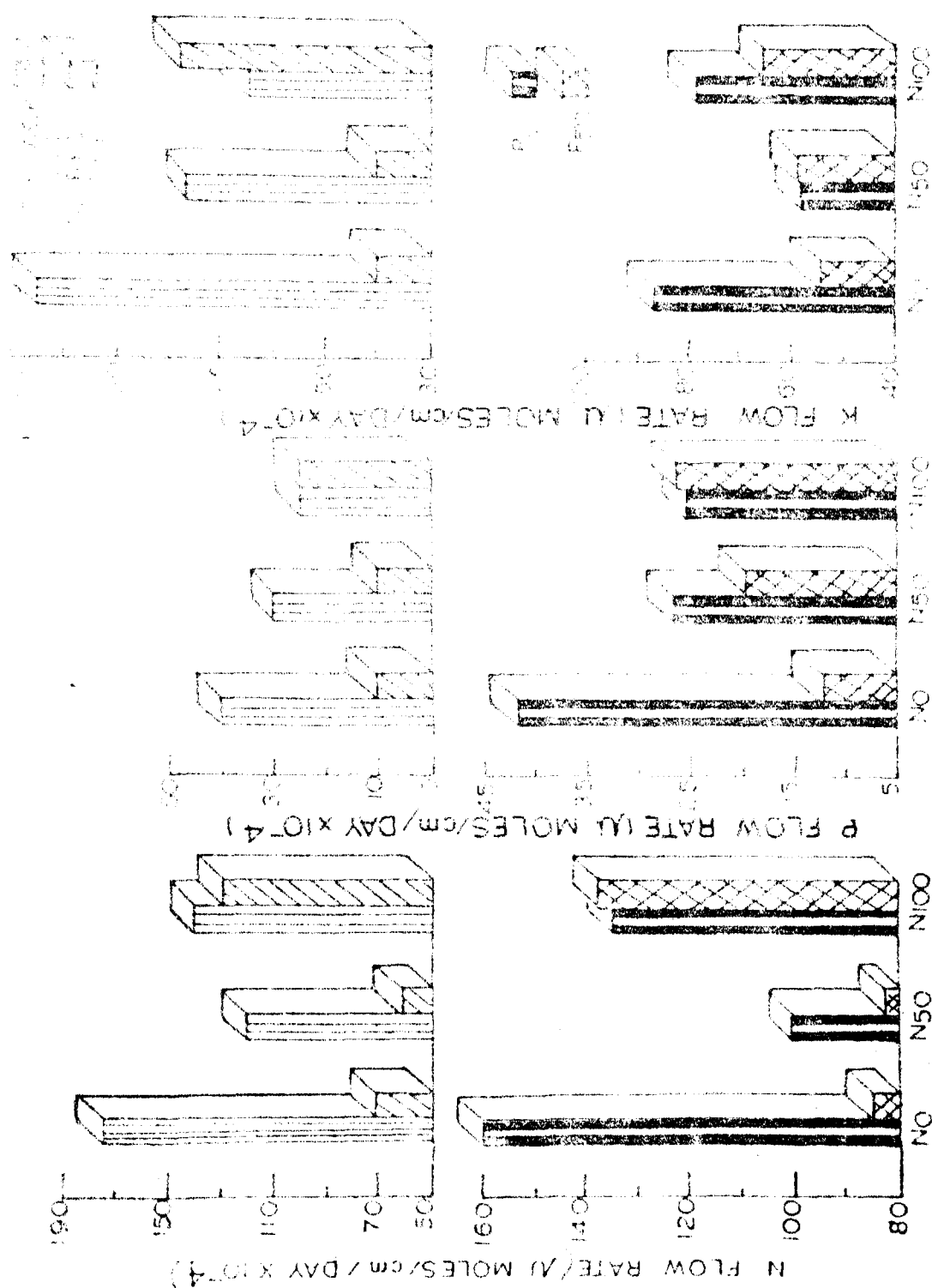


FIG. 9 FLOW RATE OF MAJOR NUTRIENTS AS INFLUENCED BY SOIL TYPES AND N AND P APPLICATION

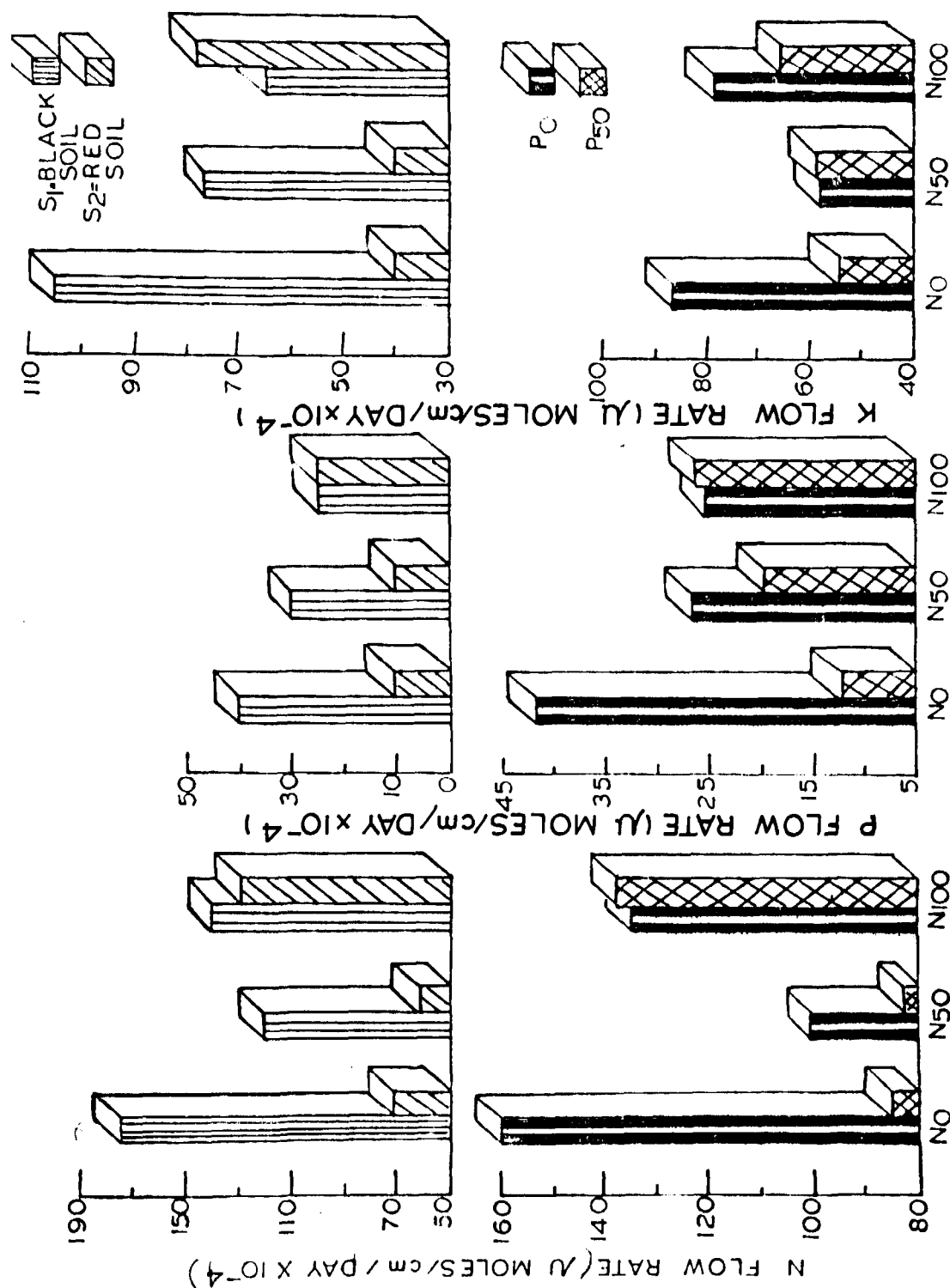


FIG. 9 FLOW RATE OF MAJOR NUTRIENTS AS INFLUENCED BY SOIL TYPES AND N AND P APPLICATION

The important inferences drawn are: (i) at 30 days stage under sterilized condition of the soil, higher K flow rate was recorded than that under normal condition of the soil but at later stages under both the conditions of the soil, the effect was similar; (ii) K flow rate was high in the black soil at P_0 level and also at 30 days stage; (iii) N_{100} level had synergistic effect on K flow rate in the red soil; (iv) P application reduced K flow rate only at 30 days stage but registered numerically higher value than no P application at 60 and 90 days stages; and (v) P application reduced K flow rate significantly in the absence of N while in the presence of N it had no effect.

4.6.2. Effect on micronutrient flow rate in the plant

(Table 20) (Fig. 10)

4.6.2.1. Effect on Fe flow rate

Individual effects

i) Sterilization: Under sterilized condition of the soil Fe flow rate was significantly reduced from 645.0 to 434.6 μ moles/cm/day $\times 10^{-6}$.

ii) Soil types: The Fe flow rate was conspicuously higher in the black soil registering 686.5 μ moles/cm/day $\times 10^{-6}$ than that in the red soil (393.0 μ moles/cm/day $\times 10^{-6}$).

iii) P levels: The P application significantly reduced Fe flow rate from 610.0 to 469.4 μ moles/cm/day $\times 10^{-6}$.

iv) N levels: The N application showed an inconsistent trend in Fe flow rate.

v) Stages: The Fe flow rate at 30 days stage was found to be significantly high registering 1334.0 μ moles/cm/day $\times 10^{-6}$.

Interaction effects

The interactions viz., St x S, St x Stages, St x P, St x N, S x Stages, Stages x P and Stages x N attained statistical significance. The important inferences drawn are: (i) under sterilized condition of the soil, Fe mobility at 30 days stage was reduced as compared to that under normal conditions of the soil and the same trend was absent at 60 and 90 days stage as well as at added levels of N and P; (ii) at 30 days stage Fe flow rate was more in the black soil than that in the red soil while this difference was not observed at later stages of crop growth; (iii) P application which caused a reduction in Fe flow rate at 30 days stage, showed an increasing trend at 60 and 90 days stages; and (iv) N₅₀ level was found to be beneficial for Fe mobility at 30 days stage and the trend got reversed at later stage.

4.6.2.2. Effect on Mn flow rate

Individual effects

i) Sterilization: Under sterilized condition of the soil Mn flow rate was enhanced from 50.3 to 94.6 μ moles/cm/day $\times 10^{-6}$.

ii) Soil types: Similar to Fe flow rate, Mn flow rate was remarkably high in the black soil registering 108.0 μ moles/cm/day $\times 10^{-6}$.

iii) P levels: P application significantly reduced Mn flow rate from 102.6 to 42.2 μ moles/cm/day $\times 10^{-6}$.

iv) N levels: N application showed an inconsistent trend on Mn mobility.

v) Stages: Mn flow rate was remarkably high at 30 days stage registering 189.0 μ moles/cm/day $\times 10^{-6}$.

Interaction effects

The interactions viz., St $\times$ Stages, St $\times$ P, S $\times$ Stages, S $\times$ P, S $\times$ N, Stages $\times$ P and P $\times$ N attained statistical significance. The inferences drawn are : (i) under sterilized condition of the soil higher Mn flow rate was registered at 30 days stage than that under normal

condition of the soil, but with advancement of crop growth this trend was not observed; (ii) P application reduced Mn flow rate under sterilized condition while under normal condition of the soil, P application marginally reduced Mn flow rate; (iii) Mn flow rate was more in the black soil as that of main effect only at 30 days stage, while at 60 and 90 days stage, the same was on par with that in the red soil; (iv) application of N at two levels reduced Mn flow rate in the black soil; (v) the negative effect of P application on Mn flow rate was observed only at 30 days stage while at later stages such effect was not existing; and (vi) N application was detrimental on Mn flow rate only in the absence of P application.

4.6.2.3. Effect on Cu flow rate

Individual effects

i) Sterilization: Under normal condition of the soil, Cu flow rate exhibited only a marginal increase over that under sterilized condition of the soil.

ii) Soil types: Cu flow rate was significantly high in the black soil registering $10.7 \mu \text{ moles/cm/day} \times 10^{-6}$.

iii) P levels: P application significantly reduced Cu flow rate from 10.0 to $6.6 \mu \text{ moles/cm/day} \times 10^{-6}$.

iv) N levels: N_{100} level significantly increased Cu flow rate from 6.7 to 11.1 μ moles/cm/day $\times 10^{-6}$.

v) Stages: Cu flow rate was remarkably high at 30 days stage registering 15.2 μ moles/cm/day $\times 10^{-6}$.

Interaction effects

The interactions viz., St x Stages, St x P, S x Stages, S x P, S x N, Stages x P, St x N and P x N attained statistical significance. The important inferences drawn are: (i) on an overall basis, under sterilized condition of the soil Cu flow rate was significantly increased at 30 days stage only, while at P_{50} level it showed a negative trend; (ii) Cu flow rate was more in the black soil than in the red soil at 30 days stage and in the black soil P application reduced Cu flow rate, while N application at 100 kg level had a positive effect on Cu flow rate; (iii) P application reduced Cu flow rate, while N_{50} or N_{100} level had a positive effect on Cu flow rate at 30 days stage; and (iv) P application at N_{100} level caused a significant reduction in Cu flow rate.

4.6.2.4. Effect on Zn flow rate

Individual effects

i) Sterilization: Under sterilized conditions of the soil, a marginal increase in Zn flow rate over that under normal condition of the soil was observed.

TABLE 20. EFFECT OF TREATMENTS ON Fe, Mn, Cu AND Zn UPTAKE RATE
IN SORGHUM PLANT IN BLACK AND RED SOILS (μ moles/cm/day $\times 10^{-6}$)

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Treatments (1)	Fe uptake rate (2)	Mn uptake rate (3)	Cu uptake rate (4)	Zn uptake rate (5)
St	434.6	94.6	8.1	40.7
NSt	645.0	50.3	8.5	39.4
S ₁	686.5	108.0	10.7	46.9
S ₂	393.0	37.0	5.8	33.2
P ₀	610.0	102.6	10.0	42.8
P ₅₀	469.4	42.2	6.6	37.3
SE	37.4	11.1	0.8	3.0
CD	105.1	31.1	2.3	8.4
N ₀	593.4	98.6	7.0	38.8
N ₅₀	442.1	58.6	6.7	36.4
N ₁₀₀	583.8	60.0	11.1	45.0
St ₁	1334.0	189.0	15.2	93.7
St ₂	158.0	11.5	3.7	7.7
St ₃	127.2	10.7	6.0	18.7
SE	45.8	13.5	1.0	3.7
CD	128.7	38.0	2.9	10.3
St x S ₁	483.4	143.6	11.0	43.0
St x S ₂	385.8	45.6	5.2	38.5
NSt x S ₁	889.6	72.3	10.5	50.8
NSt x S ₂	400.2	28.2	6.5	28.0
St x P ₀	437.3	146.0	11.5	44.3
St x P ₅₀	432.0	43.3	4.7	37.2
NSt x P ₀	783.0	59.4	8.5	41.4
NSt x P ₅₀	507.0	41.1	8.5	37.3
S ₁ x P ₀	792.0	165.3	14.3	57.3
S ₁ x P ₅₀	581.0	50.5	7.2	36.5
S ₂ x P ₀	428.3	40.0	5.6	28.4
S ₂ x P ₅₀	357.7	34.0	6.1	38.0
SE	52.9	15.6	1.2	4.3
CD	148.6	43.9	3.2	11.9
St x St ₁	998.7	254.7	17.8	109.8
St x St ₂	243.5	16.2	3.5	6.6
St x St ₃	61.6	12.8	3.0	6.5
NSt x St ₁	1669.4	123.2	12.5	78.4
NSt x St ₂	72.5	6.9	3.8	8.9
NSt x St ₃	192.8	20.6	9.1	30.9

(1)	(2)	(3)	(4)	(5)
St x N ₀	597.7	143.5	6.6	39.4
St x N ₅₀	329.4	76.5	5.2	37.6
St x N ₁₀₀	376.7	63.7	12.6	45.3
NSt x N ₀	589.1	53.6	7.5	38.1
NSt x N ₅₀	554.7	40.8	8.3	35.2
NSt x N ₁₀₀	990.8	56.3	9.7	44.7
S ₁ x St ₁	1689.4	289.7	21.0	111.7
S ₁ x St ₂	234.0	16.5	4.4	7.0
S ₁ x St ₃	136.1	17.6	6.8	22.2
S ₂ x St ₁	978.7	88.3	9.3	75.8
S ₂ x St ₂	82.1	6.6	3.0	8.6
S ₂ x St ₃	118.2	15.8	5.2	15.2
S ₁ x N ₀	828.2	163.9	7.9	50.7
S ₁ x N ₅₀	564.7	85.4	8.6	45.0
S ₁ x N ₁₀₀	666.5	74.5	15.8	45.1
S ₂ x N ₀	358.6	33.3	6.2	25.8
S ₂ x N ₅₀	319.4	31.9	4.8	27.8
S ₂ x N ₁₀₀	501.0	45.6	6.5	45.0
St ₁ x P ₀	1668.1	275.8	20.8	106.0
St ₁ x P ₅₀	1000.0	102.2	9.5	81.4
St ₂ x P ₀	58.1	9.9	4.1	6.6
St ₂ x P ₅₀	257.9	13.2	3.3	9.0
St ₃ x P ₀	104.2	22.3	4.9	16.0
St ₃ x P ₅₀	150.2	11.2	7.1	21.4
N ₀ x P ₀	713.4	160.7	8.0	48.3
N ₀ x P ₅₀	473.4	36.4	6.0	29.2
N ₁ x P ₀	431.2	75.9	5.9	40.7
N ₁ x P ₅₀	452.9	41.4	7.5	32.1
N ₂ x P ₀	685.7	71.3	15.9	39.5
N ₂ x P ₅₀	481.8	48.7	6.4	50.5
SE	64.8	19.2	1.4	5.2
CD	182.0	53.8	4.0	14.6
St ₁ x N ₀	1289.6	259.4	9.6	86.6
St ₁ x N ₅₀	1132.9	153.5	11.9	83.1
St ₁ x N ₁₀₀	1579.6	154.0	24.0	111.5
St ₂ x N ₀	323.6	13.4	4.9	6.1
St ₂ x N ₅₀	91.4	15.8	3.3	11.1
St ₂ x N ₁₀₀	59.1	5.3	2.8	6.0
St ₃ x N ₀	167.0	22.8	6.5	23.6
St ₃ x N ₅₀	101.8	6.6	4.8	15.0
St ₃ x N ₁₀₀	112.6	20.8	6.6	17.5
SE	79.4	23.5	1.8	6.4
CD	223.0	65.9	4.9	18.0

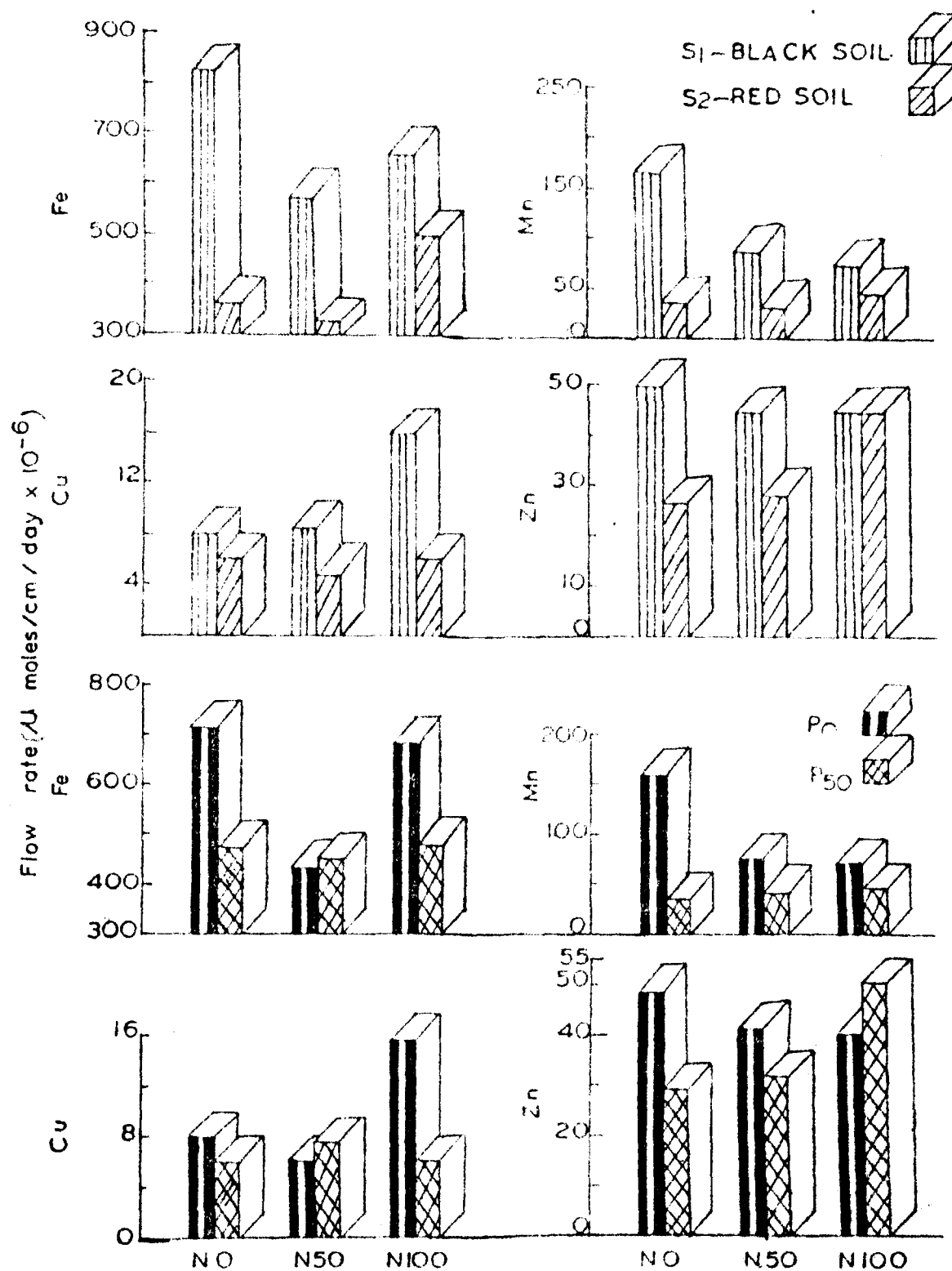


FIG. 10 FLOW RATE OF MICRONUTRIENTS AS INFLUENCED BY SOIL TYPES AND N AND P APPLICATION

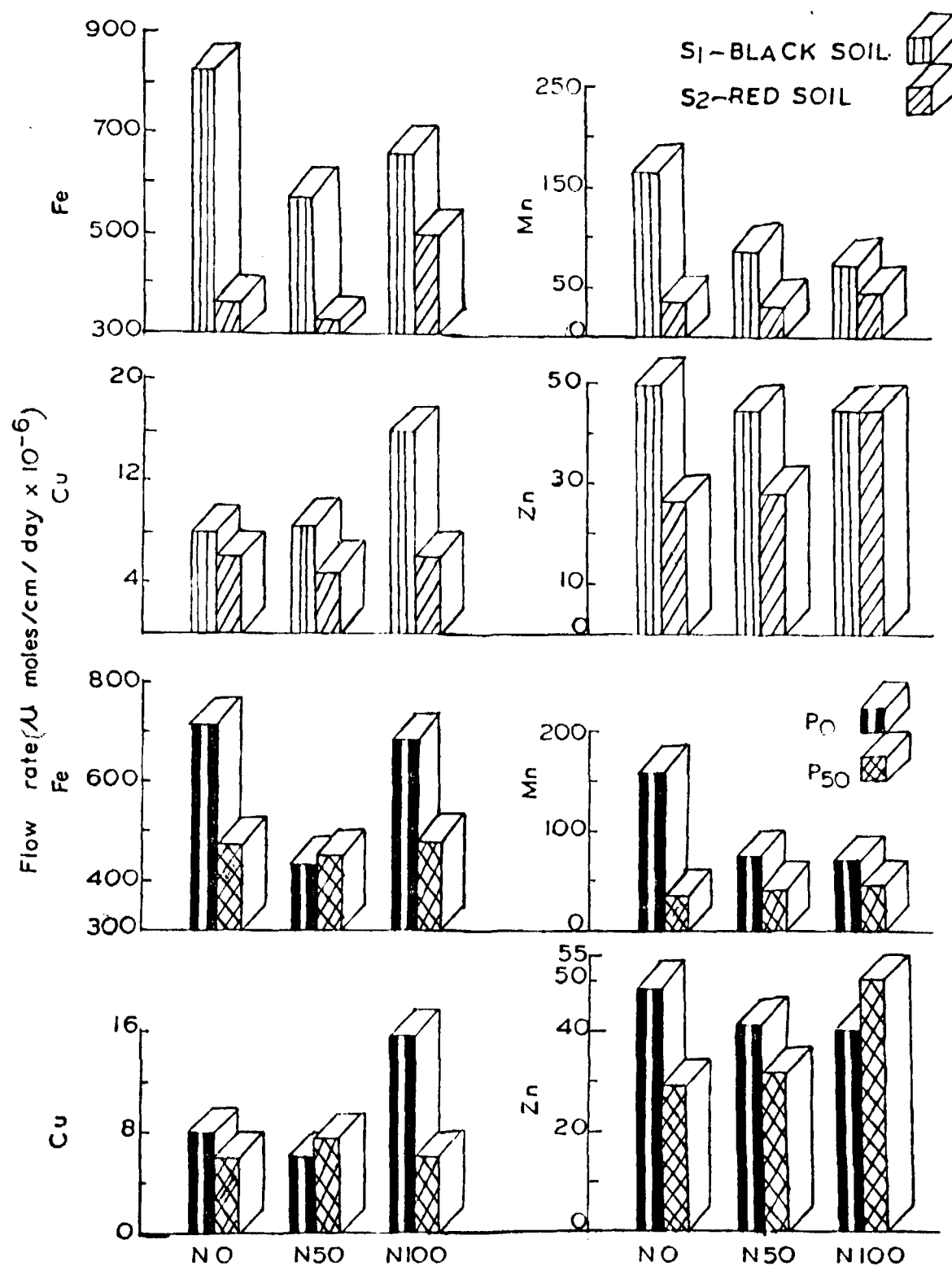


FIG. 10 FLOW RATE OF MICRONUTRIENTS AS INFLUENCED BY SOIL TYPES AND N AND P APPLICATION

ii) Soil types: The Zn flow rate was significantly higher in the black soil registering $46.9 \mu \text{ moles/cm/day} \times 10^{-6}$ than that in the red soil which registered $33.2 \mu \text{ moles/cm/day} \times 10^{-6}$.

iii) P levels: The P application showed no significant effect on Zn flow rate.

iv) N levels: The N application showed no significant effect on Zn flow rate.

v) Stages: The Zn flow rate was significantly high at 30 days stage registering $93.7 \mu \text{ moles/cm/day} \times 10^{-6}$ and got reduced with advancement of crop growth.

Interaction effects

The interactions viz., St x S, St x Stages, S x Stages, S x P, Stages x P, Stages x N and P x N attained statistical significance. The important inferences drawn are: (i) under sterilized condition of the soil at 30 days stage Zn flow rate was increased while at 90 days stage, a reverse trend was observed; (ii) the black soil recorded higher value of Zn flow rate than the red soil at 30 days stage crop growth while at later stages the difference for the soils was meagre; (iii) P application which caused a significant

reduction in Zn flow rate in the black soil, exhibited a positive effect in the red soil; (iv) P application reduced Zn flow rate at 30 days stage while at later stages P application showed marginal increase of Zn flow rate over no P application; and (v) the effect of N_{100} level was complimentary for Zn flow rate at 30 days stage; the combined application of $N_{100} P_{50}$ increased Zn flow rate.

4.7. Effect on nutrient content in plant parts

4.7.1. Effect on N, P and K content in root of sorghum plant

4.7.1.1. Effect on N content (Table 21)

Individual effects

i) Sterilization: The mean value for this mean effect ranged from 0.34 to 0.56 per cent. At 60th day, root N content was significantly increased but at 30 and 90 days of crop growth, there was no marked difference between sterilized and non-sterilized conditions.

ii) Soil types: The mean value for this main effect ranged from 0.29 per cent to 0.60 per cent. At all the three stages of crop growth, the black soil recorded significantly higher root N content than the red soil.

iii) P levels: The mean value for this main effect ranged from 0.31 to 0.48 per cent. P_{50} level significantly

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Treatments (1)	30 days (2)	60 days (3)	90 days (4)
St	0.42	0.56	0.45
NSt	0.36	0.34	0.43
S ₁	0.43	0.60	0.56
S ₂	0.36	0.29	0.33
P ₀	0.47	0.48	0.46
P ₅₀	0.31	0.42	0.43
SE	0.022	0.006	0.027
CD	0.065	0.018	0.078
N ₀	0.42	0.50	0.53
N ₅₀	0.36	0.40	0.41
N ₁₀₀	0.40	0.45	0.48
St	0.027	0.007	0.033
CD	0.029	0.022	0.035
St x S ₁	0.45	0.89	0.73
St x S ₂	0.40	0.22	0.17
NSt x S ₁	0.42	0.12	0.19
NSt x S ₂	0.31	0.36	0.48
St x P ₀	0.45	0.63	0.47
St x P ₅₀	0.40	0.48	0.43
NSt x P ₀	0.50	0.33	0.45
NSt x P ₅₀	0.23	0.35	0.42
S ₁ x P ₀	0.49	0.72	0.50
S ₁ x P ₅₀	0.37	0.48	0.62
S ₂ x P ₀	0.45	0.24	0.42
S ₂ x P ₅₀	0.26	0.35	0.23
SE	0.031	0.008	0.038
CD	0.092	0.025	0.110
St x N ₀	0.45	0.74	0.65
St x N ₅₀	0.39	0.53	0.36
St x N ₁₀₀	0.43	0.40	0.35
NSt x N ₀	0.39	0.25	0.41
NSt x N ₅₀	0.33	0.27	0.27
NSt x N ₁₀₀	0.36	0.50	0.62
S ₁ x N ₀	0.49	0.73	0.90
S ₁ x N ₅₀	0.39	0.57	0.42
S ₁ x N ₁₀₀	0.41	0.50	0.36
S ₂ x N ₀	0.35	0.26	0.17
S ₂ x N ₅₀	0.33	0.23	0.21
S ₂ x N ₁₀₀	0.39	0.40	0.60
N ₀ x P ₀	0.57	0.42	0.35
N ₀ x P ₅₀	0.57	0.57	0.72
N ₅₀ x P ₀	0.43	0.55	0.36
N ₅₀ x P ₅₀	0.40	0.24	0.27
N ₁₀₀ x P ₀	0.43	0.47	0.67
N ₁₀₀ x P ₅₀	0.47	0.43	0.29

reduced the root N content at 30 and 60 days but no significant difference was observed due to P application at 90 days stage.

iv) N levels: The mean value for this main effect ranged from 0.31 per cent to 0.53 per cent. There was no significant increase in N content due to added levels of N application at 30 and 90 days. At 60 days stage N_{50} level significantly reduced the root N content, while no N application increased the root N content.

Interaction effects

At 30th day, the interactions revealed that P application had decreased the N content at N_0 and N_{50} levels.

At 60th day, the interactions viz., $S \times N$, $St \times S$ and $St \times N$ were significant. The salient inferences drawn are: (i) P application increased the N content only in the red soil; (ii) it had a positive effect on root N content only at N_0 level; (iii) P application reduced the N content under sterilized condition; and (iv) though on overall basis sterilized conditions increased the N content of root in the red soil, it failed to do so in the black soil and at N_{100} level.

At 90th day, the interactions, S x N, S x P, S x St, N x P and N x St showed significance. The important conclusions drawn are: (i) N application had positive effect in the red soil, particularly at N₁₀₀ level; (ii) P₅₀ level increased the N content at N₀ level, it recorded significantly lower value at N₅₀ level; (iii) P₅₀ level increased the root N content in the black soil, while it was more at P₀ level than at P₅₀ level in the red soil; (iv) root N content was more in the black soil than in the red soil under sterilized condition; and (v) sterilized condition decreased the root N content at N₁₀₀ level.

4.7.1.2. Effect on P content (Table 22)

Individual effects

i) Sterilization: The mean value for this main effect ranged from 0.14 to 0.51 per cent. Under sterilized condition the root P content was significantly decreased at 30 and 90 days of crop growth, but no significant difference was observed at 60th day between sterilized and normal soil.

ii) Soil types: The mean value for this main effect ranged from 0.23 to 0.69 per cent. The black soil recorded significantly higher value of P content in the root than the red soil at 30 and 60 days crop growth, but the trend got reversed at 90 days stage.

TABLE 22. EFFECT OF TREATMENTS ON P CONTENT IN ROOT OF SORGHUM IN BLACK AND RED SOILS(%)

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Treatment (1)	30 days (2)	60 days (3)	90 days (4)
St	0.51	0.27	0.14
NSt	0.61	0.25	0.48
S ₁	0.69	0.30	0.23
S ₂	0.43	0.23	0.40
P ₀	0.75	0.30	0.27
P ₅₀	0.37	0.23	0.35
SE	0.01	0.01	0.04
CD	0.04	0.02	0.01
N ₀	0.58	0.24	0.23
N ₅₀	0.54	0.27	0.40
N ₁₀₀	0.56	0.26	0.31
SE	0.02	0.01	0.01
CD	0.05	0.02	0.02
St x S ₁	0.63	0.36	0.14
St x S ₂	0.39	0.19	0.15
NSt x S ₁	0.75	0.23	0.32
NSt x S ₂	0.46	0.28	0.64
St x P ₀	0.64	0.33	0.13
St x P ₅₀	0.39	0.23	0.16
NSt x P ₀	0.86	0.28	0.42
NSt x P ₅₀	0.36	0.23	0.54
S ₁ x P ₀	0.95	0.36	0.20
S ₁ x P ₅₀	0.43	0.24	0.26
S ₂ x P ₀	0.54	0.25	0.35
S ₂ x P ₅₀	0.31	0.21	0.44
SE	0.02	0.01	0.01
CD	0.05	0.02	0.02
St x N ₀	0.50	0.23	0.12
St x N ₅₀	0.53	0.32	0.15
St x N ₁₀₀	0.52	0.29	0.16
NSt x N ₀	0.67	0.25	0.35
NSt x N ₅₀	0.55	0.28	0.64
NSt x N ₁₀₀	0.59	0.23	0.45
S ₁ x N ₀	0.74	0.24	0.21
S ₁ x N ₅₀	0.72	0.35	0.25
S ₁ x N ₁₀₀	0.63	0.30	0.22
S ₂ x N ₀	0.43	0.25	0.26
S ₂ x N ₅₀	0.36	0.24	0.54
S ₂ x N ₁₀₀	0.49	0.22	0.39
N ₀ x P ₀	0.97	0.22	0.32
N ₀ x P ₅₀	0.21	0.26	0.15
N ₅₀ x P ₀	0.65	0.38	0.22
N ₅₀ x P ₅₀	0.43	0.22	0.57
N ₁₀₀ x P ₀	0.62	0.31	0.28
N ₁₀₀ x P ₅₀	0.49	0.21	0.33
SE	0.02	0.01	0.01
CD	0.05	0.02	0.02

iii) P levels: The mean value for this main effect ranged from 0.27 to 0.75 per cent. P application significantly decreased the root P content at 30 and 60 days stage, but at 90 days stage P_{50} level significantly increased the root P content.

iv) N levels: The mean value for this main effect ranged from 0.23 to 0.58 per cent. No significant increase in root P content was observed at 30 and 60 days stage, but at 90 days stage N_{50} level increased the P content as compared to N_0 level.

Interaction effects

At 30th day, the interactions viz., S x N, S x P, N x P, N x St and P x St were significant. The important inferences drawn are: (i) P content in root was decreased due to N application at higher level in the black soil and also at P_0 level while N and P application had synergistic effect on P content; (ii) under non-sterilized condition of the soil N application at two levels decreased the root P content; and (iii) P content in root was decreased due to sterilized condition at P_0 level, while the differences were not marked at P_{50} level.

At 60th day, the interactions viz., S x N, S x P, S x St, N x P, N x St and P x St were significant. The salient points of inferences drawn are: (i) root P content was higher under sterilized condition in the black soil than that in the red soil; (ii) P content was decreased by the combined N and P application, while it increased the P content at N_0 level; (iii) P content was significantly decreased under sterilized condition at N_0 level, while it had synergistic effect at N_{50} and N_{100} levels; and (iv) P content was more under sterilized condition at P_0 level, while with the addition of P the differences were meagre under both sterilized and non-sterilized conditions.

At 90th day, the interactions viz., S x N, S x P, S x St, N x P, N x St and P x St were significant. The important inferences drawn are: (i) root P content was higher in the red soil under non-sterilized condition than in the black soil; and (ii) root P content was increased by the combined effect of N and P.

4.7.1.3. Effect on K content (Table 23)

Individual effects

i) Sterilization: The mean value for this main effect ranged from 0.31 to 1.21 per cent. Under sterilized condition of the soil root K content was significantly increased at 30 days stage, but the trend got reversed at 60 and 90 days stage.

TABLE 23. EFFECT OF TREATMENTS ON K CONTENT IN ROOT OF SORGHUM IN BLACK AND RED SOILS(%)

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Treatments	30 days	60 days	90 days
St	1.21	0.42	0.31
Nst	0.76	0.45	0.46
S ₁	1.03	0.52	0.39
S ₂	0.95	0.35	0.38
P ₀	1.35	0.47	0.33
P ₅₀	0.62	0.40	0.44
SE	0.03	0.01	0.003
CD	0.10	0.03	0.010
N ₀	0.97	0.35	0.40
N ₅₀	1.00	0.53	0.33
N ₁₀₀	0.99	0.42	0.43
SE	0.04	0.01	0.004
CD	0.12	0.04	0.012
St x S ₁	1.28	0.55	0.34
St x S ₂	1.15	0.29	0.28
Nst x S ₁	0.77	0.49	0.44
Nst x S ₂	0.74	0.40	0.48
St x P ₀	1.49	0.44	0.27
St x P ₅₀	0.94	0.41	0.36
Nst x P ₀	1.21	0.50	0.40
Nst x P ₅₀	0.31	0.39	0.51
S ₁ x P ₀	1.35	0.62	0.27
S ₁ x P ₅₀	0.70	0.42	0.51
S ₂ x P ₀	1.35	0.31	0.40
S ₂ x P ₅₀	0.55	0.38	0.37
SE	0.05	0.01	0.01
CD	0.14	0.04	0.02
St x N ₀	1.06	0.30	0.35
St x N ₅₀	1.09	0.57	0.24
St x N ₁₀₀	1.49	0.41	0.35
Nst x N ₀	0.88	0.41	0.45
Nst x N ₅₀	0.92	0.50	0.42
Nst x N ₁₀₀	0.48	0.43	0.51
S ₁ x N ₀	1.31	0.49	0.63
S ₁ x N ₅₀	1.14	0.60	0.29
S ₁ x N ₁₀₀	0.63	0.47	0.25
S ₂ x N ₀	0.63	0.21	0.18
S ₂ x N ₅₀	0.87	0.47	0.36
S ₂ x N ₁₀₀	1.34	0.36	0.60
N ₀ x P ₀	1.38	0.44	0.26
N ₀ x P ₅₀	0.56	0.26	0.55
N ₅₀ x P ₀	1.26	0.58	0.25
N ₅₀ x P ₅₀	0.74	0.49	0.40
N ₁₀₀ x P ₀	1.41	0.38	0.50
N ₁₀₀ x P ₅₀	0.57	0.45	0.36
SE	0.06	0.02	0.01
CD	0.14	0.05	0.02

ii) Soil types: The mean value for this main effect ranged from 0.35 to 1.03 per cent of root K content. The black soil recorded significantly higher root K content than the red soil at all the three stages of crop growth.

iii) P levels: The mean value for this main effect ranged from 0.33 to 1.35 per cent of K content in root. Though there was no effect for P application at 30 and 60 days stage, beneficial effect of P application was observed only at 90 days stage.

iv) N levels: The mean value for this main effect ranged from 0.35 to 1.00 per cent of root K content. Though N application did not increase the K content at 30 days stage, N₅₀ and N₁₀₀ levels significantly increased the K content at 60 and 90 days stages respectively.

Interaction effects

At 30th day, the root K content was increased due to N₁₀₀ level, in the red soil and also at sterilized condition as revealed by the interactions of N x St and S x N respectively.

At 60th day, the interactions viz., S x P, S x N, S x St, N x P, N x St and P x St were significant. The salient inferences drawn are: (i) P₅₀ level increased the

root K content in the red soil while negative effect was observed in the black soil; (ii) though under sterilized condition increased root K content in the black soil was recorded, the lowest value was associated with the red soil under sterilized condition; (iii) at N_{100} levels P_{50} application increased root K content; and (iv) P application under non-sterilized condition decreased root K content.

At 90th day, the interactions viz., S x N, S x St, S x P, N x P, N x St and P x St were significant. The salient inferences drawn include: (i) similar to that of main effect, root K content was increased by the P application in the black soil, while it was opposite in the red soil; (ii) under sterilized condition, root K content was higher in the black soil than that in the red soil; and (iii) though root K content was increased due to P application at N_0 and N_{50} levels, but it was not so at N_{100} level.

4.7.2. Effect on micronutrients content in root of sorghum plant

4.7.2.1. Effect on Fe content (Table 24)

Individual effects

i) Sterilization: The mean value for the main effect ranged from 380 to 693 ppm. Under sterilized condition of the soil the root Fe content was enhanced at 30 and 60 days stages, but reverse trend was observed at 90 days stage.

TABLE 24. EFFECT OF TREATMENTS ON Fe CONTENT IN ROOT OF SORGHUM IN BLACK AND RED SOILS (ppm)

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Treatments	30 days	60 days	90 days
St	693	442	380
NSt	538	342	419
S ₁	633	426	397
S ₂	598	358	402
P ₀	753	429	431
P ₅₀	478	355	368
SE	3.0	1.0	1.0
CD	9.0	3.0	3.0
N ₀	590	362	382
N ₅₀	620	452	457
N ₁₀₀	636	361	360
SE	4.0	1.0	1.0
CD	11.0	3.0	3.0
St x S ₁	657	499	437
St x S ₂	728	385	323
NSt x S ₁	608	353	356
NSt x S ₂	468	331	482
St x P ₀	807	477	430
St x P ₅₀	578	406	331
NSt x P ₀	699	380	432
NSt x P ₅₀	378	304	406
S ₁ x P ₀	740	446	377
S ₁ x P ₅₀	525	406	416
S ₂ x P ₀	766	412	484
S ₂ x P ₅₀	430	304	321
SE	4.0	1.0	1.0
CD	13.0	3.0	4.0
St x N ₀	670	403	356
St x N ₅₀	652	512	412
St x N ₁₀₀	755	409	373
NSt x N ₀	510	322	308
NSt x N ₅₀	589	392	408
NSt x N ₁₀₀	517	313	347
S ₁ x N ₀	532	378	382
S ₁ x N ₅₀	682	480	411
S ₁ x N ₁₀₀	684	420	397
S ₂ x N ₀	648	347	381
S ₂ x N ₅₀	559	424	504
S ₂ x N ₁₀₀	588	303	323
N ₀ x P ₀	698	386	418
N ₀ x P ₅₀	481	339	486
N ₅₀ x P ₀	802	547	388
N ₅₀ x P ₅₀	439	358	345
N ₁₀₀ x P ₀	758	354	429
N ₁₀₀ x P ₅₀	514	369	331
SE	4.0	1.0	2.0

ii) Soil types: The mean value for this main effect ranged from 358 to 633 ppm. Root Fe content was more in the black soil than that in the red soil at 30 and 60 days growth stages but at 90th day the reverse trend was observed.

iii) P levels: The mean value for this main effect remained within the range of 355 to 753 ppm. The P application tended to depress Fe accumulation in root at all the three stages studied, thereby exhibiting the antagonistic role of P on Fe.

iv) N levels: The mean value for this main effect fell within the range of 360 to 636 ppm. Though N_{100} level significantly enhanced the Fe content in root at 30 days stage but N_{50} level significantly increased the same at 60 and 90 days growth stages.

Interaction effects

At 30th day, the interactions, $S \times P$, $S \times St$ and $N \times St$ assumed relatively important significance. The salient inferences drawn include: (i) the Fe accumulation in root of sorghum crop growth in the red soil was more under P_0 level than that in the black soil, but P_{50} level accumulated more Fe in root in the black soil than in the red soil; (ii) non-sterilized condition favoured for greater accumulation of Fe in root in the black soil and the sterilized condition

favoured in the red soil; and (iii) N_{100} level under sterilized condition and N_{50} level under non-sterilized condition increased Fe accumulation in root.

At 60th day, the interactions viz., S x P, S x St and N x P showed important significance. The salient inferences drawn are: (i) irrespective of P application, the root of sorghum crop growth in the black soil showed higher concentration of Fe than that of the red soil; (ii) under both the sterilized and unsterilized conditions, the black soil favoured the Fe accumulation than the red soil; and (iii) N_{100} P_{50} combined application accounted for increased root Fe content.

At 90th day, the interactions viz., S x P, S x St and N x St showed statistical significance. The salient inferences drawn include: (i) P application enhanced the Fe accumulation in the root of sorghum crop grown in the black soil; (ii) under non-sterilized condition greater accumulation of Fe was favoured in root in the red soil than that under sterilized condition; and (iii) N_{100} level under sterilized condition enhanced the Fe accumulation in root.

4.7.2.2. Effect on Mn content (Table 25)

Individual effects

i) Sterilization: The mean values for the main effect fell within the range of 26.1 to 65.5 ppm. Under

sterilized condition, significantly higher root Mn content was recorded at 30 and 60 days stage than under non-sterilized condition, but reverse trend was observed at 90 days stage.

ii) Soil types: The mean value for the main effect ranged from 26.3 to 60.5 ppm. The root Mn content was found to be higher in the black soil than that in the red soil at 30 days stage and reverse trend was observed at 90 days stage. No such difference was observed at 60 days stage.

iii) P levels: The mean value for the main effect ranged from 28.0 to 75.0 ppm. The P application decreased root Mn content at all the three stages, thereby exhibiting antagonistic effect of P on Mn nutrition.

iv) N levels: The mean value for the main effect remained within the range of 23.5 to 64.1 ppm. Though N_{50} and N_{100} levels did not enhance root Mn content at 30th day, N application at both the levels caused a greater accumulation of Mn in root than N_0 level at 60 days stage. At 90 days stage N_{50} level increased root Mn content.

Interaction effects

The interactions viz., S x N and N x P showed important significance at 30th day. The salient inferences

TABLE 25. EFFECT OF TREATMENTS ON Mn CONTENT IN ROOT OF SORGHUM IN BLACK AND RED SOILS (ppm)

Treatments	30 days	60 days	90 days
St	65.5	32.8	26.1
NSt	49.9	26.4	37.2
S ₁	60.5	30.2	26.3
S ₂	54.9	29.0	36.9
P ₀	75.0	31.2	32.1
P ₅₀	40.5	28.0	31.1
SE	0.8	0.8	0.11
CD	2.2	2.2	0.33
N ₀	64.1	23.5	26.3
N ₅₀	53.3	32.9	36.8
N ₁₀₀	55.8	32.5	31.8
SE	0.9	0.9	0.14
CD	2.7	2.8	0.41
St x S ₁	68.6	33.9	26.3
St x S ₂	62.5	31.8	25.8
NSt x S ₁	52.5	26.5	26.4
NSt x S ₂	47.3	26.3	48.0
St x P ₀	81.1	32.4	26.9
St x P ₅₀	50.0	33.2	25.3
NSt x P ₀	68.9	30.1	33.4
NSt x P ₅₀	30.9	22.7	37.0
S ₁ x P ₀	73.9	32.6	25.0
S ₁ x P ₅₀	47.2	27.7	27.7
S ₂ x P ₀	76.1	30.0	39.3
S ₂ x P ₅₀	33.8	28.2	34.5
SE	1.10	1.10	0.2
CD	3.20	3.20	0.6
St x N ₀	68.9	27.0	21.7
St x N ₅₀	60.1	32.0	25.8
St x N ₁₀₀	67.6	39.5	30.7
NSt x N ₀	59.3	20.0	30.9
NSt x N ₅₀	46.5	33.7	47.8
NSt x N ₁₀₀	44.0	25.4	32.9
S ₁ x N ₀	66.8	20.5	22.2
S ₁ x N ₅₀	61.0	35.3	29.2
S ₁ x N ₁₀₀	53.9	34.7	24.6
S ₂ x N ₀	61.4	26.4	30.4
S ₂ x N ₅₀	45.6	30.6	44.4
S ₂ x N ₁₀₀	57.8	30.3	36.0
N ₀ x P ₀	86.1	22.9	29.7
N ₀ x P ₅₀	42.0	24.0	22.9
N ₅₀ x P ₀	67.6	36.3	37.1
N ₅₀ x P ₅₀	39.0	29.5	36.4
N ₁₀₀ x P ₀	71.3	34.6	29.6
N ₁₀₀ x P ₅₀	40.4	30.4	34.0

drawn are; (i) the black soil accumulated more of Mn in root than the red soil at N_0 and N_{50} levels, but at N_{100} level the trend was reversed; and (ii) at N_0P_0 level root Mn content was increased but at P_{50} level all N levels remained on par.

At 60th day, the notable interaction effects are $N \times P$ and $P \times St$. The important inferences drawn are: (i) in the absence of P addition N addition at two levels favoured greater Mn accumulation in root than N_0 level; (ii) sterilization or otherwise made no difference in the Mn content in root at P_0 level, but at P_{50} level Mn concentration in root was increased under sterilized condition.

At 90th day, the interactions viz., $S \times P$, $S \times St$, and $P \times St$ showed important significance. The salient inferences drawn are: (i) a synergistic role of P in the red soil and an antagonistic role of P in the black soil were observed; (ii) non-sterilized condition of the red soil and sterilized condition of the black soil caused favourable effect in the matter of Mn accumulation in root; and (iii) the antagonistic effect of P in diminishing the Mn concentration in root was pronounced only under sterilized condition.

4.7.2.3. Effect on Cu content (Table 26)

Individual effects

i) Sterilization: The mean value for this main effect ranged from 2.57 to 5.16 ppm. Under sterilized condition a significant increase in Cu content in the root was brought about at 30 days stage and the difference between sterilized and non-sterilized conditions vanished at 60 days stage. However at 90 days stage, non-sterilized condition favoured more accumulation of Cu content in root than the sterilized condition.

ii) Soil types: The mean value for this main effect ranged from 3.23 to 4.65 ppm. Root Cu content was higher in the black soil than the red soil at 60 days stage and the trend was reversed at 90 days stage. No such difference was observed at 30 days stage.

iii) P levels: The mean value for the main effect ranged from 3.09 to 5.07 ppm. P application significantly reduced root Cu content at 30 and 60 days stage, but reverse was the trend at 90 days stage.

iv) N levels: The mean value for the main effect ranged from 3.07 to 4.84 ppm. The N_{50} level significantly enhanced root Cu content at 30 and 60 days stage, but at 90 days stage N_{100} level significantly increased root Cu content.

TABLE 26. EFFECT OF TREATMENTS ON Cu CONTENT IN ROOT OF SORGHUM IN BLACK AND RED SOILS (ppm)

Treatments	30 days	60 days	90 days
St	5.16	3.72	2.57
NSt	4.08	3.79	4.44
S ₁	4.59	4.17	3.23
S ₂	4.65	3.33	3.78
P ₀	5.07	4.22	3.09
P ₅₀	4.17	3.30	3.92
SE	0.052	0.028	0.015
CD	0.151	0.082	0.045
N ₀	4.56	3.87	3.74
N ₅₀	4.84	4.33	2.98
N ₁₀₀	4.45	3.07	3.81
SE	0.063	0.034	0.019
CD	0.184	0.101	0.055
St x S ₁	5.90	5.07	2.84
St x S ₂	4.42	2.37	2.31
NSt x S ₁	3.28	3.27	3.62
NSt x S ₂	4.88	4.31	5.26
St x P ₀	5.86	3.77	2.31
St x P ₅₀	4.46	3.67	2.83
NSt x P ₀	4.28	4.66	3.88
NSt x P ₅₀	3.87	2.92	5.01
S ₁ x P ₀	4.11	4.52	2.82
S ₁ x P ₅₀	5.07	3.82	3.64
S ₂ x P ₀	6.04	3.91	3.37
S ₂ x P ₅₀	3.26	2.77	4.20
SE	0.073	0.039	0.022
CD	0.213	0.116	0.064
St x N ₀	5.33	3.91	3.00
St x N ₅₀	5.83	4.14	2.30
St x N ₁₀₀	4.33	3.11	2.42
NSt x N ₀	3.79	3.83	4.49
NSt x N ₅₀	3.86	4.51	3.66
NSt x N ₁₀₀	4.58	3.03	5.18
S ₁ x N ₀	3.74	3.63	4.11
S ₁ x N ₅₀	5.79	2.92	3.00
S ₁ x N ₁₀₀	4.24	3.47	2.58
S ₂ x N ₀	5.38	4.12	3.38
S ₂ x N ₅₀	3.90	5.73	2.95
S ₂ x N ₁₀₀	4.67	2.66	5.03
N ₀ x P ₀	5.50	3.73	3.39
N ₀ x P ₅₀	3.63	4.02	4.10
N ₅₀ x P ₀	4.79	6.12	1.79
N ₅₀ x P ₅₀	4.89	2.53	4.17
N ₁₀₀ x P ₀	4.93	2.80	4.11
N ₁₀₀ x P ₅₀	3.98	3.34	3.49
SE	0.089	0.049	0.027
CD	0.261	0.142	0.078

At 30th day, the interactions viz., S x P, S x St, N x P, N x St, S x N and P x St showed statistical significance. The salient inferences deduced are: (i) P had a synergistic effect in the black soil and an antagonistic effect in the red soil in the matter of accumulation of Cu in root; (ii) under sterilized condition root Cu concentration was enhanced in the black soil and diminished in the red soil; (iii) the antagonistic effect of P in depressing the root Cu content was observed at N₀ level and this effect was nullified at N₅₀ level and at N₁₀₀ level, no P application showed beneficial effect; and (iv) at N₀ and N₅₀ levels sterilized condition accounted for higher root Cu concentration and this effect was not observed at higher level of N.

At 60th day, the interactions viz., S x N, S x P, S x St, N x P, N x St and P x St showed statistical significance. The salient inferences deduced are: (i) under non-sterilized condition the red soil accumulated more Cu content in root than the black soil and the reverse was the case under sterilized condition; and (ii) the antagonistic effect of P in diminishing root Cu content was confined under non-sterilized condition.

At 90th day, the interactions viz., S x N; S x St N x P, N x St and P x St showed statistical significance. The salient inferences drawn include: (i) at N₀ and N₅₀ levels the black soil was found to be more favourable for Cu accumulation in root than the red soil while at N₁₀₀ level the red soil accumulated enhanced Cu concentration in root; (ii) under non-sterilized condition, the red soil caused greater accumulation of Cu in root than the black soil while under sterilized condition the black soil enhanced the Cu concentration in root; and (iii) P application showed a synergistic influence at N₀ and N₅₀ levels and an antagonistic effect at N₁₀₀ level.

4.7.2.4. Effect on Zn content (Table 27)

Individual effects

i) Sterilization: The mean value for the main effect ranged from 30.3 to 81.6 ppm. Under sterilized condition root Zn content was significantly increased at 30 and 60 days stage, but the trend was reversed at 90 days stage.

ii) Soil types: The mean value for the main effect ranged from 30.9 to 70.0 ppm. The black soil significantly enhanced root Zn content at 30 and 60 days stage, while reverse was the trend at 90 days stage.

TABLE 27. EFFECT OF TREATMENTS ON Zn CONTENT IN ROOT OF
SORGHUM IN BLACK AND RED SOILS (ppm)

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Treatments	30 days	60 days	90 days
St	81.6	40.4	30.3
NSt	52.2	31.7	5.22
S ₁	70.0	41.2	38.0
S ₂	64.0	30.9	44.5
P ₀	66.3	39.9	38.9
P ₅₀	67.5	32.3	43.6
SE	0.7	0.2	0.2
CD	2.2	0.7	0.5
N ₀	72.3	33.6	44.5
N ₅₀	68.8	41.3	42.9
N ₁₀₀	59.5	33.3	36.4
SE	0.9	0.3	0.2
CD	2.7	0.8	0.6
St x S ₁	82.8	48.9	31.8
St x S ₂	80.4	31.8	28.7
NSt x S ₁	57.0	33.4	44.2
NSt x S ₂	47.3	30.1	60.3
St x P ₀	76.7	43.6	29.0
St x P ₅₀	86.5	37.1	31.6
NSt x P ₀	55.9	36.0	48.8
NSt x P ₅₀	48.4	27.4	55.6
S ₁ x P ₀	62.2	44.8	29.0
S ₁ x P ₅₀	77.6	37.6	47.0
S ₂ x P ₀	70.4	34.8	48.8
S ₂ x P ₅₀	57.3	27.0	40.2
SE	1.1	0.3	0.2
CD	3.1	0.9	0.7
St x N ₀	91.5	38.0	33.5
St x N ₅₀	81.3	45.1	31.3
St x N ₁₀₀	72.0	37.9	26.1
NSt x N ₀	53.1	29.1	55.5
NSt x N ₅₀	56.4	37.4	54.5
NSt x N ₁₀₀	47.0	28.7	46.7
S ₁ x N ₀	77.5	35.0	47.3
S ₁ x N ₅₀	76.3	46.7	35.8
S ₁ x N ₁₀₀	55.9	41.8	30.9
S ₂ x N ₀	67.1	32.1	41.7
S ₂ x N ₅₀	61.4	35.9	50.0
S ₂ x N ₁₀₀	63.1	24.8	41.8
N ₀ x P ₀	72.1	33.7	44.3
N ₀ x P ₅₀	72.5	33.5	44.7
N ₅₀ x P ₀	76.3	55.0	38.6
N ₅₀ x P ₅₀	61.4	27.6	47.2
N ₁₀₀ x P ₀	50.5	30.8	33.8
N ₁₀₀ x P ₅₀	68.5	35.8	38.9

iii) P levels: The mean value for the main effect ranged from 32.3 to 67.5 ppm. The P application increased root Zn content at 30 and 90 days stage, but this effect was not observed at 60 days stage.

iv) N levels: The mean value for the main effect ranged from 33.3 to 72.3 ppm. N₅₀ level significantly enhanced root Zn content at 60 days stage, but the beneficial effect of N application was not observed at 30 and 90 days of crop growth.

Interaction effects

At 30th day, the interactions viz., S x N, S x P, S x St, N x P, N x St and P x St showed statistical significance. The salient inferences drawn are: (i) the black soil favoured more accumulation of Zn content in the root due to P addition than the red soil; (ii) under non-sterilized condition the black soil favoured more accumulation of zinc content in the root than the red soil and this effect was nullified under sterilized condition; (iii) in the absence of N addition application of P brought about no differential effect on root Zn content; (iv) at N₅₀ level antagonistic effect and at N₁₀₀ level synergistic effect had operated; and (v) P addition under sterilized condition enhanced root Zn content.

At 60th day, the interactions viz., S x N, S x St, N x P and P x St were significant. It was observed that in the absence of N addition P application brought about no differential effect on root Zn content.

At 90th day, the interactions viz., S x N, S x P, S x St, N x P, N x St and P x St showed statistical significance. The salient points of inferences drawn are: (i) enhanced root Zn content was observed in the red soil in the absence of P addition and more Zn content was observed in the black soil at added P level; (ii) sterilized condition favoured higher root Zn content in the black soil while non-sterilized condition proved more conducive for the red soil than the black soil; and (iii) the synergistic effect of P became pronounced at N₅₀ and N₁₀₀ levels.

4.7.3. Effect on N, P and K content in shoot of sorghum plant

4.7.3.1. Effect on N content (Table 28)

Individual effects

i) Sterilization: The mean value for this main effect ranged from 0.52 to 1.41 per cent. Under sterilized condition shoot N content was enhanced at 30 and 60 days stages but the trend was reversed at 90 days stage.

ii) Soil types: The mean value for this main effect ranged from 0.50 to 1.16 per cent. The black soil registered

significantly higher shoot N content at 30 and 60 days stages but reverse was the case at 90 days stage.

iii) P levels: The mean value for this main effect fell within the range of 0.52 to 1.23 per cent. Though P application did not increase N content in shoot at 30 days stage, it produced marginal increase at 60 days stage and spectacular increase at 90 days stage.

iv) N levels: The mean value for this main effect ranged from 0.50 to 1.33 per cent. N_{100} level enhanced shoot N content at 30 and 90 days stage, but there was no differential effect due to N application at two levels at 60 days stage.

Interaction effects

At 30th day, the interactions viz., $S \times N$, $S \times St$, $N \times P$, $N \times St$ and $P \times St$ showed statistical significance. The salient inferences drawn include: (i) N accumulation in the shoot of sorghum crop grown in the black soil was greater at N_{100} level than that in the red soil, whereas in the red soil the effect due to N application at both the levels was not observed; (ii) there was greater accumulation of N in shoot in both the soils under sterilized condition; (iii) accumulation of N was greater at $N_{100} P_0$ level than the other level of combinations; (iv) irrespective of sterilization

TABLE 28. EFFECT OF TREATMENTS ON N CONTENT IN SHOOT OF SORGHUM IN BLACK AND RED SOILS(%)

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Treatments	30 days	60 days	90 days
St	1.41	1.37	0.52
NSt	0.94	1.09	0.56
S ₁	1.30	1.30	0.50
S ₂	1.60	1.16	0.58
P ₀	1.23	1.22	0.52
P ₅₀	1.13	1.24	0.57
SE	0.01	0.01	0.002
CD	0.03	0.04	0.005
N ₀	1.26	1.25	0.52
N ₅₀	0.94	1.21	0.50
N ₁₀₀	1.33	1.23	0.61
SE	0.01	0.02	0.002
CD	0.04	0.05	0.007
St x S ₁	1.58	1.37	0.44
St x S ₂	1.25	1.37	0.60
NSt x S ₁	1.01	1.24	0.56
NSt x S ₂	0.87	0.95	0.57
St x P ₀	1.41	1.30	0.52
St x P ₅₀	1.42	1.44	0.52
NSt x P ₀	1.04	1.14	0.51
NSt x P ₅₀	0.84	1.05	0.62
S ₁ x P ₀	1.35	1.27	0.45
S ₁ x P ₅₀	1.24	1.33	0.55
S ₂ x P ₀	1.10	1.17	0.58
S ₂ x P ₅₀	1.01	1.15	0.59
SE	0.02	0.02	0.003
CD	0.05	0.06	0.008
St x N ₀	1.53	1.36	0.46
St x N ₅₀	1.09	1.39	0.46
St x N ₁₀₀	1.63	1.35	0.66
NSt x N ₀	1.00	1.15	0.59
NSt x N ₅₀	0.78	1.03	0.53
NSt x N ₁₀₀	1.04	1.10	0.57
S ₁ x N ₀	1.31	1.34	0.41
S ₁ x N ₅₀	1.14	1.24	0.53
S ₁ x N ₁₀₀	1.45	1.32	0.57
S ₂ x N ₀	1.22	1.17	0.63
S ₂ x N ₅₀	0.74	1.18	0.46
S ₂ x N ₁₀₀	1.21	1.13	0.66
N ₀ x P ₀	1.31	1.26	0.38
N ₀ x P ₅₀	1.22	1.25	0.67
N ₅₀ x P ₀	0.93	1.21	0.42
N ₅₀ x P ₅₀	0.95	1.21	0.57
N ₁₀₀ x P ₀	1.45	1.19	0.75
N ₁₀₀ x P ₅₀	1.22	1.26	0.48
..	0.02	0.02	0.003

N_{100} level proved to be much better in accumulation of N in shoot than N_0 and N_{50} levels; and (v) accumulation of N was greater in shoot under sterilized condition irrespective of P application.

At 60th day, the interactions viz., S x N, S x St, N x St and P x St showed statistical significance. The salient inferences drawn are: (i) irrespective of the levels of N tried, accumulation of N in shoot was greater in the black soil than that in the red soil; (ii) under sterilized condition as observed at 30th day, there was enhanced shoot N content in both the soils as well as at all levels of N and P tried.

At 90th day, the interactions viz., S x P, S x N, S x St, N x P, N x St and P x St assumed statistical significance. The salient inferences drawn are: (i) accumulation of N in shoot was enhanced at N_{100} level and P_{50} level in both the soils; (ii) irrespective of P application and sterilized condition there was enhanced accumulation of N in shoot of the test crop grown in the red soil; (iii) at P_0 level N_{100} level registered enhanced accumulation of N in shoot while the trend was reversed at P_{50} level; and (iv) accumulation of N in shoot was increased under sterilized condition at N_{100} level and P_0 level, while under non-sterilized condition at N_0 level and P_{50} level the same was increased.

4.7.3.2. Effect on P content (Table 29)

Individual effects

i) Sterilization: The mean value for this main effect fell within the range of 0.09 to 0.15 per cent. Under sterilized condition shoot P content was enhanced at 30 days stage, but the trend was reversed at 60 and 90 days stage.

ii) Soil types: The mean value for this main effect ranged from 0.09 to 0.14 per cent. The black soil registered significantly higher content of P in shoot than the red soil at all the three stages of crop growth.

iii) P levels: The mean value for this main effect fell within the range of 0.08 to 0.14 per cent. The P application enhanced shoot P content at 60 days stage, but such effect was not observed at 30 and 90 days stage.

iv) N levels: The mean value for this main effect fell within the range of 0.06 to 0.13 per cent. N_{100} level significantly increased shoot P content at 30 and 60 days of crop growth, but at 90 days stage either N_{50} or N_{100} level did not increase shoot P content.

Interaction effects

At 30th day, the interactions viz., S x N, S x P, S x St, N x P, N x St and P x St showed statistical

TABLE 29. EFFECT OF TREATMENTS ON P CONTENT IN SHOOT OF SORGHUM IN BLACK AND RED SOILS (%)

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Treatments	30 days	60 days	90 days
St	0.15	0.09	0.11
NSt	0.09	0.10	0.12
S ₁	0.14	0.10	0.14
S ₂	0.10	0.09	0.09
P ₀	0.14	0.08	0.14
P ₅₀	0.10	0.11	0.08
SE	0.0005	0.002	0.003
CD	0.001	0.005	0.009
N ₀	0.10	0.10	0.19
N ₅₀	0.12	0.08	0.09
N ₁₀₀	0.13	0.11	0.06
SE	0.0006	0.002	0.004
CD	0.002	0.006	0.011
St x S ₁	0.18	0.07	0.11
St x S ₂	0.12	0.10	0.11
NSt x S ₁	1.02	0.13	0.17
NSt x S ₂	0.07	0.08	0.07
St x P ₀	0.20	0.08	0.11
St x P ₅₀	0.10	0.10	0.11
NSt x P ₀	0.08	0.08	0.18
NSt x P ₅₀	0.10	0.12	0.06
S ₁ x P ₀	0.14	0.07	0.17
S ₁ x P ₅₀	0.14	0.12	0.10
S ₂ x P ₀	0.13	0.08	0.12
S ₂ x P ₅₀	0.06	0.10	0.07
SE	0.0007	0.002	0.004
CD	0.002	0.007	0.012
St x N ₀	0.09	0.08	0.15
St x N ₅₀	0.19	0.09	0.11
St x N ₁₀₀	0.17	0.09	0.06
NSt x N ₀	0.11	0.11	0.22
NSt x N ₅₀	0.05	0.07	0.07
NSt x N ₁₀₀	0.10	0.13	0.06
S ₁ x N ₀	0.10	0.09	0.22
S ₁ x N ₅₀	0.14	0.07	0.15
S ₁ x N ₁₀₀	0.18	0.13	0.03
S ₂ x N ₀	0.10	0.11	0.15
S ₂ x N ₅₀	0.09	0.08	0.04
S ₂ x N ₁₀₀	0.09	0.08	0.09
N ₀ x P ₀	0.12	0.06	0.30
N ₀ x P ₅₀	0.08	0.13	0.08
N ₅₀ x P ₀	0.17	0.10	0.06
N ₅₀ x P ₅₀	0.07	0.06	0.13
N ₁₀₀ x P ₀	0.12	0.08	0.08
N ₁₀₀ x P ₅₀	0.15	0.14	0.04
SE	0.0007	0.003	0.005

significance. The salient inferences drawn are: (i) irrespective of the levels of N and P tried and sterilized condition, there was greater accumulation of P in shoot of test crop grown in the black soil; (ii) the combined application of $N_{100} P_{50}$ level enhanced shoot P content; (iii) under sterilized condition at N_{50} and N_{100} levels shoot P content was increased, while at N_0 level the trend was reversed; (iv) under non-sterilized condition P application increased shoot P content, while under sterilized condition no P treatment increased shoot P content.

At 60th day, the interactions viz., S x N, S x P, S x St, N x P, N x St and P x St showed significance. The salient inferences drawn are: (i) the black soil at N_{100} level and the red soil at N_0 level enhanced shoot P content, while P_{50} level enhanced the same in both the soils; (ii) the black soil under non-sterilized condition and the red soil under sterilized condition enhanced shoot P content; (iii) $N_{100}P_{50}$ level and $N_{50}P_0$ level proved to be better in accumulating P content in shoot compared to other combined applications; (iv) N_{100} level under non-sterilized condition, while under sterilized condition N_{100} and N_{50} levels being on par increased shoot P content; and (v) irrespective of sterilized condition P_{50} level enhanced shoot P content.

At 90th day, the interactions viz., S x N, S x St, N x P, N x St and P x St were significant. The important

inferences drawn are: (i) N_0 level showed enhanced shoot P content in both the soils; (ii) as was observed at 60th day, the black soil under non-sterilized condition and the red soil under sterilized condition enhanced shoot P content; (iii) with N_{50} and N_{100} applications there was reduction in the accumulation of shoot P content irrespective of sterilized condition; and (iv) under sterilized condition P application was needed for increasing shoot P content.

4.7.3.3 Effect on K content (Table 30)

Interaction effects

i) Sterilization: The mean value for this main effect fell within the range of 1.44 to 2.09 per cent. Under normal condition of the soil, shoot K content was significantly higher than under sterilized condition at 30 and 60 days stage while the trend was reversed at 90 days of crop growth stage.

ii) Soil types: The mean value for this main effect ranged from 1.51 to 1.90 per cent. The black soil significantly increased shoot K content at 30 days stage and a reverse trend was observed at 90 days stage. There was no difference on K content among the two soils at 60 days stage.

iii) P levels: The mean value for this main effect ranged from 1.49 to 1.88 per cent. Though P application did

TABLE 30. EFFECT OF TREATMENTS ON K CONTENT IN SHOOT OF SORGHUM IN BLACK AND RED SOILS(2)

Treatments	30 days	60 days	90 days
St	1.45	1.59	1.70
NSt	1.71	2.09	1.44
S ₁	1.65	1.90	1.53
S ₂	1.51	1.79	1.62
P ₀	1.66	1.81	1.49
P ₅₀	1.50	1.88	1.65
SE	0.014	0.031	0.01
CD	0.041	0.089	0.03
N ₀	1.54	1.87	1.56
N ₅₀	1.51	1.84	1.51
N ₁₀₀	1.68	1.83	1.65
SE	0.017	0.037	0.012
CD	0.050	0.109	0.035
St x S ₁	1.48	1.41	1.49
St x S ₂	1.42	1.78	1.90
NSt x S ₁	1.81	2.40	1.56
NSt x S ₂	1.60	1.89	1.33
St x P ₀	1.50	1.59	1.55
St x P ₅₀	1.40	1.60	1.84
NSt x P ₀	1.81	2.04	1.42
NSt x P ₅₀	1.60	2.16	1.47
S ₁ x P ₀	1.77	1.90	1.36
S ₁ x P ₅₀	1.53	1.90	1.69
S ₂ x P ₀	1.55	1.72	1.62
S ₂ x P ₅₀	1.47	1.85	1.61
SE	0.02	0.04	0.01
CD	0.06	0.13	0.04
St x N ₀	1.34	1.56	1.52
St x N ₅₀	1.31	1.61	1.65
St x N ₁₀₀	1.71	1.61	1.93
NSt x N ₀	1.75	2.18	1.60
NSt x N ₅₀	1.71	2.06	1.36
NSt x N ₁₀₀	1.66	2.06	1.37
S ₁ x N ₀	1.54	1.84	1.46
S ₁ x N ₅₀	1.69	2.12	1.61
S ₁ x N ₁₀₀	1.71	1.75	1.51
S ₂ x N ₀	1.55	1.90	1.66
S ₂ x N ₅₀	1.33	1.55	1.40
S ₂ x N ₁₀₀	1.65	1.92	1.79
N ₀ x P ₀	1.38	1.67	1.46
N ₀ x P ₅₀	1.71	2.07	1.66
N ₅₀ x P ₀	1.45	1.72	1.32
N ₅₀ x P ₅₀	1.57	1.95	1.70
N ₁₀₀ x P ₀	2.14	2.05	1.69
N ₁₀₀ x P ₅₀	1.23	1.62	1.60
SE	0.02	0.05	0.02

not increase shoot K content at 30 days stage, its beneficial effect was marginal at 60 days stage and was pronounced at 90 days stage.

iv) N levels: The mean value for this main effect remained within the range of 1.51 to 1.87 per cent. N_{100} level markedly increased the K content in shoot at 30 and 90 days stage, while the differential behaviour due to N application was nullified at 60 days stage.

Interaction effects

At 30th day, the interactions viz., $S \times N$, $S \times P$, $S \times St$, $N \times P$, $N \times St$ and $P \times St$ assumed statistical significance. The salient inferences drawn are: (i) N_{100} level enhanced shoot K content in both the soils; (ii) irrespective of P application and irrespective of sterilized condition, the black soil showed higher K content in shoot than the red soil; (iii) the combined application of $N_{100} P_0$ and $N_0 P_{50}$ showed higher accumulation of shoot K content than the other combined applications; and (v) under sterilized condition, N_{100} level was needed for increasing shoot K content while P application showed no beneficial effect both under sterilized and normal conditions.

At 60th day, the interactions viz., $S \times N$, $S \times St$, and $N \times P$ were statistically significant. The salient inferences

drawn are: (i) accumulation of K content in shoot was greater in the black soil than that in the red soil at N_{50} level and in the red soil at N_{100} level which was on par with N_0 level; (ii) in both the soils, the non-sterilized condition proved to be much better in increasing shoot K content than the sterilized condition; and (iii) the combined application of $N_{100} P_0$ and $N_0 P_{50}$ showed higher shoot K content than the other combined applications.

At 90th day, the interactions viz., S x N, S x P, S x St, N x P, N x St and P x St assumed statistical significance. The important inferences drawn are: (i) similar to that observed at 60th day shoot K content was greater in the black soil than the red soil at N_{50} level and in the red soil at N_{100} level; (ii) P application enhanced shoot K content in the black soil while it showed no increasing trend in the red soil; (iii) the black soil under normal condition, while the red soil under sterilized condition and the combined applications of $N_{100} P_0$ and $N_{50} P_{50}$ showed beneficial effect in enhancing shoot K content; and (iv) under sterilized condition N_{100} level was needed to enhance shoot K content and irrespective of sterilized condition P application was found to be better in accumulating K content in shoot than no P application.

4.7.4. Effect on micronutrient content in shoot of sorghum plant

4.7.4.1. Effect on Fe content (Table 31)

Individual effects

i) Sterilization: The mean value for this main effect ranged from 1056 to 3328 ppm. Under sterilized condition, shoot Fe content was not enhanced at 30 days stage but at 60 and 90 days stage the same was increased.

ii) Soil types: The mean value for this main effect ranged from 1124 to 2990 ppm. The black soil significantly enhanced shoot Fe content at all the three stages of crop growth.

iii) P levels: The mean value for this main effect ranged from 1275 to 2810 ppm. The P application had no effect on shoot Fe content at 30 and 60 days of crop growth and produced marginal increase at 90 days stage.

iv) N levels: The mean value for this main effect ranged from 1172 to 2766 ppm. The N application at the two levels did not enhance shoot Fe content at all the three stages of crop growth.

Interaction effects

At 30th day, the interactions viz., S x N, S x P, S x St, N x P, N x St and P x St assumed statistical

TABLE 31. EFFECT OF TREATMENTS ON Fe CONTENT IN SHOOT OF SORGHUM IN BLACK AND RED SOILS(ppm)

197

Treatments	30 days	60 days	90 days
St	1600	3231	1504
NSt	3328	1257	1056
S ₁	2556	2990	1436
S ₂	2372	1498	1124
P ₀	2810	2380	1275
P ₅₀	2118	2158	1286
SE	4.00	13.0	27
CD	12.0	37.0	79
N ₀	2662	2766	1405
N ₅₀	2138	1672	1263
N ₁₀₀	2592	2294	1172
SE	5.0	16.0	33
CD	14.0	46.0	97
St x S ₁	988	4703	1804
St x S ₂	2213	1759	1204
NSt x S ₁	4123	1277	1068
NSt x S ₂	2532	1238	1045
St x P ₀	1777	3342	1479
St x P ₅₀	1424	3113	1529
NSt x P ₀	3843	1312	1070
NSt x P ₅₀	2812	1203	1042
S ₁ x P ₀	2686	3279	1429
S ₁ x P ₅₀	2426	2701	1443
S ₂ x P ₀	2934	1381	1120
S ₂ x P ₅₀	1810	1615	1129
SE	6.0	18.0	38.0
CD	17.0	53.0	111.2
St x N ₀	1833	4182	1847
St x N ₅₀	1439	2144	1330
St x N ₁₀₀	1530	3367	1335
NSt x N ₀	3491	1350	963
NSt x N ₅₀	2838	1201	1196
NSt x N ₁₀₀	3654	1221	1010
S ₁ x N ₀	2469	3553	1688
S ₁ x N ₅₀	2534	2155	1463
S ₁ x N ₁₀₀	2664	3262	1157
S ₂ x N ₀	2854	1979	1122
S ₂ x N ₅₀	1743	1190	1063
S ₂ x N ₁₀₀	2521	1325	1188
N ₀ x P ₀	3393	2213	1457
N ₀ x P ₅₀	1930	3319	1352
N ₅₀ x P ₀	1992	1868	1341
N ₅₀ x P ₅₀	2285	1476	1185
N ₁₀₀ x P ₀	3045	2908	1025
N ₁₀₀ x P ₅₀	2139	1679	1320
SE	7.0	22.0	47
CD	20.0	64.0	137

significance. The salient inferences drawn are: (i) the black soil at N_{100} level and the red soil at N_0 level exhibited enhanced accumulation of Fe in shoot; (ii) irrespective of P application both the soils and irrespective of the soil type normal condition of the soil exhibited enhanced Fe content in shoot; (iii) combined application of $N_{50} P_{50}$ and $N_{100} P_0$ showed higher accumulation of Fe in shoot than the other combined applications; and (iv) irrespective of N and P levels tried, the normal condition of the soil showed higher concentration of Fe in shoot than the sterilized condition.

At 60th day, the interactions viz., S x N, S x P, S x St, N x P, N x St and P x St assumed statistical significance. The salient inferences drawn are: (i) irrespective of N and P levels tried the black soil showed higher concentration of Fe in shoot than the red soil; (ii) both the soils under sterilized condition showed higher concentration of Fe in shoot than under non-sterilized condition; (iii) the combined application of $N_{100} P_0$ and $N_0 P_{50}$ showed higher accumulation of Fe in shoot than the other combined applications; and (iv) irrespective of N and P levels tried the sterilized condition showed higher concentration of Fe in shoot than the non-sterilized condition.

At 90th day, the interactions viz., S x N, S x St, N x P and N x St showed statistical significance. The

important inferences drawn are: (i) irrespective of N application, the black soil showed higher accumulation of Fe in shoot than the red soil while a marginal increase was observed in the red soil at N_{100} level; (ii) under sterilized condition there was enhanced shoot Fe content in both the soils and at all levels of N tried as compared to that under normal condition of the soil; and (iii) the combined application of N_0P_{50} on par with $N_{100}P_{50}$ and $N_{50}P_{50}$ showed higher concentration of Fe in shoot than the other combined applications.

4.7.4.2. Effect on Mn content (Table 32)

Individual effects

i) Sterilization: The mean value for this main effect ranged from 71 to 317 ppm. Under sterilized condition shoot Mn content was significantly increased at all the three stages of crop growth.

ii) Soil types: The mean value for this main effect ranged from 79 to 331 ppm. The black soil significantly enhanced shoot Mn content at all the three stages of crop growth.

iii) P levels: The mean value for this main effect ranged from 101 to 319 ppm. The P application did not enhance shoot Mn content at all the three stages of crop growth.

TABLE 32. EFFECT OF TREATMENTS ON Mn CONTENT IN SHOOT OF
SORGHUM IN BLACK AND RED SOILS (ppm)

200

Treatments	30 days	60 days	90 days
St	317	253	160
NSL	220	92	71
S ₁	331	223	152
S ₂	207	122	79
P ₀	319	179	130
P ₅₀	218	166	101
SE	1.4	1.2	0.4
CD	4.0	3.4	1.3
N ₀	289	185	129
N ₅₀	267	156	95
N ₁₀₀	250	177	122
SE	1.7	1.4	0.5
CD	5.0	4.1	1.5
St x S ₁	389	339	227
St x S ₂	245	166	94
NSL x S ₁	273	107	77
NSL x S ₂	168	78	64
St x P ₀	422	271	191
St x P ₅₀	212	234	130
NSL x P ₀	216	86	70
NSL x P ₅₀	225	98	72
S ₁ x P ₀	399	240	178
S ₁ x P ₅₀	263	206	127
S ₂ x P ₀	239	118	83
S ₂ x P ₅₀	174	127	75
SE	2.0	1.6	0.4
CD	5.7	5.0	1.3
St x N ₀	327	276	183
St x N ₅₀	333	220	126
St x N ₁₀₀	290	262	173
NSL x N ₀	252	93	76
NSL x N ₅₀	201	92	65
NSL x N ₁₀₀	209	92	72
S ₁ x N ₀	306	224	172
S ₁ x N ₅₀	342	205	121
S ₁ x N ₁₀₀	345	239	164
S ₂ x N ₀	273	146	86
S ₂ x N ₅₀	192	107	70
S ₂ x N ₁₀₀	154	114	81
N ₀ x P ₀	360	198	158
N ₀ x P ₅₀	218	172	100
N ₅₀ x P ₀	313	150	96
N ₅₀ x P ₅₀	221	162	95
N ₁₀₀ x P ₀	283	189	137
N ₁₀₀ x P ₅₀	216	165	107
SE	2.4	2.0	0.7

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iv) N levels: The mean value for this main effect ranged from 95 to 289 ppm. The N application at the two levels did not enhance shoot Mn content at all the three stages of crop growth.

Interaction effects

At 30th day, the interactions viz., S x N, S x P, S x St, N x P, N x St and P x St were significant. The salient inferences drawn are: (i) irrespective of the levels of N and P tried the black soil showed higher shoot Mn content than the red soil; (ii) under sterilized condition both the soils showed increased shoot Mn content; (iii) the combined application of $N_{50} P_{50}$ being on par with $N_0 P_{50}$ and $N_{100} P_{50}$ registered greater accumulation of Mn in shoot than the other combined applications; and (iv) at all N levels under sterilized condition and at P_0 level under sterilized condition, while at P_{50} level non-sterilized condition were found to increase the accumulation of Mn in shoot.

At 60th day, the interactions viz., S x N, S x P, S x St, N x P, N x St, and P x St were significant. The salient inferences drawn are: (i) irrespective of levels of N and P tried the black soil showed higher Mn content in shoot than the red soil; however, the black soil at N_{100} and P_0 level and the red soil at N_0 and P_{50} levels proved to be

better in increasing Mn content in shoot; (ii) sterilized condition helped to enhance Mn accumulation in shoot in both the soils and at all levels of N and P tried.

At 90th day, the interactions viz., S x N, S x P, S x St, N x P, N x St and P x St attained statistical significance. The salient inferences drawn are: (i) at all levels of N and P the black soil showed enhanced shoot Mn content; (ii) irrespective of N and P applications at all levels and irrespective of soil types sterilized condition registered increased shoot Mn content; and (iii) the combined application of N₁₀₀ P₅₀ showed higher accumulation of Mn in the shoot than the other combined applications.

4.7.4.3. Effect on Cu content (Table 33)

Individual effects

i) Sterilization: The mean value for this main effect ranged from 23.1 to 107.0 ppm. Under sterilized condition shoot Cu content at 60 and 90 days of crop growth was increased, while under normal soil condition shoot Cu content showed increasing trend at 30 days stage.

ii) Soil types: The mean value for this main effect ranged from 26.8 to 108.6 ppm. The red soil showed increased

TABLE 33. EFFECT OF TREATMENTS ON Cu CONTENT IN SHOOT OF SORGHUM IN BLACK AND RED SOILS (ppm)

203

Treatments	30 days	60 days	90 days
St	23.1	98.7	107.0
NSt	31.2	83.6	79.1
S ₁	26.8	104.0	108.6
S ₂	27.6	78.3	79.5
P ₀	29.8	90.6	85.6
P ₅₀	24.6	91.7	85.5
SE	0.3	0.7	0.6
CD	0.9	2.1	1.7
N ₀	27.3	91.5	93.1
N ₅₀	28.1	79.0	93.7
N ₁₀₀	26.2	102.9	92.4
SE	0.4	0.9	0.7
CD	1.1	2.6	2.0
St x S ₁	21.4	120.3	122.0
St x S ₂	24.8	77.2	91.9
NSt x S ₁	32.2	87.8	95.2
NSt x S ₂	30.3	79.4	64.1
St x P ₀	26.9	100.2	111.8
St x P ₅₀	19.4	97.3	102.2
NSt x P ₀	32.7	81.0	89.4
NSt x P ₅₀	29.8	86.2	68.8
S ₁ x P ₀	26.2	103.3	119.7
S ₁ x P ₅₀	27.4	104.8	97.5
S ₂ x P ₀	33.4	77.9	81.5
S ₂ x P ₅₀	21.7	78.7	73.5
SE	0.4	1.0	0.8
CD	1.3	2.9	2.4
St x N ₀	22.9	98.3	111.3
St x N ₅₀	22.9	71.7	104.5
St x N ₁₀₀	23.6	126.3	105.1
NSt x N ₀	31.6	84.7	74.9
NSt x N ₅₀	33.2	86.6	83.0
NSt x N ₁₀₀	28.9	79.5	79.6
S ₁ x N ₀	20.7	104.1	107.8
S ₁ x N ₅₀	30.5	91.7	119.4
S ₁ x N ₁₀₀	29.4	116.4	98.7
S ₂ x N ₀	33.8	78.9	78.4
S ₂ x N ₅₀	25.6	66.6	68.1
S ₂ x N ₁₀₀	23.2	89.4	86.0
N ₀ x P ₀	31.6	87.8	91.2
N ₀ x P ₅₀	22.9	95.2	94.9
N ₅₀ x P ₀	30.9	74.6	114.9
N ₅₀ x P ₅₀	25.3	83.7	72.6
N ₁₀₀ x P ₀	26.9	109.5	95.7
N ₁₀₀ x P ₅₀	25.6	96.3	89.0
SE	0.5	1.2	1.0

Cu content in shoot of sorghum crop at 30 days stage while the black soil showed increasing trend at 60 and 90 days stage.

iii) P levels: The mean value for this main effect ranged from 24.6 to 100.6 ppm. Though P application did not increase shoot Cu content at 30 and 90 days stage, it produced marginal increase at 60 days stage.

iv) N levels: The mean value for this main effect ranged from 26.2 to 102.9 ppm. The N application at 100 kg level showed marked increase of shoot Cu content at 60 days stage but at 30 and 90 days it showed only marginal increase.

Interaction effects

At 30th day, the interactions viz., S x N, S x P, S x St, N x P, N x St and P x St attained statistical significance. The salient inferences drawn are: (i) the red soil registered greater accumulation of Cu in shoot at N_0 level and P_0 level than the black soil while the black soil registered greater, accumulation of Cu in shoot at N_{50} and N_{100} levels and at P_{50} level than the red soil; (ii) in both the soils, under sterilized condition shoot Cu content was not increased in both the soil types; (iii) $N_0 P_0$ level on par with $N_{50} P_0$ and $N_{100} P_{50}$ level on par with $N_{50} P_{50}$ level

increased shoot Cu content; and (iv) at all levels of N and P tried under non-sterilized condition higher accumulation of shoot Cu content was registered than under sterilized condition.

At 60th day, the interactions viz., S x St, N x P, S x P, N x St and P x St attained statistical significance. The salient inferences drawn are: (i) under sterilized condition shoot Cu content was enhanced in the black soil at N_0 and N_{100} levels and at P_0 and P_{50} levels, whereas under non-sterilized condition it was enhanced in the red soil at N_{50} level; and ii) combined application of N_0P_{50} and $N_{100}P_0$ increased shoot Cu content, however the combined application of $N_{100}P_{50}$ was on par with N_0P_{50} application.

At 90th day, the interactions viz., S x N, S x P, N x P, N x St and P x St was significant. The important inferences drawn include: (i) the black soil registered greater accumulation of Cu in shoot at N_{50} level than the red soil while the red soil at N_{100} level than the black soil; (ii) irrespective of P application the black soil registered higher accumulation of shoot Cu content than the red soil; (iii) under sterilized condition higher accumulation of Cu in shoot was registered than under non-sterilized condition at all levels of N and P; and (iv) the combined application of $N_{50}P_0$ and N_0P_{50} were found to be significantly superior than the other combined applications in accumulating Cu content in shoot.

4.7.4.4. Effect on Zn content (Table 34)

Individual effects

i) Sterilization: The mean value for this main effect ranged from 162 to 337 ppm. Under sterilized condition shoot Zn content was increased significantly at 30 days stage only.

ii) Soil types: The mean value for this main effect ranged from 163 to 278 ppm. The black soil showed higher shoot Zn content than the red soil at 30 days stage growth, while at 60 and 90 days stage the effect due to soil types was insignificant.

iii) P levels: The mean value for this main effect ranged from 175 to 269 ppm. The P application significantly enhanced Zn content in shoot at 30 days stage only.

iv) N levels: The mean value for this main effect ranged from 171 to 274 ppm. The N application at 100 kg level significantly increased shoot Zn content at 30 days stage only.

Interaction effects

At 30th day, the interactions viz., S x N, S x P, N x P and N x St were significant. The salient inferences drawn are:

TABLE 34. EFFECT OF TREATMENTS ON Zn CONTENT IN SHOOT OF SORGHUM IN BLACK AND RED SOILS (ppm)

207

Treatments	30 days	60 days	90 days
St	196	234	337
NSt	162	255	187
S ₁	195	265	278
S ₂	163	225	246
P ₀	175	243	269
P ₅₀	183	246	255
SE	2.7	13.0	20.0
CD	7.9	NS	NS
N ₀	171	239	249
N ₅₀	173	246	274
N ₁₀₀	194	249	263
SE	3.3	16.0	25.0
CD	9.7	NS	NS
St x S ₁	209	241	352
St x S ₂	183	228	321
NSt x S ₁	181	288	204
NSt x S ₂	144	222	170
St x P ₀	194	230	333
St x P ₅₀	199	239	340
NSt x P ₀	156	256	204
NSt x P ₅₀	168	254	171
S ₁ x P ₀	177	259	279
S ₁ x P ₅₀	213	270	277
S ₂ x P ₀	173	227	258
S ₂ x P ₅₀	154	223	234
SE	4.0	17.0	29.0
CD	11.0	NS	NS
St x N ₀	179	222	319
St x N ₅₀	195	241	346
St x N ₁₀₀	214	240	345
NSt x N ₀	163	257	178
NSt x N ₅₀	151	251	202
NSt x N ₁₀₀	172	257	181
S ₁ x N ₀	173	248	273
S ₁ x N ₅₀	193	278	297
S ₁ x N ₁₀₀	220	267	265
S ₂ x N ₀	169	230	225
S ₂ x N ₅₀	154	214	251
S ₂ x N ₁₀₀	168	230	262
N ₀ x P ₀	167	241	247
N ₀ x P ₅₀	175	238	251
N ₅₀ x P ₀	195	253	274
N ₅₀ x P ₅₀	151	239	274
N ₁₀₀ x P ₀	164	235	285
N ₁₀₀ x P ₅₀	224	262	241
SE	5.0	23.0	35.0

(i) the black soil registered greater accumulation of shoot Zn content than the red soil at all levels of N and P; (ii) the combined applications of $N_{50} P_0$ and $N_{100} P_{50}$ were found to be significantly superior than the other combined applications in accumulating Zn content in shoot; and (iii) under sterilized condition higher accumulation of shoot Zn content was registered at all levels of N.

None of the interactions were found to be significant at 60 and 90 days stages.

4.7.5. Effect on N, P and K content in sorghum grain (Table 35)

4.7.5.1. Effect on N content

Individual effect

i) Sterilization: The grain N content recorded was as 0.93 per cent and 1.25 per cent under sterilized and non-sterilized conditions respectively.

ii) Soil types: The black soil recorded significantly higher grain N content (1.17%) than the red soil (1.01%).

iii) P levels: The P application significantly depressed grain N content.

iv) N levels: The N_{100} level registered 1.19 per cent N in grain while N_0 level recorded 0.97 per cent N.

Interaction effects

The interactions viz., S x N, S x P, N x P, N x St and P x St attained statistical significance. The salient inferences drawn are: (i) the black soil at $N_{50}P_0$ level and the red soil at $N_{100}P_0$ level increased the N content in grain; (ii) at both the levels of P, N_{100} level proved to be better in increasing grain N content than the other levels of N; (iii) at all levels of N and P under normal condition of the soil grain N content was increased; and (iv) the treatment combinations $N_{100}P_0$ level proved to be the best under both sterilized and non-sterilized conditions in increasing the grain N content.

4.7.5.2. Effect on P content

Individual effects

i) Sterilization: Grain P contents recorded were as 0.07 and 0.11 per cent under sterilized and non-sterilized conditions respectively.

ii) Soil types: The red soil recorded significantly higher P content in grain (0.11%) than the black soil (0.06%).

iii) P levels: P application significantly increased grain P content.

iv) N levels: N_{100} level registered 0.13 per cent in grain while N_0 level recorded 0.08 per cent P.

Interaction effects

The interactions viz., S x N, S x P, S x St, N x P, N x St, and P x St attained statistical significance. The salient inferences drawn are: (i) at all levels of N and at P₅₀ level, the red soil registered increased grain P content; (ii) in both the soils, the combined application of N₁₀₀P₅₀ increased grain P content; (iii) irrespective of the sterilized condition the red soil registered higher P content than the black soil in grain; (iv) at both the levels of P, N₁₀₀ level registered increased P content in grain; (v) similarly at all levels of N, P₅₀ level recorded higher grain P content; (vi) at all levels of N and P, the non-sterilized condition recorded higher content of P in grain than the sterilized condition; and (vii) irrespective of the process of sterilized condition N₁₀₀ P₅₀ level recorded higher P content in grain.

4.7.5.3. Effect on K content

Individual effects

i) Sterilization: Grain K content recorded was 0.31 per cent and 0.44 per cent under sterilized and non-sterilized condition respectively.

ii) Soil types: The red soil significantly recorded increased K content in grain (0.48%) than the black soil (0.34%).

TABLE 35. EFFECT OF TREATMENTS ON N, P AND K CONTENTS IN
SORGHUM GRAIN IN BLACK AND RED SOILS (%)

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Treatments	Grain N%	Grain P%	Grain K%
St	0.93	0.07	0.37
NSt	1.25	0.11	0.44
S ₁	1.17	0.06	0.34
S ₂	1.01	0.11	0.48
P ₀	1.22	0.06	0.47
P ₅₀	0.96	0.12	0.34
SE	0.005	0.001	0.003
CD	0.014	0.003	0.009
N ₀	0.97	0.08	0.38
N ₅₀	1.11	0.05	0.35
N ₁₀₀	1.19	0.13	0.49
SE	0.007	0.001	0.004
CD	0.02	0.004	0.010
St x S ₁	1.01	0.05	0.32
St x S ₂	0.85	0.09	0.43
NSt x S ₁	1.33	0.08	0.35
NSt x S ₂	1.17	0.14	0.53
St x P ₀	1.01	0.04	0.43
St x P ₅₀	0.85	0.10	0.32
NSt x P ₀	1.43	0.07	0.52
NSt x P ₅₀	1.07	0.14	0.37
S ₁ x P ₀	1.36	0.06	0.32
S ₁ x P ₅₀	0.98	0.07	0.35
S ₂ x P ₀	1.08	0.05	0.62
S ₂ x P ₅₀	0.94	0.17	0.34
SE	0.007	0.002	0.004
CD	0.02	0.005	0.012
St x N ₀	0.89	0.07	0.34
St x N ₅₀	0.92	0.04	0.34
St x N ₁₀₀	0.98	0.09	0.45
NSt x N ₀	1.06	0.09	0.43
NSt x N ₅₀	1.29	0.05	0.37
NSt x N ₁₀₀	1.40	0.18	0.53
S ₁ x N ₀	1.07	0.06	0.35
S ₁ x N ₅₀	1.28	0.03	0.28
S ₁ x N ₁₀₀	1.16	0.10	0.39
S ₂ x N ₀	0.88	0.10	0.42
S ₂ x N ₅₀	0.93	0.06	0.43
S ₂ x N ₁₀₀	1.22	0.17	0.59
N ₀ x P ₀	1.13	0.02	0.40
N ₀ x P ₅₀	0.82	0.14	0.36
N ₅₀ x P ₀	1.21	0.02	0.36
N ₅₀ x P ₅₀	1.01	0.07	0.34
N ₁₀₀ x P ₀	1.33	0.12	0.65
N ₁₀₀ x P ₅₀	1.05	0.15	0.33
---	0.000	0.002	0.005

iii) P levels: P application significantly decreased K content in grain.

iv) N levels: N application at N_{100} level registered 0.49 per cent K in grain while N_0 level recorded 0.38 per cent.

Interaction effects

The interactions viz., S x N, S x P, S x St, N x P, N x St and P x St showed statistical significance. The important inferences drawn include: (i) At all levels of N and at P_0 level, the red soil registered higher content of K in grain; (ii) the black soil at $N_{100} P_{50}$ level and the red soil at $N_{100} P_0$ level registered higher content of K in grain than the other levels of N and P; (iii) irrespective of the soil types under non-sterilized condition grain K content was increased; (iv) the combined applications of $N_{100} P_0$ and $N_0 P_{50}$ registered higher content of K in grain than the other combined applications; and (v) at all levels of N and P under non-sterilized condition grain K content was increased.

4.7.6. Effect on micronutrients content in sorghum grain

(Table 36)

4.7.6.1. Effect on Fe content

Individual effects

i) Sterilization: Under normal condition of the soil, Fe content in grain was recorded as 426 ppm while under

ii) Soil types: The red soil recorded significantly higher Fe content in grain (414 ppm) than the black soil (351 ppm).

iii) P levels: The P application significantly depressed Fe content in grain thereby exhibiting the P-Fe antagonistic effect.

iv) N levels: The N_{100} level recorded significantly higher Fe content in grain (420 ppm) than N_{50} level (363 ppm) and N_0 level (365 ppm).

Interaction effects

The interactions viz., S x N, S x P, S x St, N x P, N x St and P x St showed statistical significance. The salient inferences drawn are: (i) the black soil at N_0 , N_{50} and P_{50} levels recorded higher Fe content in grain than the red soil; (ii) under normal condition of the soil Fe content in grain was higher than that under sterilized condition in both the soil types and the red soil showed higher Fe content in grain than the black soil; (iii) the combined applications of $N_{100} P_0$ and $N_{50} P_{50}$ showed higher accumulation of Fe content in grain than the other combined applications; (iv) at all levels of N and P normal condition of the soil showed higher Fe content in grain than the sterilized condition.

4.7.6.2. Effect on Mn content

Individual effects

- i) Sterilization: Under normal condition of the soil, grain Mn content was recorded as 49 ppm, while under sterilized condition it was recorded as 38 ppm.
- ii) Soil types: The black soil registered significantly higher Mn content in grain (48 ppm) than the red soil (39 ppm).
- iii) P levels: The P application significantly increased Mn content in grain as compared to no P application from 40 to 46 ppm.
- iv) N levels: The N_{100} level recorded significantly higher Mn content in grain as 46 ppm on par with N_{50} level while N_0 level recorded as 39 ppm.

Interaction effects

The interactions viz., S x St, N x P and P x St assumed statistical significance. The salient inferences drawn are: (i) under normal condition of the soil, grain Mn content was higher than that under sterilized condition in both the soil types and the black soil showed higher Mn content in grain than the red soil under both the soil conditions; (ii) P application

was found to increase Mn content in grain under non-sterilized condition; and (iii) at all levels of N, P_0 level was found to increase the Mn content in grain.

4.7.6.3. Effect on Cu content

Individual effects

i) Sterilization: Under normal condition of the soil, grain Cu content was recorded as 4.89 ppm while under sterilized condition recorded as 3.01 ppm.

ii) Soil types: The red soil recorded significantly higher grain Cu content as (4.20 ppm) while the black soil recorded as 3.70 ppm.

iii) P levels: P application significantly depressed Cu content in grain from 5.64 to 2.27 ppm.

iv) N levels: N_{50} level recorded significantly higher Cu content in grain as 4.87 ppm while N_{100} level recorded as 2.98 ppm.

Interaction effects

The interaction effects viz., S x N, S x P, S x St, N x P, N x St and P x St attained statistical significance.

The salient inferences are: (i) the black soil, N_0 , N_{50} and P_0 levels recorded higher Cu content in grain than the red soil but at N_{50} level both the soils recorded higher grain Cu content than the other N levels; (ii) under normal condition grain Cu content was higher than that under sterilized condition in both the soil types and the red soil showed higher grain Cu content than the black soil under both the soil conditions; (iii) at all levels of N, P_0 level was found to increase grain Cu content; and (iv) all levels of N and P under normal condition of the soil accumulation of Cu in grain was increased.

4.7.6.4. Effect on Zn content

Individual effects

i) Sterilization: Under normal condition of the soil grain Zn content recorded was 98.3 ppm while in the sterilized condition, it was 6.31 ppm.

ii) Soil types: The red soil markedly increased the grain Zn content and recorded 100.3 ppm than the black soil (61.1 ppm).

iii) P levels: Similar to the effect of N application, P application had no significant effect in increasing grain Zn content.

iv) N levels: The N application had no significant effect in increasing Zn content in grain.

Interaction effects

The interactions viz., S x N, S x P, S x St, N x P, N x St and P x St showed statistical significance. The important inferences drawn are: (i) at all levels of N and P, the red soil registered higher content of Zn in grain than the black soil (ii) at all levels of N and P and in both the soil types, under normal condition of the soil grain Zn content was increased and the red soil recorded greater content of Zn in grain than the black soil under both the soil conditions; and (iii) at all levels of N, P_0 level was found to increase Zn content in grain.

4.7.6.5. Effect on yield of grain per plant (g) (Table 36)

Individual effects

i) Sterilization: Under sterilized condition the yield of grain was 8.5 g/plant while under normal condition of the soil it was recorded as 21.0 g/plant.

ii) Soil types: The black soil produced significantly higher grain yield (18.78 g/plant) than the red soil (10.8 g/plant).

TABLE 36. EFFECT OF TREATMENTS ON Fe, Mn, Cu and Zn CONTENTS IN GRAIN
AND YIELD OF SORGHUM GRAIN IN BLACK AND RED SOILS

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Treatments	Grain Fe (ppm)	Grain Mn (ppm)	Grain Cu (ppm)	Grain Zn (ppm)	Grain yield (g plant ⁻¹)
St	340	38	3.01	63.1	8.5
NSt	426	49	4.89	98.3	21.0
S ₁	351	48	3.70	61.1	18.7
S ₂	414	39	4.20	100.3	10.8
P ₀	448	40	5.64	91.0	12.3
P ₅₀	317	46	2.27	76.5	17.2
SE	1.00	1.0	0.04	0.40	0.3
CD	3.00	3.0	0.11	1.20	0.8
N ₀	365	39	4.01	90.1	13.7
N ₅₀	383	45	4.87	67.8	15.4
N ₁₀₀	420	46	2.98	84.4	15.1
SE	1.00	1.0	0.05	0.5	0.3
CD	4.00	3.0	0.14	1.4	1.0
St x S ₁	312	41	2.96	48.4	11.0
St x S ₂	367	35	3.09	77.8	6.0
NSt x S ₁	390	55	4.46	73.9	26.3
NSt x S ₂	461	42	5.32	122.8	15.6
St x P ₀	407	36	4.46	76.3	6.2
St x P ₅₀	272	40	1.56	50.0	10.8
NSt x P ₀	489	44	6.81	105.6	18.4
NSt x P ₅₀	362	53	2.94	91.1	23.6
S ₁ x P ₀	371	44	5.83	66.4	14.7
S ₁ x P ₅₀	331	52	1.57	55.8	22.7
S ₂ x P ₀	525	37	5.44	115.3	99.0
S ₂ x P ₅₀	303	41	2.97	85.3	11.7
SE	1.00	1.0	0.06	0.6	0.4
CD	4.00	4.0	0.16	1.6	1.1
St x N ₀	328	32	2.95	73.6	8.0
St x N ₅₀	307	40	3.88	58.0	8.8
St x N ₁₀₀	385	42	2.21	57.8	8.6
NSt x N ₀	403	46	5.07	106.5	19.3
NSt x N ₅₀	419	50	5.86	77.5	22.0
NSt x N ₁₀₀	456	50	3.74	111.0	21.5
S ₁ x N ₀	388	42	4.38	65.6	17.2
S ₁ x N ₅₀	372	49	5.15	56.4	18.9
S ₁ x N ₁₀₀	293	54	1.57	61.5	20.0
S ₂ x N ₀	343	36	3.64	114.5	10.2
S ₂ x N ₅₀	353	42	4.59	79.1	12.0
S ₂ x N ₁₀₀	547	39	4.38	107.3	10.2
N ₀ x P ₀	410	38	5.65	93.3	9.1
N ₀ x P ₅₀	321	40	2.38	86.9	18.3
N ₅₀ x P ₀	342	43	7.80	80.9	13.2
N ₅₀ x P ₅₀	384	47	1.94	54.6	17.6
N ₁₀₀ x P ₀	593	40	3.46	98.6	14.5
N ₁₀₀ x P ₅₀	247	52	2.49	70.1	15.6
SE	2.00	2.0	0.07	0.7	0.5

iii) P levels: The P_{50} level recorded significantly higher grain yield (17.2 g/plant) than P_0 level (12.3 g/plant).

iv) N levels: The N_{50} level recorded significantly higher grain yield (15.4 g/plant) on par with N_{100} level (15.1 g/plant) than N_0 level (13.7 g/plant).

Interaction effects

The interaction effects viz., S x N, S x P, S x St and N x P attained statistical significance. The important inferences drawn are: (i) at all levels of N the black soil recorded higher grain yield/plant than the red soil; in the black soil N_{100} level being on par with N_{50} level registered higher grain yield, while in the red soil the effect due to N application was not observed; (ii) in both the soil types P_{50} level was found to be significantly superior in increasing the grain yield and at both the levels of P the black soil recorded higher grain yield than the red soil; (iii) in both the soil types under sterilized condition the grain yield was not increased; (iv) irrespective of the soil condition, the black soil registered higher grain yield; and (v) at all levels of N, P_{50} levels recorded increased grain yield and at P_0 level, N_{100} level being on par with N_{50} level and at P_{50} level, N_0 level were found to increase the grain yield.

4.8. Effect on nutrient uptake by shoot

4.8.1. Effect on N, P and K uptake by shoot (Table 37)

4.8.1.1. Effect on N uptake

Individual effects

i) Sterilization: Under sterilized condition of the soil, N uptake by shoot was significantly reduced from 61.94 to 39.36 mg/plant.

ii) Soil types: The red soil recorded significantly higher uptake value of N (58.61 mg/plant) than the black soil (42.69 mg/plant).

iii) P levels: The P application exhibited no significant effect on N uptake.

iv) N levels: The N application showed no significant effect on N uptake by shoot.

v) Stages: The N uptake by shoot was remarkably high at 60 days stage (68.21 mg/plant).

Interaction effects

The interactions viz., St x S, and St x Stages attained statistical significance. The salient inferences drawn are: (i) under sterilized condition N uptake by shoot

was markedly reduced in the black soil, while in the red soil there was no variation due to soil conditions; (ii) reduction in N uptake was observed at 60 and 90 days stages under sterilized condition, while at vegetative stage N uptake by shoot was numerically higher under sterilized condition than that under normal condition of the soil.

4.8.1.2. Effect on P uptake

Neither the main effect nor interaction effect had any significant effect on P uptake by shoot.

4.8.1.3. Effect on K uptake

Individual effects

i) Sterilization: Under sterilized condition of the soil K uptake by the shoot was significantly decreased from 131.1 to 75.59 mg/plant.

ii) Soil types: The soil types showed no significant effect on K uptake by shoot.

iii) P levels: The P levels exhibited no significant effect on K uptake.

iv) N levels: The N levels showed no significant effect on K uptake.

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TABLE 37. EFFECT OF TREATMENTS ON N, P AND K UPTAKE BY SHOOT OF SORGHUM
PLANT IN BLACK AND RED SOILS (mg/plant)

Treatment (1)	K uptake (2)	P uptake (3)	K uptake (4)
St	39.36	4.58	75.59
NSt	61.94	10.86	131.11
S ₁	42.69	6.21	95.86
S ₂	58.61	9.23	110.84
P ₀	46.78	6.28	93.86
P ₅₀	54.53	9.14	112.84
SE	3.50		7.7
CD	9.90	NS	21.4
N ₀	51.95	7.85	108.0
N ₁	46.58	10.45	98.08
N ₂	53.42	6.94	103.96
St ₁	30.83	2.97	41.25
St ₂	68.21	10.32	122.13
St ₃	52.09	9.85	146.67
SE	4.30		9.4
CD	12.00	NS	26.4
St x S ₁	19.28	4.70	45.61
St x S ₂	59.44	4.45	105.56
NSt x S ₁	66.11	7.72	146.11
NSt x S ₂	57.78	14.00	116.11
St x P ₀	33.56	5.29	63.28
St x P ₅₀	45.17	3.86	87.89
NSt x P ₀	60.00	7.27	124.44
NSt x P ₅₀	63.88	14.43	137.78
S ₁ x P ₀	39.67	6.06	88.83
S ₁ x P ₅₀	45.72	6.36	102.89
S ₂ x P ₀	53.89	6.49	98.89
S ₂ x P ₅₀	63.33	11.92	122.78
SE	4.90		10.9
CD	13.90	NS	31.0
St x St ₁	35.83	2.14	35.83
St x St ₂	39.75	3.56	60.92
St x St ₃	42.50	8.03	130.00
NSt x St ₁	25.83	3.79	46.67
NSt x St ₂	96.67	17.08	183.33
NSt x St ₃	63.33	11.67	163.33
St x N ₀	36.42	6.88	71.00
St x N ₅₀	34.00	2.87	72.83
St x N ₁₀₀	47.67	3.98	82.92
NSt x N ₀	67.50	8.82	145.00
NSt x N ₅₀	59.17	18.07	123.33
NSt x N ₁₀₀	59.17	5.66	125.00

Contd..

(1)	(2)	(3)	(4)
$S_1 \times St_1$	25.00	2.78	33.33
$S_1 \times St_2$	54.75	4.08	115.08
$S_1 \times St_3$	48.33	11.78	139.17
$S_2 \times St_1$	36.67	3.16	49.17
$S_2 \times St_2$	81.67	16.56	129.17
$S_2 \times St_3$	57.50	7.92	154.17
$S_1 \times N_0$	44.75	7.04	106.83
$S_1 \times N_{50}$	39.83	7.35	92.83
$S_1 \times N_{100}$	43.50	4.23	87.92
$S_2 \times N_0$	59.17	8.65	109.17
$S_2 \times N_{50}$	53.33	13.58	103.33
$S_2 \times N_{100}$	63.33	9.64	120.00
$N_0 \times P_0$	46.25	9.51	86.67
$N_0 \times P_{50}$	57.67	6.18	129.33
$N_1 \times P_0$	37.00	4.53	82.00
$N_1 \times P_{50}$	56.17	16.40	114.17
$N_2 \times P_0$	57.08	4.79	112.92
$N_2 \times P_{50}$	49.75	4.85	95.00
$St_1 \times P_0$	25.83	3.29	35.0
$St_1 \times P_{50}$	35.83	2.64	47.5
$St_2 \times P_0$	63.64	4.46	104.92
$St_2 \times P_{50}$	72.75	16.18	139.33
$St_3 \times P_0$	50.83	11.08	141.67
$St_3 \times P_{50}$	55.00	8.61	151.67
SE	6.0		13.4
CD	17.00	NS	37.9
$St_1 \times N_0$	27.50	2.10	35.00
$St_1 \times N_{50}$	30.00	3.40	43.75
$St_1 \times N_{100}$	35.00	3.40	45.00
$St_2 \times N_0$	72.13	6.31	130.25
$St_2 \times N_{50}$	58.50	18.13	99.25
$St_2 \times N_{100}$	74.00	6.53	136.88
$St_3 \times N_0$	56.25	15.13	158.75
$St_3 \times N_{50}$	51.25	9.88	151.25
$St_3 \times N_{100}$	51.25	4.54	130.00
SE			
CD	NS	NS	NS

v) Stages: The K uptake by shoot increased with crop growth in a phased manner and was significantly high at 90 days stage but was on par with 60 days stage.

Interaction effects

The interactions viz., St x S, and St x Stages attained statistical significance. The negative effect on K uptake by shoot under sterilized condition was observed in the black soil, while it was marginal in the red soil under non-sterilized condition and also it caused a significant reduction at 60 days stage.

4.8.2. Effect on uptake of micronutrients by shoot (Table 38)

4.8.2.1. Effect on Fe uptake

Individual effects

All the individual effects viz., sterilization, soil types, P levels, N levels and stages failed to show significant effect on Fe uptake by shoot.

Interaction effects

The interactions viz., St x S and St x N showed statistical significance. Under sterilized condition Fe uptake was more in the red soil than that in the black soil,

while a positive influence on Fe uptake due to N application at 100 kg level at 30 days stage alone was observed.

4.8.2.2. Effect on Mn uptake

Individual effects

i) Sterilization: Under sterilized condition of the soil, Mn uptake by shoot was increased from 710 to 1366 $\mu\text{g/plant}$.

ii) Soil types: The soil types showed no significant effect on Mn uptake.

iii) P levels: The P application showed no significant effect on Mn uptake.

iv) N levels: The N application showed no significant effect on Mn uptake.

v) Stages: Mn uptake was significantly increased and it was the highest at 90 days stage. A stepwise increase was observed with advancement of crop growth.

Interaction effects

The interactions viz., St x S and St x Stages attained statistical significance. Though the red soil recorded higher Mn uptake value than the black soil under

sterilized condition, Mn uptake in the black soil under normal and sterilized condition of the soil was on par. Under sterilized condition of the soil at 90 days stage Mn uptake was significantly increased as compared under normal condition of the soil.

4.8.2.3. Effect on Cu uptake

Individual effects

i) Sterilization: Under normal condition of the soil Cu uptake was increased from 349 to 596 μg /plant.

ii) Soil types: The soil types showed no significant effect on Cu uptake.

iii) P levels: The P application showed no significant effect on Cu uptake.

iv) N levels: The N application also showed no significant effect on Cu uptake.

v) Stages: The Cu uptake was significantly high at 90 days stage registering 861 μg /plant and it increased stepwise with advancement of crop growth.

Interaction effects

The interactions viz., St x S, Stages x P and ... attained statistical significance. Under

TABLE 38. EFFECT OF TREATMENTS ON Fe, Mn, Cu AND Zn UPTAKE BY SHOOT OF SORGHUM PLANT IN BLACK AND RED SOILS

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Treatments (1)	Fe uptake (mg/plant) (2)	Mn uptake (µg/plant) (3)	Cu uptake (µg/plant) (4)	Zn uptake (µg/plant) (5)
St	9.63	1366	399	983
NSt	10.64	710	596	1410
S ₁	8.53	812	505	1156
S ₂	11.73	1264	490	1237
P ₀	8.65	919	495	1173
P ₅₀	11.61	1158	499	1219
SE		199	51	95
CD	NS	565	143	214
N ₀	9.37	1092	504	1170
N ₁	8.89	920	500	1263
N ₂	12.14	1093	488	1158
St ₁	9.79	624	71	480
St ₂	9.21	770	559	1240
St ₃	11.39	1777	861	1869
SE		244	44	92
CD	NS	692	123	262
St x S ₁	5.79	846	334	733
St x S ₂	13.45	1886	463	1233
NSt x S ₁	11.27	778	675	1579
NSt x S ₂	10.01	643	516	1240
St x P ₀	6.45	1220	370	872
St x P ₅₀	12.80	1512	427	1094
NSt x P ₀	10.85	617	619	1474
NSt x P ₅₀	10.43	804	572	1344
S ₁ x P ₀	8.08	782	519	1121
S ₁ x P ₅₀	9.02	842	490	1191
S ₂ x P ₀	9.26	1055	471	1226
S ₂ x P ₅₀	14.20	1473	508	1248
SE	2.11	282	51	33
CD	5.99	799	143	95
St x St ₁	10.94	673	58	513
St x St ₂	7.10	705	335	845
St x St ₃	10.82	2720	802	1592
NSt x St ₁	8.63	574	83	447
NSt x St ₂	11.33	834	783	1635
NSt x St ₃	11.97	724	920	2147

(1)	(2)	(3)	(4)	(5)
St x N ₀	8.06	1480	408	912
St x N ₅₀	7.03	1150	360	983
St x N ₁₀₀	13.78	1468	427	1054
NSt x N ₀	10.67	703	600	1427
NSt x N ₅₀	10.75	711	639	1547
NSt x N ₁₀₀	10.50	717	548	1261
S ₁ x St ₁	5.84	613	57	404
S ₁ x St ₂	7.59	695	475	1085
S ₁ x St ₃	12.16	1129	982	1978
S ₂ x St ₁	13.73	633	85	555
S ₂ x St ₂	10.84	844	644	1395
S ₂ x St ₃	10.63	2315	740	1760
S ₁ x N ₀	8.65	720	515	1153
S ₁ x N ₅₀	8.82	804	549	1163
S ₁ x N ₁₀₀	8.12	913	449	1053
S ₂ x N ₀	10.08	1464	492	1186
S ₂ x N ₅₀	8.96	1056	450	1262
S ₂ x N ₁₀₀	16.16	1272	526	1263
N ₀ x P ₀	9.59	757	501	1145
N ₀ x P ₅₀	9.13	1426	506	1193
N ₁ x P ₀	7.82	661	506	1160
N ₁ x P ₅₀	9.96	1200	493	1364
N ₂ x P ₀	8.54	1337	476	1215
N ₂ x P ₅₀	15.74	848	498	1100
St ₁ x P ₀	6.25	587	63	384
St ₁ x P ₅₀	13.32	660	78	575
St ₂ x P ₀	8.06	609	477	1132
St ₂ x P ₅₀	10.36	930	641	1348
St ₃ x P ₀	11.63	1560	943	2004
St ₃ x P ₅₀	11.15	1884	778	1734
SE	2.59	346	62	131
CD	7.34	979	175	370
St ₁ x N ₀	5.67	589	59	394
St ₁ x N ₅₀	6.59	688	82	478
St ₁ x N ₁₀₀	17.09	593	71	568
St ₂ x N ₀	9.99	755	568	1221
St ₂ x N ₅₀	7.50	669	478	1176
St ₂ x N ₁₀₀	10.15	885	631	1323
St ₃ x N ₀	12.42	1931	884	1893
St ₃ x N ₅₀	12.57	1435	939	2132
St ₃ x N ₁₀₀	9.19	1800	760	1583
SE			31	
CD	NS	NS	88	NS

sterilized condition Cu uptake was not reduced in the red soil to a marked extent in contrast to that in the black soil. The negative effect of sterilization on Cu uptake was confined to 30 and 60 days stages, while at 90 days stage the difference under sterilized and normal conditions of the soil was not marked.

4.8.2.4. Effect on Zn uptake

Individual effects

i) Sterilization: Under normal condition of the soil Zn uptake was significantly increased from 983 to 1410 $\mu\text{g/plant}$.

ii) Soil types: The soil types showed no significant effect on Zn uptake.

iii) P levels: The P application showed no significant effect on Zn uptake.

iv) N levels: The N application exhibited no significant effect on Zn uptake.

v) Stages: The Zn uptake was significantly higher at 90 days stage (1869 $\mu\text{g/plant}$) than at 60 and 30 days stages and Zn uptake was increased stepwise with advancement of crop growth.

Interaction effects

The interactions viz., St x S and St x Stages attained statistical significance. Under sterilized condition a significant reduction in Zn uptake was observed in the black soil, while this was not so in the red soil. The negative effect of sterilization on Zn uptake was observed only at 60 and 90 days stages and the difference between sterilized and normal condition of the soil at 30 days stage was not marked.

4.9. Effect on nutrient uptake by grain

4.9.1. Effect on N, P and K uptake by grain (Table 39)

4.9.1.1. Effect on N uptake

Individual effects

i) Sterilization: Under sterilized condition of the soil N uptake by grain was significantly reduced from 257 to 79 mg/plant.

ii) Soil types: The N uptake by grain was more in the black soil (222 mg/plant) than that in the red soil (113 mg/plant).

iii) P levels: The P application showed no significant effect on N uptake.

iv) N levels: The N_{100} level recorded significantly higher N uptake by grain (189 mg/plant) but was on par with N_{50} level.

Interaction effects

The interactions viz., St x S, St x N, St x P and P x N attained statistical significance. The salient inferences drawn are: (i) under sterilized condition N uptake by grain was reduced both in the black and the red soils; (ii) N levels which had no influence on N uptake under sterilized condition was favourable under normal condition of the soil; (iii) under sterilized condition P application had a positive effect on N uptake; and (iv) P application increased N uptake at N_0 and N_{50} levels, while at N_{100} level it had no effect.

4.9.1.2. Effect on P uptake

Individual effects

i) Sterilization: Under sterilized condition of the soil P uptake by grain was significantly reduced from 21.98 to 5.96 mg/plant.

ii) Soil types: The soil types showed no significant effect on P uptake by grain.

TABLE 39. EFFECT OF TREATMENTS ON N, P AND K UPTAKE IN GRAIN OF SORGHUM IN BLACK AND RED SOILS (mg/plant)

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Treatments	N uptake	P uptake	K uptake
St	79	5.96	30.46
NSt	257	21.98	101.67
S ₁	222	14.39	79.54
S ₂	113	13.55	52.58
P ₀	164	9.09	57.40
P ₅₀	171	18.85	74.73
SE	5	2.00	10.40
CD	14	5.78	30.30
N ₀	134	14.00	52.84
N ₅₀	180	7.24	55.00
N ₁₀₀	189	20.87	90.37
SE	6	2.50	
CD	17	7.08	
St x S ₁	108	6.03	36.08
St x S ₂	50	5.88	24.83
NSt x S ₁	337	22.75	123.00
NSt x S ₂	176	21.21	80.33
St x P ₀	65	2.13	25.87
St x P ₅₀	93	8.79	35.04
NSt x P ₀	263	15.04	88.93
NSt x P ₅₀	250	28.72	114.41
S ₁ x P ₀	214	12.56	50.58
S ₁ x P ₅₀	230	16.22	108.50
S ₂ x P ₀	113	5.61	64.22
S ₂ x P ₅₀	112	21.48	40.95
SE	7	2.80	13.90
CD	20	8.10	40.10
St x N ₀	71	7.07	27.23
St x N ₅₀	81	3.80	28.34
St x N ₁₀₀	84	7.00	35.80
NSt x N ₀	196	20.93	78.45
NSt x N ₅₀	279	10.67	81.63
NSt x N ₁₀₀	294	34.35	144.94
S ₁ x N ₀	179	14.76	63.54
S ₁ x N ₅₀	245	6.88	57.06
S ₁ x N ₁₀₀	243	21.53	118.03
S ₂ x N ₀	88	13.24	42.14
S ₂ x N ₅₀	116	7.59	52.90
S ₂ x N ₁₀₀	135	19.81	62.71
N ₀ x P ₀	109	2.06	36.00
N ₀ x P ₅₀	158	25.94	68.68
N ₅₀ x P ₀	175	3.23	48.76
N ₅₀ x P ₅₀	185	11.24	61.20
N ₁₀₀ x P ₀	207	21.96	87.44
N ₁₀₀ x P ₅₀	171	19.38	93.30

iii) P levels: The P fertilization resulted in increased P uptake from 9.09 to 18.85 mg/plant.

iv) N levels: The beneficial effect of N application on P uptake by grain was not consistent since N_{100} level recorded increased P uptake, but was on par with N_0 level which in turn differed only marginally with N_{50} level.

Interaction effects

The interactions viz., S x P, St x N and P x N attained statistical significance. The important inferences drawn are: (i) P application which had no significant effect in the black soil, resulted in significant increase of P uptake in the red soil; (ii) N_{100} level was superior under normal condition of the soil than under sterilized condition; and (iii) P at 50 kg level and N at 100 kg level were found to be favourable on P uptake by grain.

4.9.1.3. Effect on K Uptake

Individual effects

i) Sterilization: Under sterilized condition of the soil K uptake by grain was significantly reduced from 30.46 to 101.67 mg/plant.

ii) Soil types: The soil types showed no significant effect on K uptake.

iii) P levels: The P application did not result in increased K uptake by grain.

iv) N levels: The N application did not result in increased K uptake by grain.

Interaction effects

Interaction effect of S x P revealed that P application had a positive effect in the black soil while it had opposite effect in the red soil.

4.9.2. Effect on micronutrient uptake by grain (Table 40)

4.9.2.1. Effect on Fe uptake

Individual effects

i) Sterilization: Under sterilized condition, Fe uptake by grain was significantly reduced from 8.57 to 2.59 mg/plant.

ii) Soil types: The Fe uptake by grain was more in the black soil (6.55 mg/plant) than the red soil (4.60 mg/plant).

iii) P levels: The P application did not result in increased Fe uptake by grain.

iv) N levels: The N application also did not result in increased Fe uptake by grain.

Interaction effect

The significant interaction of S x P revealed that P application which had favourable effect on Fe uptake by grain in the black soil got reversed its positive influence in the red soil.

4.9.2.2. Effect on Mn uptake

Individual effects

i) Sterilization: Under sterilized condition Mn uptake by grain was significantly reduced from 1.930 to 0.456 mg/plant.

ii) Soil types: The soil types did not show any significant effect on Mn uptake.

iii) P levels: The P application did not result in increased Mn uptake by grain.

iv) N levels: The N application also did not exhibit any significant effect on Mn uptake.

Interaction effect

The significant interaction P x N revealed that P application had a positive influence on Mn uptake at N₀ level.

TABLE 40. EFFECT OF TREATMENTS ON Fe, Mn, Cu AND Zn UPTAKE BY SORGHUM GRAIN IN BLACK AND RED SOILS (mg/plant)

Treatments (1)	Fe uptake (2)	Mn uptake (3)	Cu uptake (4)	Zn uptake (5)
St	2.59	0.456	20.47	0.466
NSt	8.57	1.930	92.03	1.929
S ₁	6.55	2.00	61.33	1.200
S ₂	4.60	1.196	51.16	1.196
P ₀	5.28	1.118	73.09	1.118
P ₅₀	5.88	1.278	39.40	1.278
SE	0.44	0.095	5.9	0.090
CD	1.27	0.275	17.1	0.278
N ₀	4.81	1.219	52.35	1.219
N ₅₀	6.08	1.067	74.11	1.067
N ₁₀₀	5.84	1.307	42.28	1.306
SE			7.3	
CD	NS	NS	20.9	NS
St x S ₁	3.12	0.481	23.49	0.481
St x S ₂	2.05	0.450	17.44	0.450
NSt x S ₁	9.98	1.918	99.17	1.918
NSt x S ₂	7.15	1.941	84.88	1.941
St x P ₀	2.15	0.438	26.00	0.439
St x P ₅₀	3.02	0.492	14.93	0.492
NSt x P ₀	8.40	1.796	120.18	1.796
NSt x P ₅₀	8.73	2.062	63.86	2.062
S ₁ x P ₀	5.18	1.000	83.03	1.000
S ₁ x P ₅₀	7.92	1.399	39.63	1.400
S ₂ x P ₀	5.37	1.235	63.15	1.235
S ₂ x P ₅₀	3.83	1.156	39.16	1.156
SE	0.62			
CD	1.79	NS	NS	NS
St x N ₀	2.22	0.504	19.42	0.504
St x N ₅₀	2.61	0.435	26.18	0.435
St x N ₁₀₀	2.93	0.457	15.80	0.456
NSt x N ₀	7.40	1.933	85.28	1.933
NSt x N ₅₀	9.56	1.699	122.04	1.699
NSt x N ₁₀₀	8.74	2.156	68.75	2.156
SE	0.76	0.165	8.3	0.13
CD	2.20	0.477	24.2	0.39
S ₁ x N ₀	5.78	1.098	62.94	1.100
S ₁ x N ₅₀	7.83	1.110	84.84	1.110
" "	6.04	1.280	36.21	1.389

ii) Soil types: The soil types did not exhibit any significant effect on Zn uptake by grain.

iii) P levels: The P application showed no significant effect on Zn uptake by grain.

iv) N levels: The N application showed no significant effect on Zn uptake by grain.

Interaction effect

The significant interaction P x N revealed that P application had a positive effect on Zn uptake at N_0 level.

4.10. Effect on root growth characteristics

4.10.1. Effect on number of roots/ plant (Table 41)

Individual effects

i) Sterilization: The mean value for this main effect fell within the range of 14.6 to 33.6. Under sterilized condition of the soil number of roots/plant was significantly reduced at all the three stages of crop growth.

ii) Soil types: The mean value for this main effect ranged from 14.5 to 34.5. The red soil significantly produced more number of roots/plant than the black soil at all the three stages of crop growth.

TABLE 41. EFFECT OF TREATMENTS ON NUMBER OF ROOTS/PLANT OF BORGHUM
IN BLACK AND RED SOILS

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Treatments	30 days	60 days	90 days
St	17.2	25.4	14.6
NSt	22.4	33.6	17.8
S ₁	15.3	26.5	14.5
S ₂	24.3	34.5	17.8
P ₀	16.5	25.6	14.4
P ₅₀	23.1	33.3	17.9
SE	0.2	0.5	0.1
CD	0.5	1.4	0.4
N ₀	16.6	27.0	16.6
N ₅₀	21.4	29.7	14.1
N ₁₀₀	21.4	31.8	17.8
SE	0.2	0.6	0.2
CD	0.6	1.7	0.5
St x S ₁	10.0	15.5	12.1
St x S ₂	24.3	35.3	17.1
NSt x S ₁	20.5	33.4	16.9
NSt x S ₂	24.3	33.8	18.6
St x P ₀	13.4	29.3	12.2
St x P ₅₀	20.9	31.4	17.0
NSt x P ₀	19.5	32.2	16.7
NSt x P ₅₀	25.3	35.1	18.8
S ₁ x P ₀	20.5	21.3	15.7
S ₁ x P ₅₀	10.0	27.7	13.3
S ₂ x P ₀	24.3	30.3	13.2
S ₂ x P ₅₀	24.3	38.8	22.5
SE	0.2	0.7	0.2
CD	0.7	2.0	0.6
St x N ₀	12.1	21.4	14.9
St x N ₅₀	20.4	26.3	13.1
St x N ₁₀₀	19.0	28.5	15.8
NSt x N ₀	21.1	32.6	18.3
NSt x N ₅₀	22.4	33.1	15.1
NSt x N ₁₀₀	23.8	35.1	19.9
S ₁ x N ₀	15.1	19.3	14.0
S ₁ x N ₅₀	15.0	27.5	12.3
S ₁ x N ₁₀₀	15.6	26.6	17.3
S ₂ x N ₀	18.1	34.8	19.1
S ₂ x N ₅₀	27.8	31.9	16.0
S ₂ x N ₁₀₀	27.1	37.0	18.4
N ₀ x P ₀	12.1	24.1	12.6
N ₀ x P ₅₀	21.1	29.9	20.5
N ₅₀ x P ₀	19.5	25.5	12.6
N ₅₀ x P ₅₀	23.3	33.9	15.6
N ₁₀₀ x P ₀	17.8	27.6	18.0
N ₁₀₀ x P ₅₀	25.0	36.0	17.6

iii) P levels: The mean value for this main effect fell within the range of 14.4 to 33.3. The P application significantly increased the number of roots/plant at all the three stages of crop growth.

iv) N levels: The mean value for this main effect remained within the range of 14.1 to 31.8. Though the effect of N application at 100 kg level was on par with N₅₀ level at 30 days stage, but its effect was more pronounced at 60 and 90 days of crop growth.

Interaction effects

At 30th day, the interactions viz., S x N, S x St, N x P, N x St and P x St showed the level of significance. The important inferences drawn are: (i) greater proliferation of root was observed in the red soil than in the black soil at all levels of N and under both the sterilized and normal conditions of the soil; (ii) the combined application of N₅₀ P₀ and N₁₀₀ P₅₀ increased the proliferation of root than the other combined applications; and (iii) under normal condition of the soil N₁₀₀ and P₅₀ levels and under sterilized condition N₅₀ and P₅₀ levels enhanced the number of roots/plant.

At 60th day, the interactions viz., S x N, S x St, N x P, N x St and P x St showed statistical significance. The salient inferences drawn are: (i) as in the previous case at

all levels of N there was greater proliferation of roots in the red soil than that in the black soil at all levels of N application; (ii) the black soil under normal condition and the red soil under sterilized condition but on par with normal condition increased the number of roots/plant; and (iii) the combined application of $N_{100}P_{50}$ and $N_{100}P_0$ significantly increased the number of roots/plant and at all levels of N and P under normal condition greater number of roots/plant was observed than under sterilized condition.

At 90th day, the interaction effects viz., S x N, S x P, S x St, N x P, N x St and P x St attained statistical significance. The important inferences drawn are: (i) at all level of N application greater proliferation of root/plant was observed in the red soil than that in the black soil; (ii) the red soil required P application for increasing the root proliferation; (iii) the same trend as was observed at 60 days stage, the combined application of $N_{100}P_{50}$ and $N_{100}P_0$ significantly increased the number of roots/plant and (iv) all levels of N and P as well as in both the soils, the normal condition of the soil showed increased number of roots/plant.

4.10.2. Effect on root volume (Table 42)

Individual effects

i) Sterilization: The mean value for the main effect remained within the range of 2.45 to 15.79 ml. The

sterilized condition significantly reduced root volume at all the three stages of crop growth.

ii) Soil types: The mean value for this main effect ranged from 2.01 to 18.89 ml. The red soil significantly recorded higher root volume than the black soil at all the three stages of crop growth.

iii) P levels: The mean value for this main effect ranged from 2.58 to 17.30 ml. The P application enhanced root volume significantly at all the three stages of crop growth.

iv) N levels: The mean value for this main effect fell within the range of 3.06 to 17.81 ml. Though N_{100} level showed marginal increase of root volume at 30 days stage, it significantly registered higher values at 60 and 90 days stages than N_{50} and N_0 levels.

Interaction effects

At 30th day, the interactions viz., S x N, S x P, N x P and N x St attained statistical significance. The important inferences drawn are; (i) at all levels of N and P root volume was greater in the red soil than that in the black soil; (ii) the black soil at N_0P_{50} level and the red soil at $N_{100}P_{50}$ increased root volume; and (iii) under normal

TABLE 42. EFFECT OF TREATMENTS ON VOLUME OF ROOT OF SORGHUM IN BLACK AND RED SOILS(ml)

Treatments	30 days	60 days	90 days
St	2.45	14.21	11.11
NSt	3.81	15.79	14.26
S ₁	2.01	11.11	7.80
S ₂	4.25	18.89	16.57
P ₀	2.58	12.70	10.00
P ₅₀	8.69	17.30	14.38
SE	0.05	0.20	0.70
CD	0.14	0.97	0.19
N ₀	3.10	12.84	10.47
N ₅₀	3.06	14.36	12.24
N ₁₀₀	3.23	17.81	13.84
SE	0.06	0.24	0.08
CD	0.17	0.70	0.24
St x S ₁	1.41	8.06	5.62
St x S ₂	3.50	20.37	16.60
NSt x S ₁	2.62	14.17	9.98
NSt x S ₂	5.00	17.42	16.53
St x P ₀	2.00	11.08	9.33
St x P ₅₀	2.92	17.35	12.89
NSt x P ₀	3.16	14.33	10.65
NSt x P ₅₀	4.46	17.25	15.87
S ₁ x P ₀	1.14	7.45	6.41
S ₁ x P ₅₀	2.88	14.78	9.19
S ₂ x P ₀	4.00	17.96	13.57
S ₂ x P ₅₀	4.49	19.83	19.57
SE	0.07	0.28	0.09
CD	0.20	0.81	0.27
St x N ₀	2.30	10.81	9.56
St x N ₅₀	2.13	11.21	9.61
St x N ₁₀₀	2.94	20.61	14.16
NSt x N ₀	3.90	14.88	11.38
NSt x N ₅₀	4.00	17.50	14.88
NSt x N ₁₀₀	3.53	15.00	13.53
S ₁ x N ₀	2.83	9.04	6.58
S ₁ x N ₅₀	1.80	12.84	6.99
S ₁ x N ₁₀₀	1.41	11.46	9.84
S ₂ x N ₀	3.38	16.65	14.36
S ₂ x N ₅₀	4.33	15.88	17.50
S ₂ x N ₁₀₀	5.05	24.15	17.84
N ₀ x P ₀	1.83	13.13	8.78
N ₀ x P ₅₀	4.38	12.56	12.16
N ₅₀ x P ₀	2.83	10.15	9.01
N ₅₀ x P ₅₀	3.30	18.56	15.48
N ₁₀₀ x P ₀	3.08	14.84	12.18
N ₁₀₀ x P ₅₀	3.39	10.78	15.50

condition of the soil root volume was increased significantly at all levels of N application.

At 60th day, the interactions viz., S x N, S x P, S x St, N x P, N x St and P x St attained statistical significance. The important inferences drawn are: (i) as in the previous case at all levels of N and P applications root volume was greater in the red soil than that in the black soil; (ii) the black soil at $N_{50}P_{50}$ level and the red soil at $N_{100}P_{50}$ level increased the volume of root; (iii) irrespective of the soil conditions the red soil registered higher root volume than the black soil; and (iv) under the sterilized condition of the soil $N_{100}P_{50}$ level, while under normal condition of the soil $N_{50}P_{50}$ level increased the root volume.

At 90th day, the interactions viz., S x N, S x P, S x St, N x P, N x St and P x St attained statistical significance. The important inferences drawn are: (i) at all levels of N and P applications and irrespective of the soil conditions the red soil registered greater root volume than the black soil; (ii) though N_{100} level registered increased root volume in both the soils, N_{100} level on par with N_{50} level in the red soil and P application at 50 kg level was needed to increase root volume in both the soil types; and (iv) the combined applications of $N_{100}P_0$ and $N_{100}P_{50}$ increased root volume, but $N_{100}P_{50}$ level was on par with $N_{50}P_{50}$ level and the sterilized condition of the soil required higher N and P levels to increase root volume.

4.10.3. Effect on root mass (Table 43) (Fig.11)

Individual effects

i) Sterilization: The mean value for the main effect remained within the range of 2.70 to 7.58 g. Under the sterilization condition of the soil root mass was significantly reduced at all the three stages of crop growth.

ii) Soil types: The mean value for the main effect ranged from 2.33 to 7.43 g. The red soil registered significantly higher root mass than the black soil at all the three stages.

iii) P levels: The mean value for the main effect ranged from 2.95 to 7.30 g. The P application registered significantly higher root mass than no P application at all the three stages.

iv) N levels: The mean value for the main effect remained within the range of 2.48 to 7.86 g. The N application at 100 kg level registered significantly higher root mass than N_{50} and N_0 levels at all the three stages of crop growth.

Interaction effects

At 30th day, the interactions viz., S x N, S x P, S x St, N x P, N x St and P x St attained statistical

TABLE 43. EFFECT OF TREATMENTS ON ROOT MASS OF SORGHUM IN BLACK AND RED SOILS (g)

Treatments	30 days	60 days	90 days.
St	2.93	2.70	6.46
NSt	4.19	3.87	7.58
S ₁	2.72	2.35	6.61
S ₂	4.41	4.22	7.43
P ₀	2.95	3.14	6.74
P ₅₀	4.18	3.43	7.30
SE	0.016	0.022	0.06
CD	0.046	0.063	0.18
N ₀	3.41	3.36	6.88
N ₅₀	3.27	2.48	6.31
N ₁₀₀	4.01	4.02	7.86
SE	0.019	0.026	0.07
CD	0.056	0.077	0.22
St x S ₁	1.99	0.76	4.73
St x S ₂	3.87	4.64	8.19
NSt x S ₁	3.45	3.94	8.48
NSt x S ₂	4.94	3.81	6.67
St x P ₀	2.90	2.28	6.08
St x P ₅₀	2.96	3.12	6.84
NSt x P ₀	3.00	4.00	7.40
NSt x P ₅₀	3.40	3.75	7.75
S ₁ x P ₀	1.74	2.13	6.28
S ₁ x P ₅₀	3.71	2.57	6.94
S ₂ x P ₀	4.16	4.14	7.20
S ₂ x P ₅₀	4.65	4.30	7.66
SE	0.022	0.031	0.085
CD	0.065	0.089	0.25
St x N ₀	2.48	2.67	6.45
St x N ₅₀	2.37	1.47	4.87
St x N ₁₀₀	3.95	3.96	8.06
NSt x N ₀	4.34	4.04	7.31
NSt x N ₅₀	4.18	3.49	7.76
NSt x N ₁₀₀	4.07	4.08	7.66
S ₁ x N ₀	3.49	2.74	7.25
S ₁ x N ₅₀	2.37	2.12	5.98
S ₁ x N ₁₀₀	2.31	2.18	6.58
S ₂ x N ₀	3.33	3.97	6.51
S ₂ x N ₅₀	4.18	2.84	6.64
S ₂ x N ₁₀₀	5.71	5.85	9.14
N ₀ x P ₀	2.08	4.41	5.35
N ₀ x P ₅₀	4.74	2.30	8.41
N ₅₀ x P ₀	3.25	1.89	6.45
N ₅₀ x P ₅₀	3.30	3.08	6.18
N ₁₀₀ x P ₀	3.51	3.11	8.41
N ₁₀₀ x P ₅₀	4.51	4.92	7.31
SE	0.027	0.037	0.10
CD	0.079	0.100	0.28

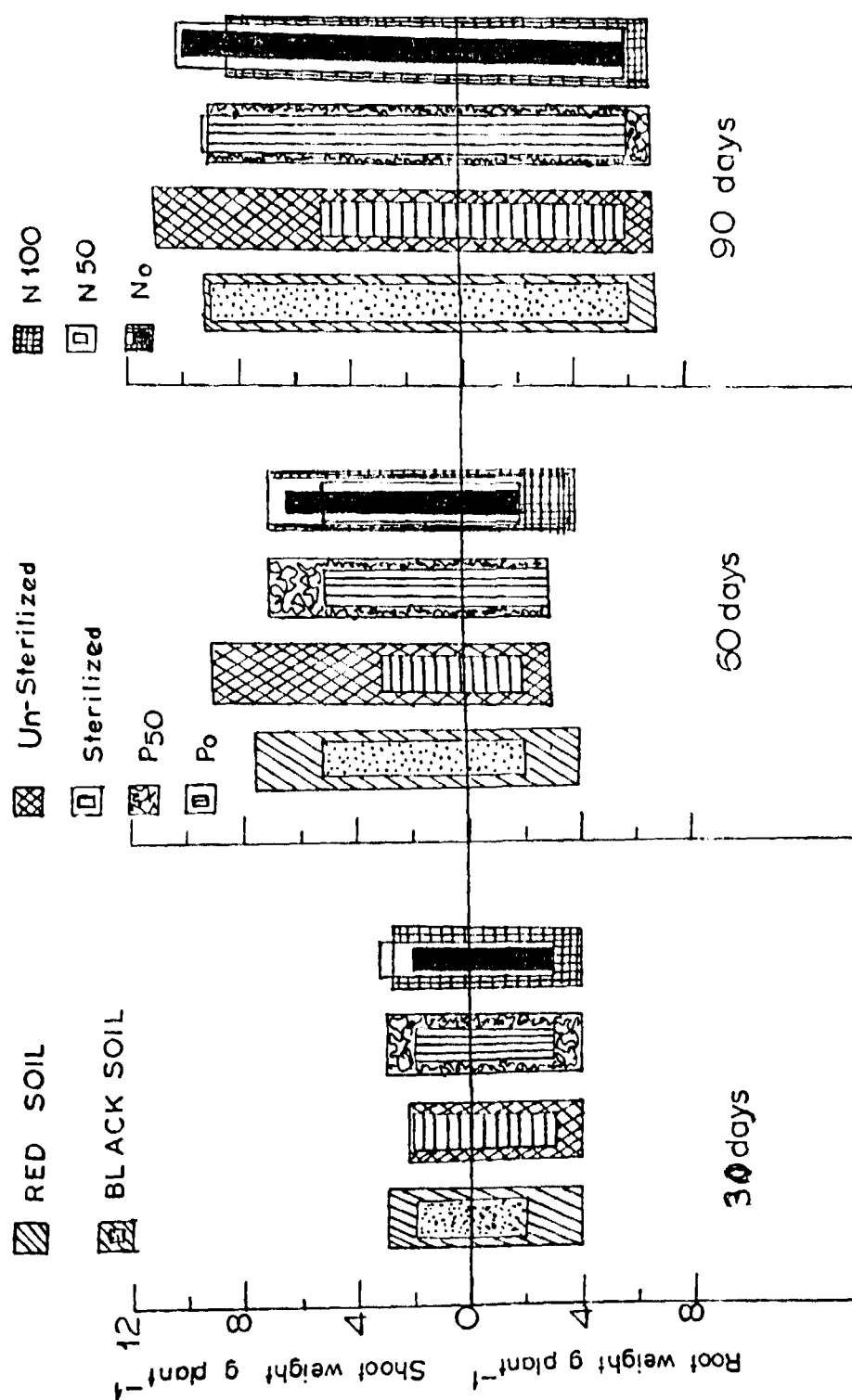


FIG. 11 ROOT AND SHOOT WEIGHT OF SORGHUM CROP AS INFLUENCED BY TREATMENTS AT DIFFERENT STAGES OF CROP GROWTH

significance. The important inferences drawn are; (i) the red soil at N_{50} and N_{100} levels and at P_0 and P_{50} levels registered higher root mass than the black soil; (ii) the black soil at N_0P_{50} level increased the root mass; however in the case of red soil P_{50} level was on par with P_0 level; (iii) under the normal condition of the soil the root mass was increased in both the soil types; (iv) the combined applications of $N_{100}P_0$ and N_0P_{50} registered higher root mass than the other combined applications; and (v) under the normal condition of the soil root mass was enhanced at all levels of N and P applications.

At 60th day, the interactions viz., $S \times N$, $S \times P$, $S \times St$, $N \times P$, $N \times St$ and $P \times St$ attained statistical significance. The important inferences drawn are: (i) at all levels of N and P applications the red soil registered higher root mass than the black soil and the black soil at N_0P_{50} level and the red soil at $N_{100}P_{50}$ level increased the root mass; (ii) the black soil under normal condition and the red soil under sterilized condition enhanced the root mass; (iii) the combined application of $N_{100}P_{50}$ increased the root mass; and (iv) irrespective of the condition of the soil at N_{100} level and irrespective of P fertilization under the normal condition of the soil the root mass was enhanced.

At 90th day, the interactions viz., S x N, S x St, N x P, N x St and P x St attained statistical significance. The main inferences drawn are: (i) the red soil at N₅₀ and N₁₀₀ levels while the black soil at N₀ level registered increased root mass; (ii) as observed at 60th day the black soil under normal condition and the red soil under sterilized condition enhanced the root mass; however under normal condition of the soil, N₅₀ level was on par with N₁₀₀ level.

4.10.4. Effect on total root length (Table 44)

Individual effects

i) Sterilization: The mean value for the main effect fell within the range of 1177 to 13941 cm. Under the sterilized condition of the soil total root length at 30 days stage exhibited a marginal increase than that under normal condition of the soil, but it showed significant increase at 60 and 90 days stage.

ii) Soil types: The mean value for the main effect remained within the range of 683 to 10602 cm. The red soil registered significantly higher total root length than the black soil at all the three stages of crop growth.

iii) P levels: The mean value for this main effect ranged from 868 to 10502 cm. The P application

TABLE 44. EFFECT OF TREATMENTS ON TOTAL ROOT LENGTH OF SORGHUM IN BLACK AND RED SOILS (cm)

250

Treatments	30 days	60 days	90 days
St	1242	9667	13941
NSt	1177	9385	7371
S ₁	683	8666	7435
S ₂	1736	10386	10602
P ₀	868	8549	9824
P ₅₀	1550	10502	8212
SE	168	243	284
CD	491	712	831
N	1159	7815	6579
N ₅₀	1463	8108	9821
N ₁₀₀	1006	12654	10656
SE	206	298	348
CD	601	872	1017
St x S ₁	498	9614	8714
St x S ₂	1986	9719	12511
NSt x S ₁	867	7717	6156
NSt x S ₂	1486	11053	8694
St x P ₀	867	8662	12819
St x P ₅₀	1618	19671	8406
NSt x P ₀	876	8436	6831
NSt x P ₅₀	1484	10333	8019
S ₁ x P ₀	343	7134	8079
S ₁ x P ₅₀	1023	10197	6791
S ₂ x P ₀	1394	9964	11571
S ₂ x P ₅₀	2079	10807	9634
SE	168	344	402
CD	NS	1007	1175
St x N ₀	975	7105	7624
St x N ₅₀	1777	6746	10273
St x N ₁₀₀	976	15149	13941
NSt x N ₀	1343	8525	5535
NSt x N ₅₀	1150	9471	9370
NSt x N ₁₀₀	1037	10159	7271
S ₁ x N ₀	907	7037	5498
S ₁ x N ₅₀	601	7264	7580
S ₁ x N ₁₀₀	541	11696	9228
S ₂ x N ₀	1411	8593	7661
S ₂ x N ₅₀	2326	8953	12063
S ₂ x N ₁₀₀	1472	13612	12084
N ₀ x P ₀	633	9811	7655
N ₀ x P ₅₀	1684	5819	5503
N ₅₀ x P ₀	933	7311	10305
N ₅₀ x P ₅₀	1994	8906	9338
N ₁₀₀ x P ₀	1038	8526	11514
N ₁₀₀ x P ₅₀	975	16782	9797

recorded higher total root length than no P application at ²⁵¹30 and 60 days stage, but the trend was reversed at 90 days stage.

iv) N levels: The mean value for this main effect ranged from 1006 to 12654 cm. The N_{100} level significantly produced higher total root length than N_{50} and N_0 levels at 60 and 90 days stage, but at 30 days stage, N_{50} level recorded only marginal increase.

Interaction effects

No interaction was significant at 30th day.

At 60th day, the interactions viz., $S \times P$, $S \times St$, $N \times P$ and $N \times St$ attained the level of significance. The important inferences drawn are: (i) in both the soil types P application increased total root length; (ii) the black soil under sterilized condition and the red soil under non-sterilized condition increased total root length and irrespective of the condition of the soil, the red soil and N_{100} level registered enhanced total root length; and (iii) the combined application of $N_{50}P_0$ on par with $N_{100}P_0$ level and $N_{100}P_{50}$ recorded significantly increased total root length.

At 90th day, the interactions viz., $N \times St$ and $P \times St$ showed statistical significance which revealed that under sterilized condition of the soil total root length at all levels of N and P applications was increased and that the $N_{50}P_{50}$ level under normal condition of the soil and $N_{100}P_0$ level under sterilized condition of the soil increased total

4.10.5. Effect on root diameter (Table 45)

Individual effects

i) Sterilization: The mean value for the main effect remained within the range of 0.36 to 0.64 mm. Under sterilized condition of the soil root diameter was significantly reduced at all the three stages of crop growth.

ii) Soil types: The mean value for the main effect fell within the range of 0.37 to 0.61 mm. The red soil registered significantly higher root diameter than the black soil at 60 and 90 days stage but the difference was small at 30 days.

iii) P levels: The mean value for the main effect ranged from 0.36 to 0.61 mm. The P application enhanced the root diameter at 60 and 90 days stage of crop growth but at 30th day stage, it exhibited no beneficial trend.

iv) N levels: The mean value for this main effect ranged from 0.38 to 0.65 mm. The N_{100} level at 30 days stage and N_{50} level at 60 days stage significantly increased root diameter but at 90 days stage, N application did not enhance root diameter.

TABLE 45. EFFECT OF TREATMENTS ON ROOT DIAMETER OF SORGHUM IN BLACK AND RED SOILS (mm)

253

Treatments	30 days	60 days	90 days
St	0.57	0.42	0.36
NSt	0.64	0.47	0.47
S ₁	0.61	0.39	0.37
S ₂	0.60	0.50	0.46
P ₀	0.61	0.40	0.36
P ₅₀	0.60	0.49	0.47
SE	0.008	0.002	0.005
CD	0.023	0.006	0.013
N ₀	0.60	0.43	0.45
N ₅₀	0.56	0.48	0.38
N ₁₀₀	0.65	0.42	0.41
SE	0.008	0.002	0.006
CD	0.029	0.007	0.016
St x S ₁	0.58	0.30	0.28
St x S ₂	0.56	0.54	0.43
NSt x S ₁	0.64	0.49	0.45
NSt x S ₂	0.64	0.46	0.49
St x P ₀	0.54	0.34	0.28
St x P ₅₀	0.59	0.50	0.44
NSt x P ₀	0.69	0.47	0.45
NSt x P ₅₀	0.60	0.48	0.49
S ₁ x P ₀	0.62	0.33	0.33
S ₁ x P ₅₀	0.60	0.46	0.40
S ₂ x P ₀	0.60	0.48	0.39
S ₂ x P ₅₀	0.60	0.52	0.53
SE	0.011	0.003	0.007
CD	0.033	0.008	0.019
St x N ₀	0.60	0.39	0.39
St x N ₅₀	0.49	0.47	0.34
St x N ₁₀₀	0.62	0.40	0.35
NSt x N ₀	0.61	0.47	0.51
NSt x N ₅₀	0.64	0.50	0.43
NSt x N ₁₀₀	0.68	0.44	0.47
S ₁ x N ₀	0.66	0.35	0.38
S ₁ x N ₅₀	0.60	0.47	0.36
S ₁ x N ₁₀₀	0.57	0.36	0.36
S ₂ x N ₀	0.55	0.51	0.52
S ₂ x N ₅₀	0.53	0.50	0.41
S ₂ x N ₁₀₀	0.72	0.48	0.46
N ₀ x P ₀	0.63	0.37	0.39
N ₀ x P ₅₀	0.58	0.49	0.51
N ₅₀ x P ₀	0.61	0.42	0.32
N ₅₀ x P ₅₀	0.52	0.55	0.45
N ₁₀₀ x P ₀	0.61	0.42	0.38
N ₁₀₀ x P ₅₀	0.69	0.42	0.44

Interaction effects

At 30th day, the interactions viz., S x N, N x P, N x St and P x St attained statistical significance. The main inferences drawn are: (i) the black soil at N_0 level and the red soil at N_{100} level recorded enhanced root diameter; (ii) the combined application of $N_{100}P_{50}$ increased the root diameter and (iii) irrespective of the condition of the soil N_{100} level and P application at 50 kg level under sterilized condition enhanced this parameter.

At 60th day, the interactions viz., S x N, S x P, S x St, N x P, N x St and P x St attained statistical significance. The important inferences drawn are: (i) at all levels of N and P applications the red soil registered greater root diameter; in both the soils N_{50} and P_{50} levels increased root diameter; however in the red soil N_{50} level was on par with N_0 level; (ii) the black soil under normal condition and the red soil under sterilized condition increased root diameter; (iii) at both the levels of P, N_{50} level enhanced root diameter; however at P_0 level, N_{50} level was on par with N_{100} level and (iv) irrespective of the condition of the soil N_{50} and P_{50} levels increased root diameter.

At 90th day, the interactions viz., S x N, S x P, S x St, N x P, N x St and P x St attained statistical

significance. The salient inferences drawn are: (i) at all levels of N and P applications the red soil registered higher root diameter than the black soil; the black soil at N_0 level being on par with N_{50} and N_{100} levels and P_{50} level increased root diameter, while the red soil at N_0 and P_{50} levels increased root diameter; (ii) both the soils under normal condition enhanced root diameter; at P_0 level, N_0 level being on par with N_{100} level and at P_{50} level N_0 level was found to increase root diameter in a significant manner and (iii) irrespective of the condition of the soil N_0 level and P_{50} level increased this parameter.

4.10.6. Effect on shoot weight (Table 46) (Fig.11)

Individual effects

i) Sterilization: The mean value for this main effect ranged from 2.69 to 11.54 g. Under normal condition of the soil significantly higher shoot weight was recorded than that under sterilized condition at all three stages of crop growth.

ii) Soil types: The mean value for the main effect ranged from 2.07 to 9.79 g. The red soil registered significantly higher shoot weight than the black soil at all the three stages of crop growth.

iii) P levels: The mean value for this main effect ranged from 2.14 to 9.73 g. The P application at 50 kg level registered significantly higher shoot weight at 30 and 60 days stage than no P application but such difference was not observed at 90 days stage.

iv) N levels: The mean value for this main effect remained within the range of 2.23 to 10.46 g. The N_{50} level showed significantly higher shoot weight than N_{100} and N_0 levels at 30 and 90 days stages, but at 60 days stage N_{100} level registered higher shoot weight than the other N levels.

Interaction effects

At 30th day, the interactions viz., S x N, S x P, S x St, N x P, N x St and P x St attained statistical significance. The important inferences drawn are: (i) the black soil at P_{50} level and the red soil at N_{50} and P_{50} levels registered increased shoot weight; (ii) irrespective of the condition of the soil the red soil registered higher shoot weight than the black soil; (iii) irrespective of P application N_{50} level registered higher shoot weight than other N levels; however at P_0 level N_{50} level was on par with N_{100} level; and (iv) under sterilized condition N_{50} and P_{50} level applications were required to exhibit increased shoot weight while such fertilizer application was not needed under normal condition of the soil to increase shoot weight.

TABLE 46. EFFECT OF TREATMENTS ON SHOOT WEIGHT OF SORGHUM IN BLACK AND RED SOILS(g)

257

Treatments	30 days	60 days	90 days
St	2.69	3.63	7.66
NSt	2.82	9.32	11.54
S ₁	2.07	5.21	6.40
S ₂	3.45	7.75	9.79
P ₀	2.14	5.63	9.73
P ₅₀	3.38	7.33	9.46
SE	0.023	0.072	0.071
CD	0.067	0.212	0.207
N ₀	2.23	6.50	9.87
N ₅₀	3.20	5.87	10.46
N ₁₀₀	2.84	7.07	8.46
SE	0.028	0.089	0.086
CD	0.082	0.259	0.253
St x S ₁	1.58	1.47	6.69
St x S ₂	3.81	5.80	8.61
NSt x S ₁	2.56	8.94	12.11
NSt x S ₂	3.09	9.71	10.97
St x P ₀	1.87	2.78	7.20
St x P ₅₀	3.52	4.49	8.10
NSt x P ₀	2.41	8.49	12.26
NSt x P ₅₀	3.23	10.16	10.82
S ₁ x P ₀	1.66	4.32	9.79
S ₁ x P ₅₀	2.47	6.09	9.01
S ₂ x P ₀	2.62	6.95	9.67
S ₂ x P ₅₀	4.28	8.56	9.91
SE	0.033	0.102	0.100
CD	0.095	0.300	0.29
St x N ₀	1.92	3.33	7.79
St x N ₅₀	3.49	2.63	8.45
St x N ₁₀₀	2.67	4.94	6.72
NSt x N ₀	2.55	9.67	11.96
NSt x N ₅₀	2.90	9.10	12.47
NSt x N ₁₀₀	3.01	9.20	10.20
S ₁ x N ₀	2.24	5.56	9.41
S ₁ x N ₅₀	1.98	4.79	9.95
S ₁ x N ₁₀₀	1.98	5.27	8.84
S ₂ x N ₀	2.23	7.44	10.33
S ₂ x N ₅₀	4.41	6.95	10.97
S ₂ x N ₁₀₀	2.71	8.87	8.08
N ₀ x P ₀	1.56	6.59	9.19
N ₀ x P ₅₀	2.90	6.41	10.55
N ₅₀ x P ₀	2.45	4.51	10.34
N ₅₀ x P ₅₀	3.95	7.23	10.58
N ₁₀₀ x P ₀	2.41	5.79	9.66
N ₁₀₀ x P ₅₀	3.28	8.34	7.26
SE	0.039	0.125	0.12

At 60th day, the interactions viz., S x N, S x St, N x P and N x St were found to be significant. The main inferences drawn are: (i) at all levels of N, the red soil registered higher shoot weight than the black soil; (ii) irrespective of the soil condition the red soil registered greater shoot weight than the black soil; (iii) at N_{50} and N_{100} levels, P_{50} level recorded increased shoot weight and (iv) N_{100} level was needed to show enhanced shoot weight under sterilized condition while under normal condition no N application was needed and at all levels of N normal condition of the soil proved to be better than the sterilized condition in increasing shoot weight.

At 90th day, the interactions viz., S x N, S x P, S x St, N x P, N x St and P x St showed statistical significance. The salient inferences drawn from the above interactions are: (i) the black soil at N_{50} level with no P application and the red soil at N_{50} and P_{50} levels showed increased shoot weight; (ii) in both the soils types under normal condition, shoot weight was increased; (iii) at P_0 and P_{50} levels N_{50} level increased shoot weight; however at P_{50} level, N_{50} level was on par with N_0 level; (iv) irrespective of the soil condition N_{50} level showed higher shoot weight than the other levels of N; and (v) at all levels of N and P applications and under normal condition of the soil, shoot weight was increased and P application was needed under sterilized condition to increase shoot weight.

TABLE 47. CORRELATION STUDIES - RELATIONSHIP OF ROOT LENGTH, ROOT MASS AND GRAIN YIELD WITH SOIL CHARACTERISTICS AND OTHER FACTORS

S.No.	Dependent variable Y	Independent variable X	Stage of the crop	'r' value	Regression Equation
1.	Root length	Available K	30 days	-0.4807*	$Y = 2330 - 1.6923 X_K$
2.	"	P content in root	"	-0.5442**	$Y = 2271.4 - 1828.5 X_P$
3.	"	Fe content in root	"	-0.4108	$Y = 2551.2 - 2.168 X_{Fe}$
4.	"	N uptake by shoot	"	0.6307**	$Y = -105.02 + 42629 X_N$
5.	"	K uptake by shoot	"	0.6667**	$Y = -249.72 + 35372 X_K$
6.	"	Zn uptake by shoot	"	0.5831**	$Y = -77.721 + 2683.78 X_{Zn}$
7.	"	P content in shoot	60 days	0.6136**	$Y = 3752.78 + 60928.8 X_P$
8.	"	Fe uptake by shoot	"	0.4181*	$Y = 5024 + 518.99 X_{Fe}$
9.	"	Available Fe	90 days	0.4459*	$Y = 2427.84 + 187.19 X_{Fe}$
10.	Root mass	N content in root	30 days	-0.4368*	$Y = 5.6674 - 5.351 X_N$
11.	"	P content in root	"	-0.5863**	$Y = 5.6821 - 3.545 X_P$
12.	"	Fe content in root	"	-0.4428*	$Y = 6.2408 - 0.0043 X_{Fe}$
13.	"	N content in shoot	"	-0.4757*	$Y = 6.671 - 2.605 X_N$
14.	"	K uptake by shoot	"	0.6311**	$Y = 1.0098 + 61.942 X_K$
15.	"	Zn uptake by shoot	"	0.5862**	$Y = 1.1712 + 4.991 X_{Zn}$
16.	"	Available N	60 days	-0.4124*	$Y = 8.203 - 0.027 X_N$
17.	"	Available K	"	-0.4212*	$Y = 5.422 - 0.00633 X_K$
18.	"	N content in root	"	-0.5048*	$Y = 4.6085 - 2.9631 X_N$
19.	"	P content in root	"	-0.5454**	$Y = 6.4004 - 11.036 X_P$
20.	"	Fe content in root	"	-0.6089**	$Y = 7.9742 - 0.01197 X_{Fe}$
21.	"	Zn content in root	"	-0.5917**	$Y = 6.9527 - 0.1021 X_{Zn}$
22.	"	Fe content in shoot	"	-0.5113*	$Y = 4.747 - 0.0006 X_{Fe}$
23.	"	N uptake by shoot	"	0.7842**	$Y = 0.07099 + 44.398 X_N$
24.	"	K uptake by shoot	"	0.5329**	$Y = 1.6303 + 13.523 X_K$
25.	"	Fe uptake by shoot	"	0.7569**	$Y = -0.1436 + 0.3718 X_{Fe}$
26.	"	Zn uptake by shoot	"	0.7694**	$Y = 0.3066 + 2.399 X_{Zn}$
27.	Root mass	Available Mn	90 days	0.4895*	$Y = -21.598 + 0.4894 X_{Mn}$
28.	"	Fe content in root	"	-0.4248*	$Y = 10.957 - 0.01 X_{Fe}$
29.	"	N content in shoot	"	-0.6540**	$Y = 2.1825 + 8.802 X_N$
30.	"	N uptake by shoot	"	0.5587**	$Y = 3.672 + 62.363 X_N$
31.	"	K uptake by shoot	"	0.4445*	$Y = 3.826 + 21.454 X_K$
32.	Grain yield	N uptake by grain	"	0.9194**	$Y = 3.4043 + 64.999 X_N$
33.	"	P uptake by grain	"	0.5807**	$Y = 10.4144 + 310.028 X_P$
34.	"	K uptake by grain	"	0.8478**	$Y = 3.7523 + 185.85 X_K$
35.	"	Fe uptake by grain	"	0.7979**	$Y = 5.0363 + 1.7140 X_{Fe}$
36.	"	Zn uptake by grain	"	0.7511**	$Y = 5.997 + 7.2659 X_{Zn}$

* Significant at 5% probability level

Correlation studies (Table 47)

Co-efficient of correlation of grain yield and root growth parameters with availability of nutrients in soil, nutrient content in roots, nutrient content and uptake by shoot at different growth stages of sorghum crop were worked out after consolidating the data for types of soils and sets of soils. The data is presented in table 47.

5

N

CHAPTER 5

DISCUSSION

The concept of availability of plant nutrients in the soils is a complex phenomena. A plithora of evidences have accumulated to indicate that there exists considerable differences in the nutrient status between rhizosphere and non-rhizosphere soils. In view of several physico- chemical and biological changes continuously encountered in the soil. There are significant changes in the nutrient availability, transformation, and absorption of nutrients. These processes differ between rhizosphere and non-rhizosphere soils, again contributed by several plant factors like root exudation, solughing off root tissues, absorption, adsorption, root interception, etc. Therefore, a case study with sorghum as test crop was taken up employing various experimental factors viz., soil types, sterilization, N levels, P levels and site of soil collection in order to have a clear understanding of chemistry of rhizosphere soils in relation to nutrient availability, transformation, flow rate, crop nutrition and yield. The salient points emanating from the above experiments are briefly discussed in this chapter.

5.1. Studies on the root exudation pattern

In order to find out the exudation pattern of sorghum plant, root exudate study was conducted as explained under 'Materials and Methods'.

5.1.1. Root exudation pattern in sorghum plant at different stages of plant growth

The results of this study (Table 2a, b and c) indicated that there were qualitative and quantitative changes in the exudation of aminoacids and sugars by roots over the period of growth. In general, the number and concentration of the aminoacids and sugars exuded by the plant roots increased upto 30 days of growth after which they declined. Such reduction in the exudate with plant age has been observed by many workers (Rovira, 1959 and 1962; Balasubramaniam and Rangaswamy, 1978).

5.1.2. Pot experiment to study the nutrient availability transformation, flow rate and crop relationships

This experiment involved an indepth appraisal of the physico-chemical differences in the root environment, yield and nutrient uptake by sorghum crop in two predominant soil types as influenced by varying levels of N and P application under sterilized and normal conditions of the soil. The rhizosphere and non-rhizosphere soil samples under each of the above cases were investigated separately for the above said phenomena, apart from assessing the variation in the growth characteristics.

As is well known, the red and black soils differ considerably in many properties. The nutrient environment in the rhizosphere and non-rhizosphere also vary considerably (Barber, 1971, Kozlowski, 1973, Arunachalam, 1975 and Marschner, 1983). The availability of plant nutrients in the red and black soils is considerably influenced by the soil microflora and perhaps the nutrient availability in most cases is conditioned by the organic matter content in conjunction with the quality and quantity of microbes existing in the soil. It is also obvious that due to several physico-chemical and biological phenomena, the rhizosphere soil of any plant remains little different from the non-rhizosphere soil, (Balasubramanian and Rangaswamy, 1978 and Marschner, 1983) and this is accomplished by such effects like mass flow of nutrients (Barber, 1971), exudation of organic substances by the roots etc., (Rovira, 1959 and 1962, Balasubramanian and Rangasamy, 1978). On account of these factors, the pot experiment involved different soil types, induced fertility variation, sterilized and unsterilized condition and also consideration of rhizosphere and non-rhizosphere soils. Thus the pot experiment covered many of the normal variations encountered in growing sorghum crop and provided an opportunity to have an indepth understanding of nutrient availability - plant growth relationships as applied to sorghum.

5.1.2.1. Pot culture experiment

Studies on nutrient availability, transformation and flow rate in rhizosphere and non-rhizosphere soils of sorghum crop as influenced by soil types, fertilization and sterilization were carried out under pot culture experiment.

5.1.2.2. Characteristics of soils used for the experiment

The physico-chemical characteristics of the black soil and red soil used for the experiment are presented in table 3. These two soils occupy a major area in the state of Tamil Nadu varying widely in textural make up, thus imparting perceptible differences in the physico-chemical characteristics which would give sufficient scope for the study.

Sorghum crop constitutes the main millet grown in the soils both under rainfed and irrigated conditions and occupies a unique position among the cultivated crops in Tamil Nadu and forms the staple food for hundred millions in the country. It is cultivated in nearly 10.0 lakh hectares in the state. The suitability of the crop to all the three seasons viz., South West monsoon season, North East monsoon and summer irrigated season offers scope to substantially increase the production by stabilizing sorghum yield (Anon., 1985).

The black soil was clayey in nature, while red soil was sandy loam. The CEC was higher in the black soil than in the red soil due to the content and type of clay minerals (Chinnadurai, 1967). Earlier works on the black and red soils of Tamil Nadu have shown that these soils exhibited marked differences in some of their properties (Menon and Mariakulandai, 1957 a; Ray Chaudhury and Govindarajan, 1958; Dhanapalan Mosi, 1960; Manickam, 1961; Krishnamoorthy, 1966; Chinnadurai, 1967; Jose, 1973; Kothandaraman, 1975; and Ramanathan, 1977). These workers observed that black soils were characterized by higher clay content and greater CEC while red soils were relatively rich in iron oxides. In the present study also, the differences between the black and red soils were quite marked and this may be attributed to the difference in the kind of parent material from which they have been derived and the degree of weathering undergone by them (Menon and Mariakulandai, 1957b; RayChaudhury and Govindarajan, 1958). The wide variation in the total contents of both macro and micro nutrients in soils is attributed to the differences in the nature of their parent material and soil forming processes in different climatic conditions (Kanwar and Randhawa, 1967; Arunachalam and Dhanapalan Mosi, 1973).

5.2. Dynamics of rhizosphere soils in relation to nutrient availability

5.2.1. Effect on availability of N, P and K in soils

5.2.1.1. Effect on available N (Table 4)

The status of available N was found to be influenced, not by the varying levels of N, but by the other factors such as rhizosphere soil, soil types and sterilization. The increasing trend of available N status in the black soil under sterilized condition and in the rhizosphere soil is attributable to several factors. The black soil by virtue of high colloidal material and organic matter content (Kanwar, 1976) obviously favoured greater accumulation of available N status in the black soil than in the red soil. A relatively high available N in the rhizosphere soil might be attributed to the mass flow phenomena (Barber, 1971). This is evidenced by the work of Marschner (1983) who stated that at the soil-root interface, i.e., rhizosphere, the availability of nutrients can be considerably influenced by the plant root itself.

Under sterilized condition of the soil, the build^{up} of microflora was inhibited resulting in poor mineralization rates and prevention of leaching and volatile losses. The more or less same trend was reflected in the other stages of crop growth as well. Possible reason for the absence of any build^{up} of available N with increasing levels of N

attributable to the present conditions of the experiment, where the entire dose of N was basally applied and tropical conditions that existed have favoured rapid transformation with the result what one would visualise large scale differences in available N upon enhanced fertilization has not been observed in this case. Further, the highly mobile nature of the nutrient has nullified any difference that would arise in different levels of N. Such experimental results were also reported by Cornish and Raison (1976) in the case of rye seedlings. The available N content was the highest at 30 days stage and thereafter it declined progressively its value being low at 90 days stage. Such a result could also be expected since there was a continuous removal of N by the growing crop. Similar results of decrease of available N during crop growth have been reported by different workers in sorghum crop (Ramalingam, 1975; Bhalerao et al., 1976; Viswanathan, 1976; Durairaj Muthiah, 1978 and Muthukrishnan, 1979).

5.2.1.2. Effect on available P (Table 5)

The forms and amounts of P in the soil have a considerable effect on the availability of P to crops. The rhizosphere region contained more available phosphorus in relation to non-rhizosphere region (Barber et al., 1963; Lewis and Quirk, 1967; and Riley and Barber, 1971). The red soil inherently contained more of available P as was observed by Kandasamy et al. (1973) and Krishnasamy (1982). The

sterilized condition and N addition tended to decrease the available P content in soil, while P addition favoured greater accumulation of available P. Phosphorus is usually absorbed from a small volume of soil surrounding the root because P diffuses very slowly through the soil (Barber et al., 1963; Lewis and Quirk, 1967). Thus the status of available P was found to be conditioned by several factors. The effect of sterilization resulting in decrease of the available P might be ascribed to the poor decomposition of organic matter on account of reduced microflora and formation of favourable organic compounds for mobile P (Arunachalam, 1975).

As is the case with N, the rhizosphere soil accumulated relatively more available P (Arunachalam, 1975) and this effect might be due to not only the solubilizing effect of root exudates, but also enhanced microbial population e.g., phosphate solubilizing bacteria (Chandrasekaran, 1965 and 1968). in the region. Riely and Barber (1971) recognised that the rhizosphere microflora and exudates from the roots have been postulated as factors influencing P availability. Olsen's P values were higher in the rhizosphere soil than that in the non-rhizosphere soil and this might be attributed to the solubilization of insoluble phosphate compounds because of organic acids as a result of increased microbial activity in the rhizosphere

(Duff et al., 1963; Sharma and Saxena, 1982). In addition to this, the P movement and absorption in soil might have occurred through diffusion and interception which influenced the availability of phosphorus in the rhizosphere soil (Sharma and Saxena, 1982).

Another point of interest is that the N addition brought about decrease in available P in the earlier stages i.e., from 3.17 to 3.07 ppm at 30th day and from 3.85 to 3.23 ppm at 60th day of crop growth and this effect got reversed near about the harvest stage. Perhaps the influence of N on microbes and the enhanced utilization of P brought about by enhanced growth of plant by N might have accounted for such a phenomena (Fried and Broeshart, 1967).

5.2.1.3. Effect on available K (Table 17)

The black soil contained more available K (434 ppm at 30 days, 394 ppm at 60 days and 370 ppm at 90 days) than the red soil (204 ppm at 30 days, 180 ppm at 60 days and 163 ppm at 90 days) obviously attributable to the higher clay content (Jayaraj and Dhanapalan Mosi, 1973). The rhizosphere region recorded higher available K than non-rhizosphere region which could be accounted for the twin effects of enhanced solubilization of K on the one hand and the interaction of other elements with fixed K on the other

(Arunachalam, 1975). The rhizosphere region of black soil had high quantities of available-K content than the non-rhizosphere region of red soil. The application of P did not bring about any significant effect on available K content in the soil and this was contrary to the findings of Negi et al. (1981) who stated that application of higher dose of P decreased the available K status. The available K content decreased significantly with advancement of stages of crop growth. It was possible that such progressive reduction was brought about by crop uptake or by continuing transformation leading to conversion of water soluble-K into insoluble forms or fixation of K in the crystal lattice of clay minerals. Earlier workers like Antony Joseph (1969), Raju (1977) etc. also adduced similar reasoning to the decrease of available-K content of the soil with advancement of crop growth.

5.2.2. Effect of availability of micronutrients

5.2.2.1. Effect on available Fe (Table 6)

The available Fe content found to be high in the black soil could be attributed to the inherent nature of the black soil and higher clay content (Kanwar, 1976). The available Fe content was observed to be increased at all the three stages of crop growth. Similar results were also reported by Francis (1976). Lower concentration of available Fe was recorded in the black soil (Arunachalam, 1975). The effect of sterilization on available Fe was found to be a

time-bound process. During the initial stages, under sterilized condition of the soil microbial build-up was lowered thereby providing less opportunities for chelation and this resulted in lowered available Fe. But with time the microbial build up proceeded, decomposition processes setting up providing more opportunities for such mechanisms like chelation (Himes and Barber, 1957) solubilization, mineralization, etc. and these processes favoured more available Fe. The rhizosphere region recorded higher available Fe attributable to the lowered pH and solubilization effect (Sauchelli, 1969; Arunachalam, 1975; Mortvedt et al., 1972 and 1977).

5.2.2.2. Effect on available Mn (Table 7)

A comparison of soils with regard to their influence on available Mn content showed that the red soil which recorded increased initial value of available Mn content as 20.6 ppm was found to record increased values of available Mn content and this may be attributable to the inherent nature and low soil pH. But Arunachalam (1975) and Krishnasamy (1982) reported higher concentration of available Mn content in the black soil than that in the red soil. Under sterilized condition of the soil, the available Mn content was diminished and this could be explained by the fact that the availability of Mn was closely linked to the organic matter-microflora relationships (Katznelson, 1965, Ramasamy

and Raj, 1973). Contrary to this observation, Boyd (1971) reported Mn-toxicity in autoclaved soil resulting from the release of the Mn complexed with soil organic matter and the killing of microorganisms which normally transform available Mn to higher oxides. But Jager *et al.* (1969 a and 1969 b) reported increased buffer soluble Mn content in the soil. Arunachalam (1975) recorded higher concentration of available Mn under sterilized condition.

As is the case with Fe, the rhizosphere region contained more available Mn than the non-rhizosphere region, obviously associated with solubility, chelatability and pH relationships associated with rhizosphere region soils and this is in line with the findings of Arunachalam (1975). Nitrogen application at 100 kg ha^{-1} level increased the available Mn content in the soil at 60th day. Phosphorus application at 50 kg ha^{-1} increased the available Mn content at 30 and 60 days growth stage and this was not in confirmity with the findings of Gupta and Bhadra (1980) who studied the Mn-P relationship in rice in an alluvial soil of West Bengal. They reported that P application reduced Mn availability in the first and second sampling stage, but increased it in the third sampling stage of rice crop.

5.2.2.3. Effect on available Cu (Table 8)

The black soil contained more available Cu content in view of higher clay content associated with it, as

was observed by Arunachalam (1975) and the higher initial available Cu content in the soil. This is in consonance with the findings of Krishnasamy (1982). Under sterilized condition of the soil the available Cu content was increased. This might be due to lessening of release of organic compounds by way of decomposition which was known to immobilise Cu (Mortvedt et al., 1972). As in the case of Fe and Mn, more available Cu was observed in the rhizosphere region (Arunachalam, 1975) and the reasons already attributed for Fe and Mn hold good for Cu as well. Moreover, the strong binding effect of Cu with organic ligands is well established (Fried and Broeshart, 1967). The effect of N addition was found to increase available Cu in the soil and this was more pronounced at later stages. The addition of N could be expected to enhance the microbial content and also the rate of decomposition of available organic substances. This effect might result in the temporary lock up of available Cu in the initial stages. With time the cessation of microbial multiplication could be expected and the available Cu got enhanced again.

5.2.2.4. Effect on available Zn (Table 9)

The red soil was associated with higher Zn availability at all the three stages of crop growth and this is in line with the results observed by Krishnasamy (1982)

and Nagarajan (1984). But Kanakaraj (1979) reported that available Zn was lower at maturity stage than at flowering stage. Arunachalam (1975) reported a higher concentration of available Zn in the black soil. Under sterilized condition of the soil the available Zn content was found to be decreased at initial stages and perhaps this might be due to absence of organic matter-zinc interaction (Himes and Barber, 1957). The effect of organic matter in diminishing Zn availability had been reported by several workers like Fried and Broeshart, 1967 and Mortvedt et al., 1972 . But Arunachalam (1975) reported that Zn availability was more under sterilized condition. As was the case with other micronutrients, Zn availability was found to be more in the rhizosphere region (i.e., 0.50 ppm at 30 days; 1.30 ppm at 60 days and 0.90 ppm at 90 days stage) than that in the non-rhizosphere region and the reasons already stated hold good for this effect as well (Arunachalam, 1975). The effect of lowered pH values, root exudates and microbial content in enhancing Zn availability are well evidenced by several earlier workers (Barber, 1962; Katznelson, 1965; Balasubramaniam and Rangaswamy, 1978). The effect of N application in increasing the availability of Zn was observed only at later stages of crop growth and this is in confirmity with the findings of earlier workers.

5.3. Dynamics of rhizosphere soils in relation to nutrient transformations

5.3.1. Effect of transformation of N, P and K in soils

5.3.1.1. Effect on N transformation (Tables 10 and 11)

i) $\text{NH}_4\text{-N}$:

A consideration of the build up of $\text{NH}_4\text{-N}$ revealed that among the five factors, under sterilized condition of the soil, rhizosphere environment and P levels brought about significant differences in the $\text{NH}_4\text{-N}$ content. Sterilization kept down the $\text{NH}_4\text{-N}$ content to a marked degree from 26.6 to 21.3 ppm at 30th day, from 51.2 to 42.2 ppm at 60th day and from 10.0 to 7.6 ppm at 90th day, obviously attributable to the absence of nitrification process by bacteria. The effect due to sterilization was very highly pronounced suggesting the significant role of microflora in conditioning the soil N transformation (Katznelson, 1946; Rouatt et al., 1960). Sonneveld et al. (1970) reported that although steam sterilization killed most of the nitrifying microorganisms little NH_4^+ or NO_3^- was found at 40-50 days after treatment.

The other point of interest is that the rhizosphere soil contained relatively higher $\text{NH}_4\text{-N}$ content at 30 days growth stage and this is in conformity with results reported by Tinker (1969). This might perhaps be due

to a more congenial environment for microbes in the rhizosphere soil as compared to non-rhizosphere soil and the processes viz., the mass flow and the adsorption mechanisms could be expected to be higher during the younger stages of the plant (Barber, 1962 and Marschner, 1983). The lowered values of $\text{NH}_4\text{-N}$ content at 90th day was ascribed to the overall diminishing effect in the microbial activity apart from utilization of nitrogen by the crop. The matter of interest also lies in the fact that the soil differences and N application have not resulted in any differential build-up of $\text{NH}_4\text{-N}$ content (Cornish and Raison, 1976); however, differences in $\text{NH}_4\text{-N}$ content occurred during the advancement of the growth of the crop. The red soil accumulating more $\text{NH}_4\text{-N}$ again at 60th day, all N levels associating with more $\text{NH}_4\text{-N}$ again at 60th day were observed. This might be due to enhanced adsorption of $\text{NH}_4\text{-N}$ ions in the black soil in relation to the red soil (Fried and Broeshart, 1967). Another possible reason is that the black soil on account of its organic matter content, higher clay content, CEC and adsorption capacity (Kanwar, 1976) and the conducive environment in the black soil may result in rapid nitrification of any NH_4^+ that is formed (Katznelson, 1965 and Allison, 1973). The effect of P on $\text{NH}_4\text{-N}$ content at all the three stages of crop growth was found to be antagonistic. This might be due to the effect of P on microflora resulting in greater nitrification of $\text{NH}_4\text{-N}$ and enhanced root growth (Rouatt and Katznelson,

ii) $\text{NO}_3\text{-N}$:

A consideration of $\text{NO}_3\text{-N}$ gave evidence for the more important nature of rhizosphere soil and the effect of sterilization to cause pronounced differences in $\text{NO}_3\text{-N}$ accumulation. The rhizosphere soil was associated with higher $\text{NO}_3\text{-N}$ content (41.8 and 47.3 ppm at 30 and 60 days growth stages respectively). This is ascribable to the higher microflora associated with rhizosphere soils (Rouatt et al., 1960) and higher mass flow rate could be expected to be more during active growth stage (Barber, 1971). Under sterilized condition of the soil the $\text{NO}_3\text{-N}$ accumulation was found to be observed obviously due to lack of sufficient microflora for nitrification process. The above trend of results are in line with the findings of earlier workers like Katznelson (1965) and Sonneveld et al. (1970). But Burgos (1964) reported that soils sterilized with gamma radiation increased total N, $\text{NO}_3\text{-N}$ and P probably through releasing these nutrients after the destruction of the living microflora. The effect of N levels depended again on the stage of sampling. Nitrogen application was associated with lowered $\text{NO}_3\text{-N}$ content on 30th day, the reverse was the case at later stages as was observed by Parkinson and Thomas (1969). It is again a factor associated with microbial content as it is well known that soon after N addition, there is a build-up of microflora (Mosolov et al., 1959) and decline of the same with time.

Phosphorus application also reacted in a similar manner viz., higher $\text{NO}_3\text{-N}$ content at the initial stage and declined thereafter again-a case closely linked to microbial activity.

5.3.1.2. Effect on P transformation (Tables 12 to 15)

Transformation of phosphorus in soil is a dynamic process which is influenced by rhizosphere besides other soil and plant characteristics. The sum of the contents of saloid-P (NH_4Cl extractable), Al-P ($\text{NH}_4\text{-F}$ extractable), Fe-P (NaOH extractable) and Ca-P (H_2SO_4 extractable) may be collectively designated as active inorganic P because these are the soil P fractions which are usually related with plant availability and undergo enrichment or depletion by fertilization or crop removal (Volk and McLean, 1963; Singh *et al.*, 1966).

i) Saloid-bound P

The saloid-bound P also showed variation due to treatments. This was observed to be maximum at 30 days growth stage, which might be due to hydrolysis of added and native phosphates and the decrease thereafter, might be due to the transformation of water soluble-P into other insoluble fractions with time (Singh and Bahaman, 1976). Among the two soils the red soil was associated with higher saloid-P than the black soil since the red soil provided a more congenial environment for saloid-P in view of high anion exchange capacity associated with Kaolinitic clay. The evidence for

high AEC in kaolinitic clay could be deduced from the work of Buckman and Brady (1967) and Grimshaw (1971). The effect of sterilization was synergistic in the earlier stages and vice versa at later stages.

The rhizosphere region recorded relatively low saloid-P at 30 days stage (4.84 ppm) as compared to non-rhizosphere region (9.65 ppm). It might be attributable to a slightly more acidic nature in the rhizosphere soil accomplished by root exudates (Rovira, 1959). This, coupled with the acid root exudates, could be expected to solubilise the saloid-bound P in the rhizosphere region. This also signified the natural ability of the plant roots to obtain phosphorus by such mechanisms. However, at 90 days stage this was not the case obviously due to lowered activity of the roots (Scott, 1977). The amount of saloid-bound P in the soil was found to be related to the microbial activity. Under sterilized condition of the soil, the absence of microbial content in the soils resulted in poor P utilization by microbes and this tended to enhance saloid-bound P i.e., .95 ppm as against 6.54 ppm under normal condition of the soil. This was further evidenced by the fact that at 90 days stage the effect due to sterilization was not evident and the microbial factor became prominent and consequently the saloid-bound P got reduced.

ii) Al-P:

Unlike saloid-P, the black soil recorded more Al-P than the red soil and sterilized condition tended to cause increased Al-P content in the soil. As was the case with other forms of P, the rhizosphere soil contained more Al-P than the non-rhizosphere soil. This is in line with the observation of Jain and Sarkar (1980) who suggested that a major portion of the applied P was transformed into Al-P and Fe-P during the initial stages. The effect of N addition was to diminish Al-P while that of P addition tended to enhance the same. The higher Al-P content in the black soil than that in the red soil might be attributed to high clay content (Kothandarman, 1975 and Singaram, 1988). The lowered microflora, caused by sterilized condition accompanied by reduced decomposition of available organic matter might have contributed to the enhanced accumulation of Al-P in the soil (Allison, 1973). The enhanced Al-P in the rhizosphere soil was attributable to slightly more acidic nature of the soil than that of non-rhizosphere soil (Sharma et al., 1980), combined with the release of Al-P that could be expected due to acid exudates. The interaction effect between Al-P accumulation and added N though significant did not reflect any consistent trend. The effect of P application was to increase Al-P with time obviously due

the more time available for the fixation. It was well evidenced that any P applied remains unfixed initially but becomes unavailable due to fixation by such elements like Fe and Al at a later stage (Bapat and Badekar, 1965).

iii) Fe-P:

The Fe-P content differed among the experimental factors due to soil, sterilized condition and also the stages of sampling. The red soil contained more Fe-P on account of higher Fe content associated with it. Under sterilized condition Fe-P content was enhanced since the decomposition mechanism was upset by lowered microbial activity and lowered chemical effects on Fe-P formed. The effect of N addition to decrease Fe-P content in the earlier stages was again a phenomenon related to the microbial effect conditioned by N addition. It was also observed that at 90 days stage the effect of N application was not seen and the Fe-P content enhanced due to lowered microbial activity (Rovira, 1959) and this might be due to the reduction of insoluble ferric phosphates to soluble ferrous phosphates (Singh and Bahaman, 1976). The effect of P addition causing enhanced Fe-P accumulation in the soil was attributable to greater access of P to Fe existing in the soil (Kothandraman, 1975, Thakur et al., 1975, Singaram, 1988) and with advancement of crop growth Fe-P content decreased as against the observation made by Chang and Chu (1961).

iii) Ca-P:

The black soil registered more Ca-P content than the red soil on account of higher Ca content in soil. Under sterilized condition of the soil Ca-P content was decreased due to lowered microflora and enhanced Fe activity. The rhizosphere soil contained more Ca-P mainly attributable to the release of more Ca on account of solubility effect of the root exudates. The acid extractable Ca-P made comparatively smaller contribution (2.93 to 7.56 ppm) as was reported by Mishra and Khanna (1982). The effect of P addition was to enhance Ca-P content attributable to the enhanced reactivity of Ca with added P (Thakur et al., 1975) and also the possible conversion of Al-P and Fe-P into Ca-P (Jain and Sarkar, 1980). The above observations indicated that the plant feeds initially on Al-P and Fe-P and subsequently on Ca-P which is not readily available to the crop as suggested by Jain and Sarkar (1980).

5.3.1.3. Effect on K transformation (Tables 16 to 18)

i) Water soluble-K

The rhizosphere soil contained more water soluble-K content than the non-rhizosphere soil. Nitrogen application showed no beneficial effect in enhancing the water soluble-K content at all the three stages of crop growth. Phosphorus application tended to decrease the water soluble-K content at 30 days of crop growth stage. Under

sterilized condition of the soil the water soluble-K content was increased in the soil at 30 days growth stage. This falls in line with the findings of Jager et al. (1969 a and 1969 b) who reported that soil steaming enhanced the K solubility. Higher water soluble-K in the red soil (61.5 ppm) than in the black soil (50.4 ppm) was attributable to its inherent nature and low CEC of the red soil (Kanwar, 1976) and higher clay content of the black soil (Subramanyeswara Rao and Rajagopal, 1981). Higher water soluble-K content in the rhizosphere soil was again a case of solubilization effect of root exudates.

ii) Exchangeable-K:

Since the exchangeable-K was considered as available-K due to small fraction of water soluble-K content in the soil, the discussion put forth under available K holds good for exchangeable-K also.

iii) HNO_3 extractable-K

The black soil on account of its expanding clay type registered more HNO_3 extractable-K (377 ppm at 30 days stage) than the red soil (296 ppm at 30 days stage) (Prasad et al., 1971). Ramanathan (1978) reported a value of 100 to 1400 ppm for HNO_3 extractable-K in the alluvial soil groups of South India. The rhizosphere soil also influenced the

HNO_3 extractable-K content and this could be attributed to the possible ammonium-K interaction and $\text{K-H}_2\text{O}$ interchange (Bear, 1964; Buckman and Brady, 1967). Nitrogen addition at 50 kg ha^{-1} tended to decrease HNO_3 extractable-K content. Perhaps the ammonium ions resulting from mineralization dislodged the exchangeable-K and the phenomenon of equilibration had operated (Narayanan Nambiar, 1972).

5.4. Dynamics of rhizosphere soil in relation to nutrient flow rate or flux or uptake rate in sorghum plant (Tables 19 and 20)

The higher flow rate of all the nutrients in the sorghum plant grown in the black soil than that in the red soil may be attributed to the higher fertility status of soil (Kanwar, 1976 and Viswanath et al., 1978). The nutrient uptake rate of N and K were the highest followed by P, Fe, Mn, Zn and Cu as was observed by Patel and Ghildyal (1980) in the case of rice crop. The rate of uptake of micronutrients was approximately one per cent of the rate of uptake of macronutrients.

In the case of N, P, K, Cu and Zn flow rates the sterilized condition of the soil did not produce any significant influence in the concerned nutrient flow rate as was expected and this might be due to lower dry matter yield. The enhanced Mn flow rate in the plant under sterilized condition might be due to higher Mn content in the root

under sterilized condition and this is in agreement with the findings reported by Arunachalam (1975). Under sterilized condition of the soil Fe flow rate was decreased in the plant and this might be due to the lowered Fe content in the plant, lowered availability of the element and poor dry matter yield.

The rate of uptake of major and micronutrients increased rapidly and recorded maximum at the vegetative stage (30 days stage) and the rate then decreased as the plant advanced from the vegetative to the reproductive stage of growth. Similar findings were reported by Brewster and Tinker (1972). These results gained experimental evidence from the work of Warncke and Barber (1974) and Mengel and Barber (1974) who reported similar results in the case of root development and rate of nutrient uptake in corn crop and from the work of Patel and Ghildyal (1980) in rice roots. The decrease in the nutrient uptake rate was due to more rapid increase in root length than in the rate of nutrient uptake from vegetative to reproductive stage of growth (Rovira and Bowen, 1968 ; Mengel and Barber, 1974).

By and large, the effect of N and P application on the nutrient flow rate of the major and micronutrients was not observed because of the significant increase in root length at vegetative and preflowering stages (Mengel and Barber, 1974) and this may be the reason for the of the applied nutrients on the nutrient flow

5.5. Effect on crop nutrition

5.5.1. Effect on N, P and K content in root (Tables 21 to 23)

Higher values of root N content was recorded in the black soil obviously due to higher available N associated with the black soil. This is in line with the findings of Viswanath et al. (1978). But Krishnasamy (1982) reported that the effect of soil was not significant on the root N content in sorghum crop. Francis (1976) reported that the treatments imposed did not influence the N content of roots of sorghum crop in both the black and red soils. The varying doses of N employed had no differential impact on the content of N in the root. This may be attributable to the nutrients available in the root zone might have been depleted due to continuous uptake. The results gained support from the work of Kandasamy et al. (1973). Further, the added N enhanced the root growth and the extra nitrogen taken up by the plant underwent dilution effect with the result the content remained on par with no nitrogen treatment. The effect of P application on root N content was observed to be negative. Here again it was the dilution phenomenon that had operated, since P is known to enhance the root growth and this can be expected to result in the dilution of the absorbed N.

The black soil recorded higher value of root P (0.69 and 0.30 per cent at 30 and 60 days growth stage respectively) than the red soil (0.43 and 0.23 at 30 and 60

days growth stage respectively). But Krishnasamy (1982) reported that the red soil recorded higher value of root P than the black soil. The inherent high P supplying capacity of the soil may be responsible for such variation. Francis (1976) reported that the treatments imposed did not influence the root P content of sorghum crop in both the black and red soils. Under sterilized condition of the soil available P content in the soil was decreased as already discussed and this resulted in lowered content of P in the root. This observation is in line with the work of Arunachalam (1975) who also observed reduced P content in the root due to sterilized condition. The addition of N and P had no impact on the content of P. This might be attributed to the dilution effect on account of root growth that accompanied by N and P fertilization. Similar results were also reported by Singaram (1988).

Higher values of root K content were observed in the black soil and this might be due to the high available K status associated with black soil (Viswanath et al., 1978). Krishnasamy (1982) also reported similar results. The effect of sterilization decreased root K content, attributable to the lowered available-K status in soil on account of sterilized condition. Similar results were also reported by Arunacalam (1975). Nitrogen addition enhanced root K content

particularly at later stages of crop growth and this might be ascribed to the release of K in conjunction with NH_4^+ ion liberation. Similar results were reported by Kanwar (1976). Phosphorus application decreased the root K content and this is a case of dilution effect of absorbed K due to enhanced root growth accompanying P application.

5.5.2. Effect on micronutrient content in root (Tables 24 to 2

The black soil registered higher concentration of Fe (633 and 426 ppm at 30 and 60 days respectively) than the red soil (598 and 358 ppm at 30 and 60 days respectively). This could be ascribed to the enhanced available Fe content in the black soil combined with the concentration effect on account of lowered root yield. Similar observations were reported by Viswanath et al. (1978). It was reported that accumulation of Fe in root was governed by available status of the element in the soil. Francis (1976) reported a higher concentration of Fe in 30 and 60 days old root of sorghum crop in the red soil than that in the black soil. But Krishnasamy (1982) reported that soil types had no significant effect on root Fe content. The root Fe content under sterilized condition was considerably more-a case of concentration effect again. The addition of P decreased the root Fe content at all the three stages giving evidence to a strong Fe antagonistic effect both in the matter of availability and uptake of Fe (Dev and Mann, 1972; Velu, 1977 ; Verma and Tripathi, 1986). The

root Fe content decreased with the progress of growth of the crop indicating the absorption of Fe to be more during the early stages of crop growth. Such a phenomenon was also evidenced from the work of Tiffin (1972) and Francis (1976).

Similar to Fe content in root, the black soil recorded higher value of Mn content than the red soil attributable again to the inherent initial high Mn availability in the soil. Similar results were also reported by Francis (1976). But Viswanath et al. (1978) reported that the root of maize crop grown in the red soil accumulated more Mn content followed by black and laterite soils. Krishnasamy (1982) reported that soil types had no significant effect on root Mn content. Under sterilized condition of the soil root Mn content was enhanced as was reported by Arunachalam (1975) and this might be due to concentration effect on account of reduced root growth. The P-Mn antagonistic effect had also operated as evidenced by lower Mn concentration (40.5 ppm at 30th day, 28.0 ppm at 60th day and 31.1 ppm at 90th day) in the root due to P application. This is supported by the findings of earlier workers like Baser and Ram Deo (1967) who reported P-Mn antagonistic effect in jowar and maize plant.

The above trend of results were also reflected in respect of root Cu content more or less in a similar fashion. The red soil showed higher root Cu content at 30 days growth stage than the black soil as was observed by Viswanath et al.

(1978). Krishnasamy (1982) also reported that the red soil recorded an increase of 10 per cent of root Cu content over the black soil. But Francis (1976) reported that the black soil recorded higher root Cu content than the red soil and that the root Cu content decreased with advancement of crop growth. However, the effect of N in increasing root Cu content was also observed. This might be due to the possible nitrifying bacteria organic matter decomposition factor by which Cu availability was enhanced (Mortvedt et al., 1972). The P-Cu interaction was again found to be negative.

The black soil showed higher root Zn content than the red soil and this might be attributable to the concentration effect. But Viswanath et al. (1978) and Krishnaswamy (1982) reported that the red soil accounted for increased concentration of root Zn. Under sterilized condition of the soil root Zn content was enhanced. The decrease of root Zn at later stages of crop growth might be attributable to the dilution effect of the absorbed Zn. Similar results were also reported by Francis (1976) and Singaram (1988). This also suggests that much of the Zn is taken up by the plant during the early stages of crop growth. The decrease in root Zn content at the three stages of crop growth with the application of N might be due to translocation of more Zn from root to shoot. This investigation is in consonance with the findings of Satinder Dev and Shukla (1980).

5.5.3. Effect on N, P and K contents in shoot (Tables 28 to 30)

The salient results include high shoot N content in the black soil, enhanced N content under sterilized condition of the soil and due to N and P fertilization. Enhanced values of shoot N content in the black soil and under sterilized condition are also cases of concentration effects. This is in consonance with the experimental evidence of Jager et al., (1969 a and 1969 b) who reported that soil steaming increased N and Mn contents, fresh and dry matter production of lettuce.

Krishnasamy (1982) reported that the soil types had no influence on the shoot N content of sorghum. Under sterilized condition of the soil despite reduced N availability in the soil both root and shoot recorded higher N content and this might partly be on account of reduced growth and lower dry matter yield both in the case of root and shoot. This finds support from the work of Satinder Dev and Shukla (1980). The plant could get N even under sterilized condition, but it could not have been utilized for the growth due to limitation of other factors induced by sterilization. This observation gains experimental support from the results of Jenkinson et al. (1972) who reported that irradiation of soil increased the growth and N uptake of wheat and ryegrass in pots. With wheat, the increase in growth could be solely attributed to extra mineral N released by irradiation. As it

could be expected, N application enhanced N in the shoot (Hanway, 1962; Roy and Wright, 1974). Higher N content was recorded in the plant at 30 days stage thereby indicating the stage at which higher absorption occurs. The shoot N content declined at 90 days growth stage. At the early stage the plants are active enough to absorb higher proportion of N and this may be due to increased availability of N in the soil and better absorption of nutrients by extensive root system caused by higher doses of N. This is in agreement with earlier findings of Ramalingam (1975), Durairaj Muthiah (1978) and Muthukrishnan (1979). At the early stage of crop growth the N content was the highest which further declined at 90 days growth stage. This is in accordance with the findings of Kamalam (1964) who reported a sudden decline in the N content of straw at maturity stage due to translocation of accumulated N to the grain sorghum. Kaf Kafi (1967) reported that all the nutrients decreased after the appearance of flower primordia. At 60 days growth stage, there was higher concentration of N in the shoot. Similar results were observed by Chhabda et al., (1979) in different sorghum cultivars.

The black soil registered higher P concentration in the shoot than the red soil and this may be due to the inherent high P supplying capacity of the black soil and

lowered shoot dry matter yield. But Krishnasamy (1982) recorded higher shoot P content in sorghum crop grown in the red soil. The shoot P content of sorghum indicated variation at various growth stages and this finding gains support from the work of Chhabda et al. (1979). In spite of sterilized condition favouring reduced availability of P in the soil, the shoot carried higher concentration of P again attributable to the concentration effect and to the poor shoot growth under sterilized condition. Nitrogen addition in enhancing the P content might be attributable to the indirect effect of enhanced root growth and enhanced P availability in the soil (Hanway, 1962; Roy and Wright, 1974). Krantz (1958) also obtained increased concentration of P in oat which was top dressed with fertilizer. Phosphorus content in the shoot was higher in the primary stage of growth. This is in agreement with the results of Francis (1976) who recorded similar results in sorghum crop and Singh and Singh (1981) who reported similar results in rice and wheat crop.

The black soil recorded significantly higher shoot K content than the red soil and similar results were reported by Krishnasamy (1982). Under sterilized condition shoot K content was decreased due to reduced K availability in the soil and in turn reduced K diffusion to the root since the

effect of the root on the inorganic ion distribution in the rhizosphere is less (Barber, 1971). The N and P application favoured higher shoot K content in the crop grown in the black soil (Chhabda et al. 1979). The effect of N and P application in increasing the shoot K content might be attributable to the natural tendency of the plant to balance the enhanced absorption of N and P (Hanway, 1962; Roy and Wright, 1974). It also implies that both red and black soil provide a congenial medium in respect of K requirement and once N and P are sufficiently available, K absorption also proceeds uninterrupted and more rapid in the early stages of plant growth as was observed by Roy and Wright (1974) and Singh and Singh (1981).

5.5.4. Effect on micronutrient content in shoot (Tables 31 to 34)

The black soil recorded higher shoot Fe content than the red soil at all the three stages of crop growth. This might be attributable to greater availability of Fe and relatively reduced growth in the black soil. But Krishnaswamy (1982) reported that soil types produced no difference in shoot Fe content. Under sterilized condition of the soil the shoot Fe content was decreased at 30 days stage but was increased at later growth stages. The lowered availability of the element and poor dry matter yield under sterilized

condition are primarily responsible for this effect. The increase in shoot Fe content with growth is attributable to the progressive nullifying effect of sterilization with time (Sonneveld et al., 1970). In other words the effect of sterilization was not seen in the early stages though favourable conditions like high CEC, organic matter etc. were found. Similar results were reported by Arunachalam (1975).

The results observed for shoot Fe content were more or less reflected in the case of shoot Mn concentration as well. The black soil registered enhanced shoot Mn content. Krishnasamy (1982) reported that the black soil enhanced shoot Mn content over the red soil to the extent of 36.0 per cent. The N and P applications significantly reduced the shoot Mn content at all the three stages and the Mn content decreased with advancement in growth stage. In the case of jowar and maize crop, Baser and Ram Deo (1967) and Mishra and Tripathi (1973) in the case of wheat crop reported that availability and uptake of Mn was adversely affected by phosphorus fertilization.

As is the case with other micronutrients, the black soil registered higher shoot Cu content and this effect was observed only at later stages of crop growth. At 30 days stage of crop growth the black soil registered shoot Cu

content as 26.8 ppm as against 27.6 ppm for the red soil. This might be due to the lowered Cu availability in the black soil and lowered absorption of the element that could be expected due to formation of unstable Cu complexes due to higher organic matter content of the black soil. Krishnasamy (1982) reported that soil types attributed no significant difference in shoot Cu content. The shoot Cu content of 98.7 ppm and 107.0 ppm recorded under sterilized condition at 60 and 90 days growth stages respectively might be ascribed to increased Cu availability under sterilized conditions of the soil on the one hand and concentration effect arising out of poor shoot dry matter production on the other hand. Phosphorus application showed no effect on shoot Cu content in the shoot was observed by Ellis et al., (1964) who reported that P application decreased Cu concentration in beans and maize. Nitrogen application at 100 kg ha⁻¹ level increased the shoot Cu content at 60 days growth stage and this is in confirmity with the results of Ebert et al. (1972) who reported that high rates of N increased Cu, Mn, Mo and Zn uptake by crops especially rye grass and beet by 10-20 per cent.

The black soil registered enhanced shoot Zn content due to concentration effect of the element brought about by lowered shoot dry matter production. Krishnasamy (1982)

observed no significant difference in shoot Zn content due to soil types. Under sterilized condition of the soil the shoot Zn content at 30 days growth stage was increased and this might be attributable to the concentration effect. This is in consonance with the findings of Arunachalam (1975). Nitrogen application at 100 kg ha^{-1} level significantly increased the shoot Zn content at 30 days growth stage which indicated the efficiency of native Zn utilization by the crop as was observed by Satinder Dev and Shukla (1980) for maize crop and by Ebert et al. (1972) for rye grass and beet crop. Phosphorus application had no significant effect on shoot Zn content at the later stages of crop growth. This is in line with the work of Verma and Tripathi (1986) who reported that P application reduced Cu and Zn content of rice plants P-Zn antagonistic effect was proved by many workers.

5.5.5. Effect on N, P and K content in grain (Table 35)

The black soil recorded higher N content (1.11%) in sorghum grain than the red soil (1.01%) and this might be attributable to the initial fertility status of soil, cation exchange capacity and added fertilizers to the crop. Under sterilized condition soil microbes were absent around the root zone and this caused reduction in the N, P and K contents of the grain (Chandrasekaran, 1965; Katznelson, 1965; Chandrasekaran, 1968; Balasubramaniam and Rangaswami,

1978). The N and P application increased the N and P contents in grain and similar results were reported by Muthukrishnan (1979) in sorghum crop. The utilization of P was found to be greater in the presence of N.

The root P content at 90 days stage decreased considerably which might have been utilised for the formation of the root at the earlier stages of the crop growth and this resulted in the subsequent increase in grain P content. This coincides with the results of Chhabda et al. (1979) who reported that P content in the plant at harvest stage decreased considerably with subsequent increase in grain P content. The K content in the shoot declined at 90 days growth stage and accumulated in grain which is in conformity with the findings of Chhabda et al. (1979). There were marked differences in the P content of grain between the two soils studied. This finding is in agreement with the work of Muthuswamy (1972) and Muthukrishnan (1979).

The red soil recorded higher grain K content (0.48%) than the black soil (0.34%) and this might be ascribable due to greater fixation of K in the black soil than the red soil because of the presence of increasing clay content which impeded K diffusion (Grimme et al., 1971). In the case of red soil in addition to the added K at constant

dose, exchangeable K and fixed K were increased by the oxidation of the organic matter (Ross, 1971). Potassium content was less in the grain as compared to that in the shoot. This is in confirmity with the observations of Singh and Singh (1981) who reported that K content was low in wheat grain than in shoot.

5.5.6. Effect on content of micronutrients in grain (Table 36)

The red soil recorded higher accumulation of Fe (414 ppm); Cu (420 ppm) and Zn (100.3 ppm) in sorghum grain than the black soil. This might perhaps be due to higher accumulation of native and available Fe, Cu and Zn content in soil during the growth phase of the crop. The black soil recorded higher accumulation of Mn (48 ppm) in sorghum grain and this might be attributable to the higher native available Mn content in the soil. Under sterilized condition of the soil Fe, Mn, Cu and Zn contents in grain were decreased due to the absence of microorganisms around the root zone (Chandrasekaran, 1965; Katznelson, 1965; Chandrasekaran, 1968; Balasubramanian and Rangasamy, 1973). Nitrogen application increased the Fe, Mn and Cu contents but decreased Zn content in grain.

Phosphorus application at 50 kg ha⁻¹ level depressed Fe, Cu and Zn content in grain and increased Mn

content in grain thereby showing an antagonistic effect of P on Fe, Cu and Zn. This is evidenced by many workers like Verma and Tripathi, (1986). Jozsa and Gyori (1982) reported that NPK application at increased levels had not affected Mn and Zn concentrations and increased Cu concentration in grain of sweet sorghum. Higher accumulation of Zn in shoot might have reduced Zn content in grain (Satinder Dev and Shukla, 1980).

5.5.7. Effect on uptake of N, P and K by shoot (Table 37)

The uptake values are generally related to the content and dry matter production. Eventhough the availability of N in the soil did not differ between two types of soils, the higher shoot N content at 90 days stages in the red soil caused higher uptake of N in the shoot in the red soil. This is in line with the work of Krishnasamy (1982) who reported increased N uptake by sorghum crop in the red soil to an extent of 23.0 per cent over the black soil. Though the availability of N and K in soil was increased under sterilized condition of the soil from the beginning of crop growth, the reduced N and K uptake in the shoot would have been caused by the reduced growth, dry matter production and lower absorption of nutrients (Barber and Loughman, 1967 and Barber and Frankenburg, 1972). The increased N uptake at 60 days stage and decline at 90 days stage (Mohamed Ali and

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Morachan, 1973) might be attributable to the translocation of N from shoot to grain. A conspicuous effect for N and P uptake was not observed for N and P application due to lower dry matter production and utilization of P by the crop at the early stages (Vig and Dev, 1982). The soil types showed no significant effect on K uptake by shoot. But Krishnasamy (1982) reported that the red soil enhanced the total K uptake to the extent of 15.5 per cent over the black soil.

5.5.8. Effect on uptake of micronutrients by shoot (Table 38)

Iron uptake was not influenced by any of the main effects due to reduced Fe content in the shoot. The soil types also failed to exhibit their influence on Fe uptake by shoot. Krishnasamy (1982) also reported similar results. Eventhough under sterilized condition of the soil dry matter yield and Mn availability in the soil were reduced, the effect of sterilization turned to be favourable towards Mn nutrition as revealed by Mn content and uptake by the shoot. The soil types showed no significant effect on Mn uptake by the shoot. krishnaswamy (1982) reported that the total Mn uptake was promoted by the black soil.

Copper uptake by shoot was significantly higher under non-sterilized i.e., normal condition of the soil due to increased availability of Cu in the soil (Moore, 1972). The negative effect of sterilization on Cu uptake by shoot

was clearly felt in the study due to reduced dry matter production under sterilized condition. The soil types showed no significant effect on Cu uptake contrary to the findings of Krishnasamy (1982) who reported that the red soil promoted total Cu uptake by sorghum plant to the extent of 43.0 per cent over the black soil. Though under sterilized condition of the soil available Zn status in the soil and Zn content in the shoot at preharvest stage were increased, the reduced Zn uptake by the shoot due to sterilization effect might be attributable to the lesser dry matter yield. The higher dry matter yield at 90 days stage caused $4\frac{1}{2}$ times more of Zn uptake by the shoot than at 30 and 60 days stage. The soil types showed no significant effect on Zn uptake by the shoot. Krishnasamy (1982) reported that the red soil recorded increased total Zn uptake by sorghum plant to the extent of 55.0 per cent over the black soil.

5.5.9. Effect on uptake of N, P and K by grain (Table 39)

The black soil registered higher N uptake by grain than the red soil due to enhanced grain N content and increased grain yield. The adverse effect of sterilization on N, P and K uptake by grain was clearly felt and this might be due to lower grain N, P and K contents and reduced grain yield. A concomittant increased N uptake with increased

levels of N was observed in spite of the fact that the yield was more at N₅₀ level, but the grain N content truly followed the trend of N uptake by grain. The grain N uptake was not influenced by P application, but Singaram (1988) reported increased grain N uptake by blackgram crop due to P application. Though P fertilization did not increase the grain N uptake, but it increased the P uptake by grain due to the increased grain yield and increased P availability in the soil (Sheik Dawood, 1986; Singaram, 1988).

5.5.10. Effect on uptake of micronutrients by grain (Table 40)

Higher grain Fe uptake in the black soil might be explained by higher availability of Fe in the rhizosphere region, despite the fact that the red soil recorded higher Fe content in grain. Under sterilized condition of the soil the decrease of grain Fe, Mn, Cu and Zn uptake might be attributable to the reduced grain Fe, Mn, Cu and Zn content and reduced Fe, Mn, Cu and Zn availability in the soil. Following P-Cu antagonistic effect in grain Cu content, P fertilization exhibited an antagonistic effect on grain Cu uptake (Bingham, 1963; Verma and Tripathi, 1986).

5.6. Effect on root growth characteristics (Tables 41 to 46)

The production of more number of roots/plant, enhanced root volume, increased root mass, increased total

root length, increased root diameter and shoot weight in the red soil might be attributed to the light textured nature of the soil which helped in the easy penetration of roots for absorbing plant nutrients and water requirement. Krishnasamy (1982) reported that the red soil increased the root mass and shoot weight of sorghum crop over the black soil. The number of roots/plant, root volume, root mass, root diameter and shoot weight at all the three stages were reduced due to sterilized condition of the soil because of the fact that the microbial activity was considerably reduced in the soil which is mostly needed for various nutrient transformations taking place in the soil. The observations gain experimental support from the work of Kluge (1971) who reported decreased shoot and root elongation, stunting of roots, a low number of small and chlorotic leaves and decreased yield of different crops when grown in the sterilized soil and the effects of sterilization could not be eliminated, even after storing the soil for 3-12 months at room temperature and with an additional supply of NPK + Fe fertilization. There was increased total root length at 60 and 90 days stage due to sterilized condition which may be attributable to the attainment of normal conditions in the sterilized soil after 60 days (Sonneveld et al., 1970; Kluge, 1971).

At the early stages the levels of N used did not increase the root production, while at later stages of crop growth, the highest level of N i.e., 100 kg N ha⁻¹ recorded

the soil N might have been utilized by the crop, while at later stages the added N through fertilization might have been utilized. The significant increase in the number of roots/plant, root volume, root mass, total root length, and root diameter at all the three stages of crop growth for N application at 100 kg ha^{-1} and P application at 50 kg ha^{-1} indicated that P nutrition is required for the proliferation and development of roots. This is in agreement with the findings of Jena et al., (1980) on wheat crop and Krishnamoorthy and Iruthayaraj (1984) on sorghum crop. The root system consisting of long roots would contact more of soil volume and hence can utilize both nutrients and water to the maximum extent (Jena et al., 1980). At higher level of N the root diameter increased at 30 days of crop growth stage showing that higher level of N is required for the root to become thicker so that there will be strong foothold for the crop.

5.7. Effect on grain yield (g/plant) (Table 36)

Among the two soil types, the black soil registered higher grain yield per plant than the red soil. It was associated with an overall mean yield increase of 73.2 per cent over the red soil. In other words, the black soil proved more congenial for sorghum growth. Francis (1976) reported that the red soil recorded higher grain yield than the black

soil. Although in the black soil less number of roots/plant were produced and shoot weight, by way of mass factor it carried equal amounts of nutrients and favoured greater mobilization of nutrients through roots thereby accounting for enhanced yield. The sorghum grain yield was considerably different for sterilized and non-sterilized conditions registering 8.5 g/plant and 21.0 g/plant respectively. It is a matter of interest to note that the sterilized soil under the experimental conditions could be expected to move to normalcy at a faster rate. Yet this made considerable difference and the yield was markedly affected (Kluge, 1971). Nitrogen application at 50 kg ha^{-1} level also significantly increased the grain yield registering a mean yield of 15.4 g/plant as compared to 13.7 g/plant at N_0 level and 15.18 g/plant at 100 kg ha^{-1} level. Thus the optimum requirement of N remained within the limits of N levels tried. The grain yield was also found to be enhanced by P application. P application at 50 kg ha^{-1} level accounted for an yield 17.2 g/plant as compared to 12.3 g/plant with P_0 level thus representing 39.8 per cent increased yield thereby revealing the beneficial role of P on root growth and grain formation. This is in conformity with the results of Subbarao (1986) who reported that increased levels of phosphorus significantly increased the grain yield.

5.8. Interrelationships among root length, root mass and grain yield with soil chemical characteristics and other factors

Data relating to nutrient availability in soil, concentration and uptake of nutrients by plant as also the biometric data during different stages of crop growth were collected and this provided an excellent opportunity to have an understanding of the interrelationships that had existed among the different characteristics. Hence simple correlations were worked out by the method of Panse and Sukhatme (1978). Out of a number of interrelationships worked out, the significant correlations were found to be confined to the root growth characteristics viz., root length and root mass. The meaningful and significant correlations are presented in Table 47.

As could be seen, the grain yield was positively correlated with uptake of nutrients like N, P, K, Fe and Zn. This implies that the accumulation of the above nutrients possess a favourable effect on the grain yield.

The studies brought to light the profound influence of the root length and root mass on the several parameters investigated. The root growth either by way of increase of

root length or mass seemed to contribute significantly for the uptake of nutrients. The existence of a positive correlation between root length and the uptake of N, K and Zn revealed that a higher degree of proliferation is quite conducive for enhanced accumulation of N, P, K, Fe and Zn in the shoot, perhaps attributable to the enhanced rhizosphere volume and increased forage area that can be expected to occur with increased root length. Such beneficial effects of root growth on the impact of enhanced uptake of nutrients by plant, more particularly by shoot have been evidenced by earlier several workers. It may, however, be pointed out that the increase in root length resulted in decreased concentration of P and Fe in the root. This is obviously attributable not only to the dilution effect, but also to the enhanced translocation of nutrients as already explained above.

The root mass was also found to influence significantly the content of nutrients in the shoot such as N, K and Zn and N, K, Fe and Zn nutrient uptake by shoot. The increase in root mass can obviously be expected to account for enhanced forage area thereby facilitating enhanced utilization of the available nutrients in the soil. Such root mass - nutrient uptake synergistic influence have been reported by a number of earlier workers.

The root mass was also found to be negatively correlated with the content of nutrients like N, P, Fe and Zn in root, possibly due to the dilution effect on account of enhanced root volume. The existence of such negative relationships between root mass and nutrient concentration have been illustrated by workers like Jena et al. (1980).

CHAPTER 6

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CHAPTER 6

SUMMARY AND CONCLUSIONS

An appraisal of the nutrient availability, transformation and mobility of plant nutrients in the root environment of sorghum crop with particular reference to nutrient flow rate and uptake was thought to be of great interest from the point of view of fertilization of sorghum crop and hence studies were carried out in this investigation.

Pot culture experiment was carried out in black and red soils collected from the farm of Tamil Nadu Agricultural University, Coimbatore with sorghum Co.24 as test crop employing various experimental factors viz., soil types, sterilization, N levels (0, 50, 100 kg N ha⁻¹), P levels (0, 50 kg P₂O₅ ha⁻¹) and site of soil collection (rhizosphere and non-rhizosphere regions). The initial and stagewise soil samples as well as stagewise plant samples were collected and analysed for the respective parameters to understand the differences prevailing in the rhizosphere and non-rhizosphere regions with reference to nutrient availability, transformation and absorption of nutrients mainly contributed by factors viz., treatment effect, exudation, absorption, adsorption, root interception, etc. The various relevant biometric data were also recorded for the test crop and subjected to statistical scrutiny. Simple correlations were also worked

out to find the strength of relationship between any two variables. From the salient results obtained, the inferences and conclusions emanating from the various phases of study are briefly summarized in this chapter.

* Sorghum plant root exuded relatively more number and greater quantity of amino acids and sugars at 30 days than at 15 and 45 days of crop growth thereby exhibiting decline in the quantity of exudates with advancement of crop growth.

The effects of the different treatments on the various fractions of macronutrients and on the availability of macro- as well as micronutrients bring to light the following important points:

* The presence of microorganisms possessed a strong influence on the availability of macro and micronutrients. In most cases, the presence of microorganisms favoured the availability of plant nutrients in the rhizosphere soils. This is evidenced by the sterilized condition of the soil tending to depress the build up of available nutrients.

* The rhizosphere soils carried relatively higher amounts of both macro and micronutrients than the non-rhizosphere soils. The organic acids accumulating

within the vicinity of root environment, the origin of these organic acids being the root exudates themselves, formation of organic acids formed from sugars present in the exudate and by way of encouraging microbial growth within the vicinity of root environment as reflected under normal condition of the soil that may aid in complexing and chelating reactions play a vital role in the availability and transformation of plant nutrients in the soil.

* The concentration difference of the different nutrients in the root is closely linked to the root dry matter production rather than any appreciable treatment effect. The black soil was associated with reduced root growth and this has resulted in higher concentration of the different nutrients in general. So also, the effect of sterilization reduced the root growth due to lowered availability of many plant nutrients and absence of micro-organisms and root exudates. However, this had not reflected in the lowered concentration of the element in the root, but on the contrary, the concentration of some of the nutrients viz., available Cu content in soil N and P contents in the shoot, Fe, Mn, Cu and Zn contents both in root and shoot of the crop under sterilized condition were found to be higher than under non-sterilized condition, obviously attributed to the concentration effect, whatever nutrients the root would absorb. It also gave evidence that though the sterilized

condition could interfere with nutrient availability by way of reducing nutrient content, it had little effect on the amount of nutrients entering into the root. In the present study, whether the soil was sterilized or not, the root could absorb sufficient nutrients, but in view of the other limiting factors, the root growth got depressed under sterilized condition, thereby causing higher concentration of the nutrients.

* Phosphorus - micronutrient interactions were well projected. It is appropriate to indicate that P not only tended to decrease the availability of micronutrients but also hindered their absorption as in the case of P-Fe and P-Mn interactions which proved antagonistic. However, this antagonism was more a dilution effect of the absorbed nutrients due to better growth brought about by P application.

* With reference to the concentration of plant nutrients in the shoot, more of them in general, accumulated in the shoot relating to the black soil. This was due to concentration effect rather than enhanced absorption. In the present study, the black soil could produce relatively lesser shoot dry matter than the red soil and the absorbed nutrients tended to concentrate. This implied that there had not been any absorption problem, but on account of other factors, the dry matter got reduced in the black soil

resulting in greater accumulation of the absorbed nutrients. The enhanced concentration of the plant nutrients in the shoot viz., N, P, Fe, Cu, Mn and Zn due to sterilized condition is again a similar phenomenon. In other words, even under sterilized condition which had caused lowered availability of most of the nutrients, the amount of nutrients going into the plant system had not appreciably altered. The point of focus is that both under sterilized and normal conditions of the soil, sufficient nutrients moved into the system and got distribution over a larger mass in the red soil and vice versa in the black soil.

* The black soil possessed more clay content thereby possessing higher CEC and several other advantageous factors such as more organic matter and as a result, the black soil recorded higher availability of N, K, Fe and Cu.

* The reduction in microbial content due to sterilized condition of the soil which had brought forth many undesirable effects such as lowering of nutrient availability, lowering of nutrient transformation and mobility and interference with nutrient absorption thereby causing poor root formation interfered with the early vigour of emerged seedlings and accounted for lowered yields in the long run.

* Sorghum, being a cereal and C₄ tropical photosynthetic crop, responded to N fertilization and the curvilinear response had been evidently exhibited as well. Phosphorus application at 50 kg ha⁻¹ level brought about yield improvement to the tune of 39.8 per cent over control thereby suggesting that the zinc availability had not been reduced to the point of critical condition.

* The nutrient flow rate into the plant at vegetative stage was the most rapid and decreased with the advancement of plant growth. The high nutrient flow rate in the young sorghum plant indicated that a much higher quantity of available plant nutrients in the soil is needed during the early plant growth stage than at later stages of the plant growth cycle. The amount and length of root grown in the soil would appear to be important during the early growth stage of the crop.

* The nutrient uptake both by shoot and grain is related not only to the yield of dry matter and grain but also to the nutrient availability in the rooting environment of the soil. The sterilized condition of the soil depressed the uptake of macro and micronutrients both in the shoot and grain. The uptake of nutrients by the plant was annihilated by the absorption mechanism.

* The root growth parameters viz., number of roots/plant, root volume, root mass, total root length, root diameter and shoot weight were observed to be more in the red soil than that in the black soil, mainly attributed to the light textured nature of the soil which helped in the easy penetration of roots for absorbing plant nutrients and water requirement. The same got reduced under sterilized condition of the soil.

* Although the black soil produced lesser amount of plant growth parameters, by way of mass factor it carried equal amounts of nutrients and favoured greater mobilization of nutrients through the root system as evidenced by the nutrient flow rate, thereby accounted for enhanced grain yield as compared to that of the red soil.

* With reference to the grain yield of sorghum crop, N P and K application at 50:50:50 kg N, P₂O₅ and K₂O ha⁻¹ was observed to be favourable for getting increased yield.

* The root length was positively correlated with N, K and Zn uptake by shoot at vegetative growth stage while the root mass was positively correlated with K and Zn uptake by shoot at vegetative stage of crop growth. The grain yield was positively correlated with N, P, K, Fe and Zn uptake by grain.

56. Copper status in soils

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* Originals not seen

APPENDICES

Effects	df	Available N					Available P					Available K					Available Fe					Available Mn					Available Cu					Available Zn																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																								
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A - Significant at 1% level
B - Significant at 5% level
- - Non significant

[illegible]

EFFECTS	df	Uptake rate							Shoot uptake						
		N	P	K	Fe	Mn	Cu	Zn	N	P	K	Fe	Mn	Cu	Zn
<u>I. MAIN EFFECTS</u>															
1. Soils	1	A	A	A	A	A	A	A	A	-	-	-	-	-	-
2. Sterilization	1	-	-	-	A	A	-	-	A	-	A	-	A	A	A
3. N levels	2	B	-	-	B	-	A	-	-	-	-	-	-	-	-
4. P levels	1	B	A	A	A	A	A	-	-	-	-	-	-	-	-
5. Stages	2	A	A	A	A	A	A	A	A	-	A	-	A	A	A
<u>II. INTERACTIONS</u>															
1. Soil x Sterilization	1	-	-	A	A	-	-	B	A	-	A	B	B	A	A
2. Soil x Nitrogen	2	A	A	A	-	B	B	-	-	-	-	-	-	-	-
3. Soil x Phosphorus	1	A	A	A	-	A	A	A	-	-	-	-	-	-	-
4. Soil x Stages	2	A	A	A	A	A	A	A	-	-	-	-	-	A	-
5. Sterilization x Nitrogen	2	-	-	-	A	A	-	-	-	-	-	-	-	-	-
6. Sterilization x Phosphorus	1	-	B	-	A	A	A	-	-	-	-	-	-	-	-
7. Sterilization x Stages	2	A	-	A	A	A	A	A	A	-	A	-	A	A	A
8. Nitrogen x Phosphorus	2	-	A	B	-	B	A	B	-	-	-	-	-	-	-
9. Phosphours x Stages	2	A	A	A	A	A	A	A	-	-	-	-	-	B	-
10. Stages x Nitrogen	4	B	B	-	A	-	A	B	-	-	-	-	-	A	-

APPENDICES (Contd.)

Sl. No.	Effects of	Roots/ plant			Voulme of root			Length of root			Root mass			Root diameter			Shoot weight			Grain yield
		Days			Days			Days			Days			Days			Days			
		30	60	90	30	60	90	30	60	90	30	60	90	30	60	90	30	60	90	
I. MAIN EFFECTS																				
1.	Soils	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2.	Sterilization	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
3.	N levels	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4.	P levels	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
II. INTERACTIONS																				
1.	Soil x Sterilization	1	A	A	A	-	A	A	-	A	-	A	A	-	A	A	A	A	A	A
2.	Soil x Nitrogen	2	A	A	A	A	A	A	-	-	-	A	A	A	A	A	A	A	A	A
3.	Soil x Phosphorus	1	-	-	A	A	A	A	-	B	-	A	A	-	-	A	A	-	A	A
4.	Sterilization x Nitrogen	2	A	B	A	A	A	A	-	-	A	A	A	A	B	A	A	A	A	-
5.	Sterilization x Phosphorus	1	A	A	A	B	A	A	-	-	-	A	A	B	A	A	A	-	A	-
6.	Nitrogen x Phosphorus	2	A	-	A	A	A	A	-	-	A	-	A	A	A	A	A	A	A	A

A - Significant at 1% level ; B - Significant at 5% level; - - Non significant

APPENDICES

(Contd.)

S	df	N			P			Root content			In			N			P			Shoot content			Grain content			Grain uptake		
		days			days			days			days			days			days			days			days			days		
		30	60	90	30	60	90	30	60	90	30	60	90	30	60	90	30	60	90	30	60	90	30	60	90			
TREATS	1	B	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A		
	1	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A		
	2	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A		
	1	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A		
FACTORS	1	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A		
	2	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A		
	1	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A		
	1	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A		
TREATS	1	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A		
	2	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A		
	1	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A		
	2	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A		
FACTORS	1	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A		
	2	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A		
	1	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A		
	2	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A		

A - Significant at 1 per cent level
 B - Significant at 5 per cent level
 - - Non significant

PLATES

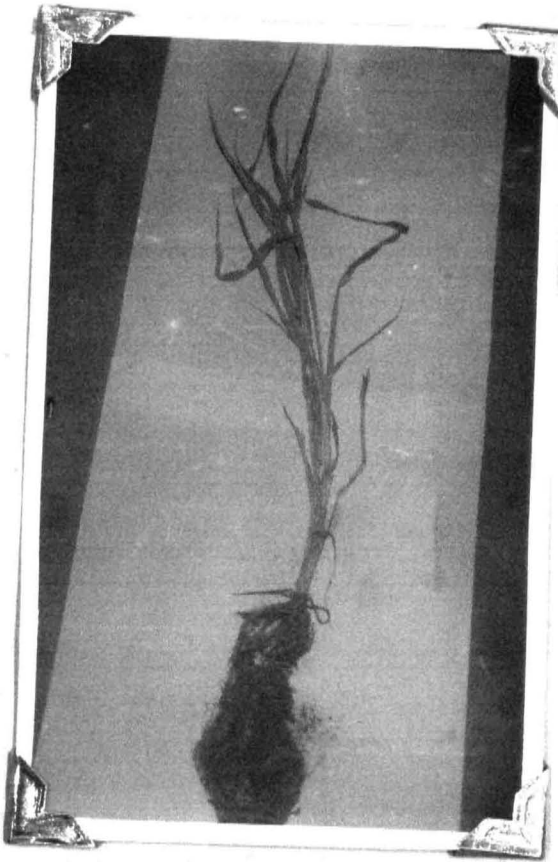


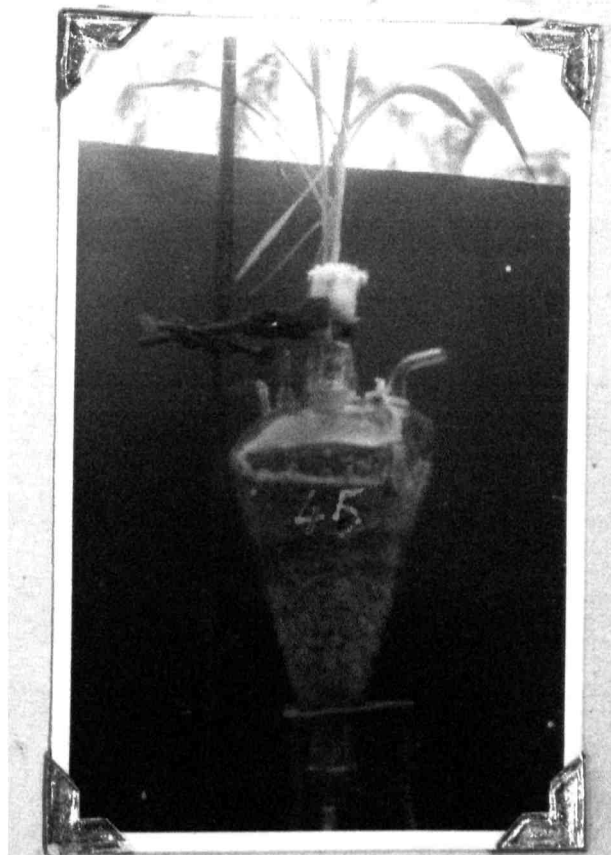
PLATE 1



PLATE 2



PLATE 3



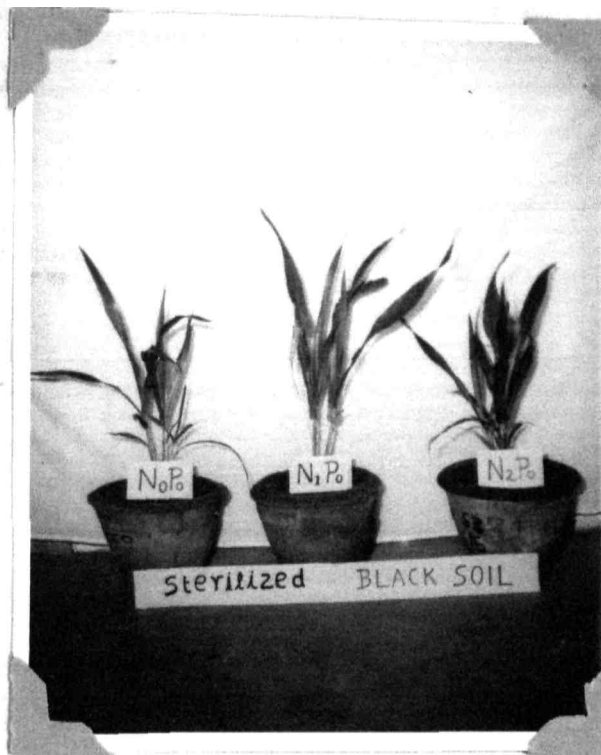
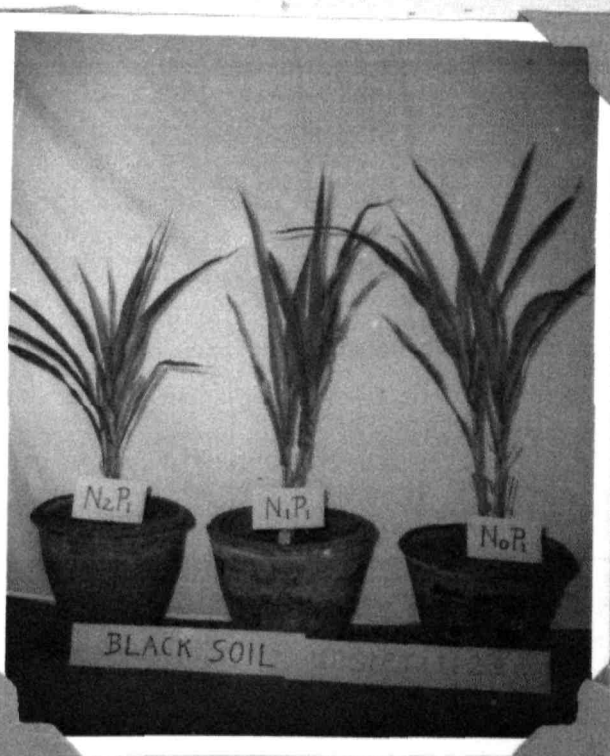
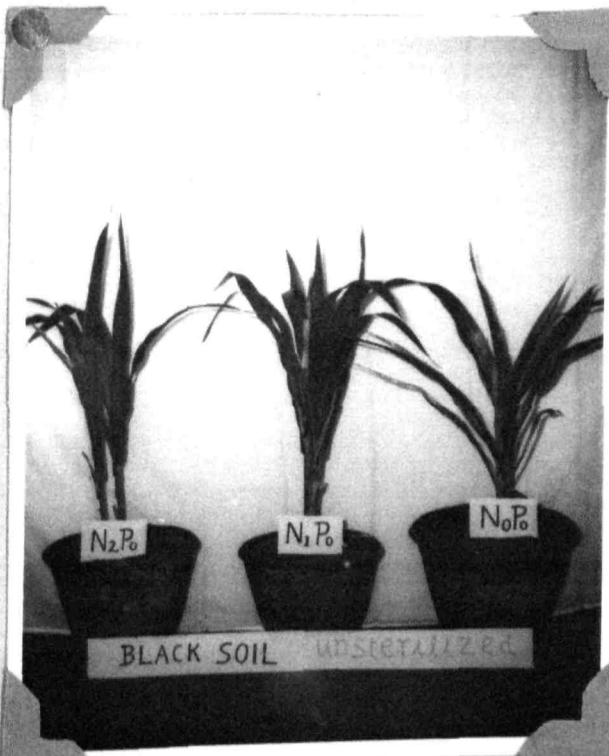


PLATE 5 (i)



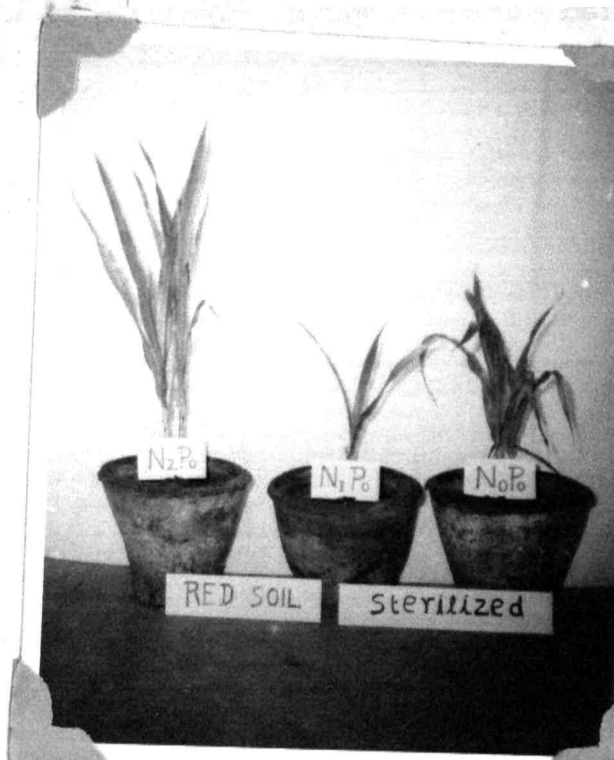
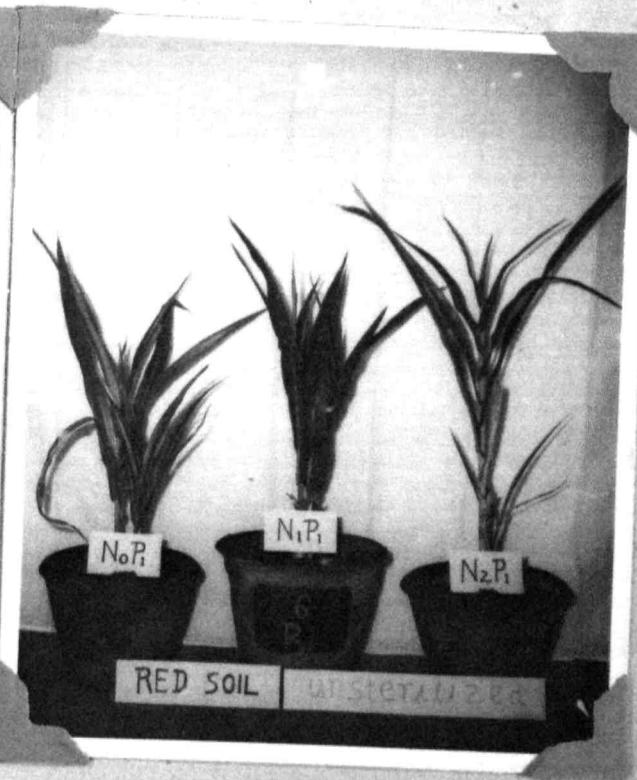
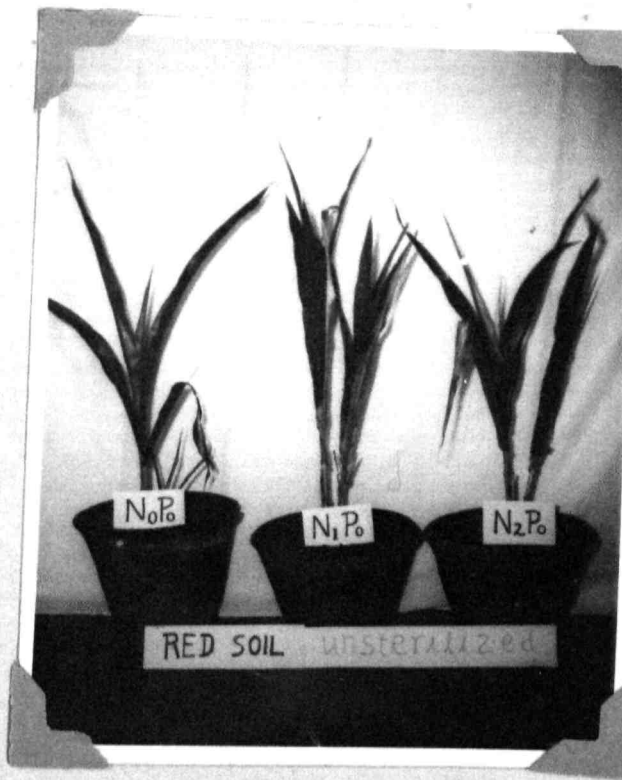
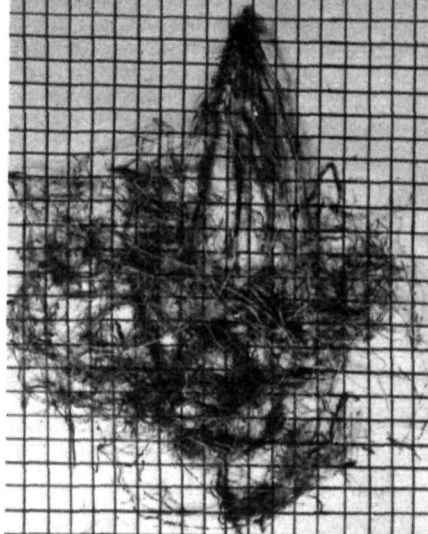


PLATE 6 (i)



BLACK SOIL UNSTERILIZED



BLACK SOIL STERILIZED

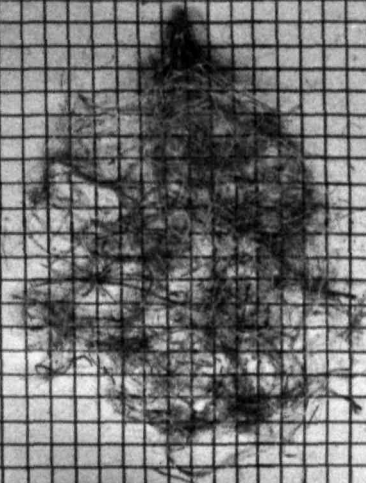
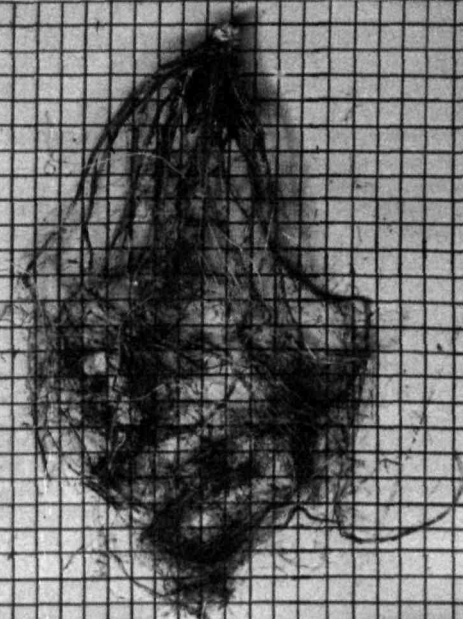


PLATE 7

RED SOIL UNSTERILIZED



RED SOIL STERILIZED

