

**EFFECT OF LONG-TERM APPLICATION OF FERTILIZERS
AND AMENDMENTS ON SOIL PHYSICAL QUALITY AND
CROP PRODUCTIVITY IN AN ACID ALFISOL**

THESIS

By

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(A-2020-30-062)**

Submitted to



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CERTIFICATE – I

This is to certify that the thesis entitled, “**Effect of long-term application of fertilizers and amendments on soil physical quality and crop productivity in an acid Alfisol**” submitted in partial fulfilment of the requirements for the award of the degree of **Master of Science (Agriculture)** in the discipline of **Soil Science** of CSK Himachal Pradesh Krishi Vishvavidyalaya, Palampur is a bonafide research work carried out by **Ms. Priyanka (Admission No. A-2020-30-062)** daughter of **Smt. Rani Devi** and **Shri Dalip Singh Verma** under my supervision and that no part of this thesis has been submitted for any other degree or diploma.

The assistance and help received during the course of this investigation have been fully acknowledged.

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CERTIFICATE- II

This is to certify that the thesis entitled, “**Effect of long-term application of fertilizers and amendments on soil physical quality and crop productivity in an acid Alfisol**” submitted by **Priyanka (Admission No. A-2020-30-062)** daughter of **Shri Dalip Singh Verma** to the CSK Himachal Pradesh Krishi Vishvavidyalaya, Palampur in partial fulfilment of the requirements for the degree of **Master of Science (Agriculture)** in the discipline of **Soil Science** has been approved by the Advisory Committee after an oral examination of the student in collaboration with an External Examiner.

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LIST OF ABBREVIATIONS USED

Abbreviation	Meaning
et al.	et alii (and other)
Fig	Figure
@	at the rate
%	per cent
<i>viz.</i> ,	videlicet (namely)
SSP	Single Super Phosphate
DAP	Di Ammonium Phosphate
MOP	Muriate of Potash
w.r.t.	with respect to
Ha	Hectare
HW	Hand Weeding
i.e.	id est (that is)
etc	Et cetera
kg	Kilogram
kg ha ⁻¹	kilogram per hectare
q ha ⁻¹	quintal per hectare
cm	Centimeter
c mol (p ⁺) kg ⁻¹	centi mol proton per kilogram
t ha ⁻¹	tonnes per hectare
g kg ⁻¹	gram per kilogram
mg kg ⁻¹	milligram per kilogram
Mg m ⁻³	Mega gram per meter cube
INM	Integrated nutrient management
RDF	Recommended dose of fertilizer
FYM	Farm Yard Manure
BD	Bulk density
PD	Particle Density
MWD	Mean weight diameter
WSA	Water stable aggregates
SHC	Saturated hydraulic conductivity

WHC	Water holding capacity
CEC	Cation exchange capacity
N	Nitrogen
P	Phosphorus
K	Potassium
Ca	Calcium
Mg	Magnesium
S	Sulphur
Al	Aluminium
Fe	Iron
Mn	Manganese
Zn	Zinc
Cu	Copper
OC	Organic carbon
SOC	Soil organic carbon
DTPA	Diethylene Triamine Penta Acetic acid

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ABSTRACT

The present investigation was carried out in an on-going long-term fertilizer experiment, initiated during 1972 at experimental farm of Department of Soil Science, CSK HPKV Palampur, to study the effect of long-term application of fertilizers and amendments on soil physical quality and crop productivity in an acid Alfisol under maize-wheat cropping system. The experiment consisted of eleven treatments. The soil of the experimental site was silt loam and classified taxonomically as “*Typic Hapludalf*” (Subgroup). Soil samples, collected from two depths *viz.*, 0-0.15 and 0.15-0.30 m after the harvest of maize (*kharif* 2021), were analyzed for determination of different physical parameters (bulk density, particle density, porosity, water holding capacity, water stable aggregates, mean weight diameter, saturated hydraulic conductivity, atterberg’s limits and infiltration rate), chemical parameters (CEC and SOC). Application of inorganic fertilizers along with FYM decreased the bulk density and increased the porosity, WHC, WSA, MWD, SHC, atterberg’s limit and infiltration rate over control. Thus, these properties showed improvement in FYM amended plots than unfertilized control plots. Grain and stover samples were also collected and analyzed to calculate nutrient uptake. Continuous application of fertilizers and amendments for forty-nine years significantly influenced the nutrient uptake and yield of maize. The treatment comprising 100 per cent NPK + FYM recorded the highest grain (64.02 q ha⁻¹) and stover yield (103.21 q ha⁻¹) and nutrient uptake and was at par with 100 per cent NPK + lime. Omission of S and K decreased the grain yield by 63.4 and 61.4 per cent, respectively over 100 per cent NPK, whereas, continuous application of N alone resulted in zero yield. Addition of manure or lime along with recommended dose of fertilizers improved the soil health in terms of physical and chemical properties of soil. Different soil physical properties were significantly and positively correlated with nutrient uptake and grain and stover yield of maize except bulk density which was negatively correlated.

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INTRODUCTION

Maize (*Zea mays* L.) is the third most important cereal crop after rice and wheat for the global economy. Maize is one of the most versatile crops having exceptional adaptability to a wide range of agro-climatic conditions and has the highest genetic output potential, hence is known as the "Queen of Cereals". It has a worldwide significance as human and animal food. It is a good source of starch, protein, fat, sugar, certain important vitamins (A, C, and E) and minerals. It is also utilized as a basic raw material for the production of alcoholic beverages, culinary sweeteners and more recently as a biofuel because of its high production, easy processing and less cost than other cereals.

In India, it is grown on an area of 9.9 million hectares with a production of 32.5 million tonnes and productivity of 3.3 tonnes ha⁻¹ (Anonymous 2022). The top eight maize producing states in India are Andhra Pradesh, Karnataka, Rajasthan, Maharashtra, Bihar, Uttar Pradesh, Madhya Pradesh and Himachal Pradesh. Together, they account for over 80 percent of the nation's total maize production. In addition to these states, Jammu & Kashmir and the North-Eastern states also grow maize. In Himachal Pradesh, maize is cultivated on an area of 290 thousand hectares with a production of 726 thousand tonnes and a productivity of 2.6 tonnes ha⁻¹ (Anonymous 2021). The crop is grown in the low and mid hills of Himachal Pradesh and is used primarily as cereal by hill farmers.

Enhancing crop production and nutritional quality while maintaining soil health through proper nutrient management is essential to feed the ever growing Indian population. Extensive research is required to develop the scientific basis for enhancing as well as sustaining food production and productivity, particularly when the population is increasing and per capita land holding is decreasing. Fertilizers supply nutrients to crops and regulate the rate of replenishment of depleted soil nutrients. Therefore, one of the key factors to increase agricultural production

economically is the efficient use of fertilizers. But, the continuous and imbalanced use of high-analysis chemical fertilizers badly influences crop production potential and soil health. Organic manures are being ignored in modern agriculture, which adversely affects the physical, chemical, and biological soil properties. Although the role of organic manures in plant nutrition is well understood, the use of organic manures alone cannot fulfil the nutritional needs of high yielding crop genotypes. Care should be taken to avoid environmental and soil health degradation. For boosting crop output and sustaining soil health, a balanced and integrated use of external inputs such as chemical fertilizers, organic manures and amendments is crucial.

The importance of long-term fertilizer experiments in studying the effects of continuous cropping and fertilizer application on the sustenance of crop production is widely recognized. Under the umbrella of the All India Coordinated Research Project (AICRP), such long-term fertilizer studies are being conducted in India, with emphasis on yield sustainability and soil health. Long-term fertilizer use has a significant influence on soil physical, chemical and biological properties under different agro-ecosystem which in turn influences the sustenance of crop productivity and soil health. Soil physical properties influences all soil ecosystem functions and are very important for sustainable crop production. In India, about 85.65 million hectares of land produces a very low yield of crops due to unfavourable soil physical conditions. Balanced use of fertilizers in combination with manures is one of the best ways to prevent organic matter depletion as well as rapid deterioration of soil physical properties, especially soil structure. The addition of organic matter not only supplies the nutrients for crop growth but also increases soil organic carbon content which directly or improves soil physical properties like hydraulic conductivity, bulk density, soil aggregation, soil compaction, infiltration rate, porosity, water holding capacity etc.

Continuous cropping and long-term fertilizer use are liable to change soil properties and affect crop production, depending upon the type of management practices. Thus, the long-term effect of farming practices on soil properties should be

well understood for advance planning of crop and soil health management. Keeping in view the all above mentioned facts, the present study was proposed with the following objectives:

1. To evaluate the effect of fertilizers and amendments on soil physical properties and crop productivity and
2. to work out the relationships of soil physical properties with crop yield and nutrient uptake.

2. REVIEW OF LITERATURE

The literature pertaining to the present study entitled “**Effect of long-term application of fertilizers and amendments on soil physical quality and crop productivity in an acid Alfisol**” has been reviewed in this chapter. Following are the headings under which the pertinent literature has been presented:

- 2.1 Long-term effect of fertilizers and amendments on soil physical properties
- 2.2 Long-term effect of fertilizers and amendments on cation exchange capacity and soil organic carbon
- 2.3 Long-term effect of fertilizers and amendments on nutrient uptake and crop productivity
- 2.4 Relationship of soil physical properties with nutrient uptake and crop yield
- 2.1 Long-term effect of fertilizers and amendments on soil physical properties**

Jo (1990) conducted an experiment on barley-early rice-late rice rotation and reported that the application of compost @ $7.5 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ for 20 years increased the liquid limit of a rice soil from 32.2 to 34.5 per cent, plastic limit from 28.4 to 30.2 per cent and plasticity index from 3.8 to 4.2 per cent. Rixon et al. (1991) found that the application of pig dung @ 22.5 Mg ha^{-1} before rice crop increased the liquid limit from 41.0 to 42.0 per cent, plastic limit from 30.0 to 30.8 per cent and plasticity index from 11.0 to 11.2 per cent.

According to Roberson et al. (1995), the application of inorganic fertilizers in combination with organic manures, under maize-wheat cropping sequence in sandy loam soil of California (USA), enhanced the amount of water stable aggregates in the surface layer and concluded that this might be due to the of enhanced microbial activity which helped in the formation of stable aggregates. Bellakki and Badanur (1997) while investigated the long-term effect of integrated nutrient management on

bulk density in Vertisol of Siruguppa (Karnataka) under dry land conditions reported that *in situ* incorporation of sun hemp in rice reduced the soil bulk density.

In calcareous silt loam soils of Bihar under rice-wheat cropping system, Mishra and Sharma (1997) found that the combined application of FYM and fertilizers had favourable effect on the hydraulic conductivity of soil. From a field experiment on a well-drained Miamian silty clay loam soil with two fertilizer levels at Ohio (USA) Subbian et al. (2000) reported that aggregate stability was not significantly affected by fertilizer levels. The fertilizer application had a significant effect on mean weight diameter (MWD).

The effect of integrated nutrient supply for sustainable rice production in an acid Alfisol of Malan (Himachal Pradesh) was studied by Premi (2003) and the results revealed that the combined use of organic and inorganic sources of nitrogen decreased the bulk density of soil. From another long-term experiment under rice-wheat cropping system on Vertic Ustropept of Madras (Tamilnadu), Selvi et al. (2003) reported that the application of 10 t FYM ha⁻¹ along with 100 per cent NPK decreased the bulk density and increased hydraulic conductivity, water stable aggregates, porosity and water holding capacity.

Sharma (2004) from a long-term experiment on rice-wheat cropping sequence revealed that the mean weight diameter (MWD) varied from 0.63 to 1.04 mm. The application of recommended dose of fertilizers (100% NPK) with FYM recorded the highest MWD, whereas, the lowest MWD was recorded in control. Mean weight diameter increased with increasing chemical fertilizer dose from sub optimal (50% NPK) to optimal dose of fertilizer (100% NPK). Mean weight diameter at 150 per cent NPK was similar to the recommended dose of NPK. In rice growing soils of Palampur (H.P.), Kumar and Verma (2005) found that the bulk density decreased with increase in the soil organic matter and varied from 0.99 to 1.62 Mg m⁻³. Long-term application of NPK along with FYM decreased bulk density of the surface soil (0-15 cm), whereas, the highest bulk density was recorded in other (N, NP and NPK) treatments (Manna et al. 2005). Pathak et al. (2005) at Ranchi (Jharkhand) reported a significant improvement in bulk density and water holding capacity with the addition of rice straw.

While studying the soil properties, Debuisser and Tessier (2004) at Versailles reported that the organic matter content declined in all treatments except those which were treated with manure. The use of ammonical fertilizers strongly decreased the cation exchange capacity, whereas, basic amendments increased the cation exchange capacity of the soil. Water retention and soil stability also increased by manure treatment. Alike this experiment, the effect of long-term continuous cropping, fertilization, and manuring on physical properties of a sandy loam soil was evaluated by Hati et al. (2006). The results revealed that soil aggregation, soil water retention, particle size distribution, bulk density and porosity were significantly improved by the application of NPK plus FYM. They suggested that the application of balanced mineral fertilizers in combination with organic manure sustained a better soil physical environment and higher crop productivity under intensive cultivation.

Selvi et al. (2005) carried out a long-term fertilizer experiment under finger millet – maize – cowpea sequence in mixed black calcareous soil (Vertic Haplustepts) of Coimbatore (Tamil Nadu). They concluded that the balanced fertilization significantly increased the MWD, hydraulic conductivity and water holding capacity and reduced the bulk density of soil. Significant improvement was observed in the physical properties of the soil under the integrated use of organics and inorganics. The unmanured control had poor physical condition. Bajpai et al. (2006) studied the soil physico-chemical properties and productivity of rice-wheat system as influenced by integrated nutrient management (INM) in an Inceptisol of Chhattisgarh and reported that the FYM or the crop residue incorporation significantly lowered the bulk density as compared to its initial status and control plot. The decrease in bulk density favourably enhanced the infiltration rate and it was found to be the highest in the green manure plot and the lowest in control.

A field experiment was conducted by Manna et al. (2007) on soybean-wheat system in a sandy loam soil of Ranchi (Jharkhand) to study the size distribution of soil aggregates. The results revealed that the macro aggregates were dominant in surface soil. From a long-term study at Punjab Agricultural University, Ludhiana, Rasool et al. (2007) concluded that integrated use of FYM and NPK resulted in increased total porosity of soil, average water holding capacity, higher grain yield and NPK uptake under rice-wheat cropping system. In a similar study an acid Alfisol, Hati et al. (2008)

found that the balanced use of fertilizers along with manure (NPKM) or lime (NPKL) soil aggregation, soil water retention, microporosity and available water capacity, whereas, reduced bulk density of the soil in 0-30 cm depth over control. Under maize-wheat system, Chakraborty et al. (2010) found that the bulk density was significantly lower (1.51 Mg m^{-3}) with manure and the saturated hydraulic conductivity was significantly higher in manure plots. Porosity was also more abundant in manure treated plots.

Du et al. (2009) documented that long-term application of crop residue plus mineral fertilizers enhanced soil aggregation, stability and saturated hydraulic conductivity in the North China Plain. Porosity was also positively affected by crop residue addition. However, the application of mineral N and P fertilizers individually showed a little favourable effect on soil physical properties. The study was conducted by Gayatri et al. (2010) to evaluate the effect of INM on soil properties in a Typic Haplustept of Udaipur (Rajasthan) under maize-wheat system. The results revealed that the application of 20 t FYM ha^{-1} alone and combined use of NPK and 10 t FYM ha^{-1} recorded significant improvement in the physical properties of the soil *viz.*, bulk density and hydraulic conductivity.

From the field study conducted by Bandyopadhyay et al. (2010) to examine the effect of INM on soil properties in a clayey soil at Bhopal (Madhya Pradesh) under soybean-wheat cropping sequence, it was concluded that conjunctive application of recommended dose of NPK and FYM resulted in a significant decrease in bulk density (9.3%), whereas, significant increase in hydraulic conductivity (95.8%) and mean weight diameter of the water stable aggregates (13.8%) was recorded in comparison to sole use of fertilizer NPK and non use of fertilizers and manure. From a similar study under maize-wheat cropping system at Udaipur (Rajasthan), Verma et al. (2010) concluded that combined application of fertilizers and manures as well as sole use of FYM increased cation exchange capacity, hydraulic conductivity and water stable aggregates and decreased bulk density of the soil as compared to sole use of fertilizers.

Nandapure et al. (2011) conducted an experiment to assess the effect of continuous fertilization and manuring on physical parameters under sorghum-wheat

copping sequence in a Vertisol of Akola (Maharashtra). They reported that use of inorganic fertilizers (100 % NPK) along with FYM @ 10 t ha⁻¹ significantly improved the bulk density, hydraulic conductivity and water stable aggregates. Similarly, Katkar et al. (2012) found that the direct addition of organic matter through FYM under sorghum-wheat sequence resulted in improvement in mean weight diameter, available water holding capacity and hydraulic conductivity in Vertisol of Akola (Maharashtra).

An investigation was undertaken by Kumar et al. (2012) to evaluate the effect of continuous application of inorganic fertilizers and organic amendments for 22 years on soil properties under pearl millet-wheat cropping sequence in a sandy loam soil at Hisar (Haryana). It was reported that continuous application of FYM, wheat straw and green manure in conjunction with inorganic fertilizers increased the hydraulic conductivity and decreased the soil bulk density. Divya et al. (2012) found that the judicious application of chemical fertilizers helped to maintain soil physical quality and productivity. From a long-term fertility experiment on rice-wheat cropping system, Mitran et al. (2018) concluded that organically amended soil had a higher proportion of stable macroaggregates, whereas, the soil receiving inorganic fertilizer alone were rich in microaggregates. In another long-term study in rice-wheat cropping system, Bhatt et al. (2019) found that the application of NPK along with organic residues decreased the bulk density. Also, there was increase in bulk density with increase in soil depth.

In calcareous soils of Islamabad (Pakistan), Hassan et al. (2013) observed that the integrated nutrient use significantly increased the amount of water stable aggregates as compared to control. They further reported that the fraction of water stable aggregates was more in the surface soil (0-15 cm) than in the sub- surface soil (15-30 cm). From an experiment conducted to study the effect of combined application of farm yard manure, inorganic nitrogen and phosphorus fertilizers on soil physico-chemical properties in maize crop at Amhra (Ethiopia), Tadesse et al. (2013) observed that the application of 15 t FYM ha⁻¹ significantly decreased the soil bulk density. Yaduvanshi et al. (2013) studied the impact of long-term integrated nutrient management on soil properties in a reclaimed sodic soil under rice-wheat sequence at

Karnal (Haryana) and concluded that the application of 100 per cent recommended dose of NPK along with organics improved the bulk density of soil.

Kalhature et al. (2014) conducted a field experiment in a silty clay loam soil of Rahuri (Maharashtra) to investigate the effect of organic and inorganic sources of nutrients on soil health in maize. It was observed that integrated application of 25 per cent recommended dose of fertilizers with bio-fertilizers (*Azotobacter chroococcum* + phosphate solubilizing bacteria), green-manuring with sunhemp and incorporation of compost @ 10 t ha⁻¹ improved the bulk density and water infiltration. From a field experiment at Liaoning province (China) to determine the effect of N application on soil physical properties under maize crop, Zhong et al. (2014) revealed that the soil porosity decreased with N application.

Brar et al. (2015) carried out a field experiment at Ludhiana (Punjab) to study the effect of long-term application of inorganic and organic fertilizers on soil organic carbon and physical properties under maize–wheat rotation in sandy soils and found that the aggregate MWD was greater with the integrated use of FYM along with 100 per cent NPK compared to control. However, application of fertilizers did not affect the bulk density. The effects of long-term mineral fertilizer and compost application on physical properties of fluvo-aquic soil was studied by Xin et al. (2016) in the North China Plain. The results revealed that the compost application decreased the bulk density, increased porosity and portion of macro-aggregates. According to them, long-term deficiency of P and excessive N input can deteriorate soil structure. Also, balanced fertilizer applications increased the amount of soil macropores and saturated hydraulic conductivity. In another long-term study, Celik et al. (2010) reported that mycorrhiza along with organic fertilizers resulted in an improvement of soil structure and compost application lowered the bulk density. In an Alfisol of Northern Guinea Savannah zone of Nigeria, Eche et al. (2013) found that the application of cow dung alone or in combination with application of urea fertilizer increased cation exchange capacity and total porosity as compared to sole application of urea, while bulk density was reduced.

From a study, Indoria et al. (2016) reported that the INM improved the soil physical properties (bulk density, porosity, aeration, soil moisture, soil aggregation

and water retention) in red Alfisol of Hyderabad (Telangana) for better crop production. Tou et al. (2017), from their study on the effect of application of fertilizers either alone or in combination with manures at Loess Plateau (China), revealed that MWD increased in all the treatments where manure was applied along with chemical fertilizers, whereas, it decreased in the treatments where only chemical fertilizers were applied. In another long-term study on rice-wheat cropping system, Choudhary et al. (2018) investigated the impact of continuous application of inorganic fertilizers and organic manures on soil properties under soybean-wheat cropping sequence in a silty clay loam soil of Almora (Uttarakhand) and found that the application of NPK fertilizers singly or in combination with organic manures for twenty-one years significantly decreased the soil bulk density and increased the total soil porosity as compared to control in surface soil (0-15 cm).

Singh et al. (2017) reported the highest bulk density (1.40 Mg m^{-3}) in 100 per cent N treatment as compared to all other treatments. According to Dhiman et al. (2019), the optimal dose of fertilizer application and FYM significantly influenced the soil physical properties *viz.*, bulk density, porosity, hydraulic conductivity, mean weight diameter and water holding capacity in acid Alfisol of Palampur (H.P.).

So, it may be concluded that the balanced fertilization along with organic amendments leads to improves the soil-physico chemical properties (bulk density, particle density, porosity, MWD, WHC, saturated hydraulic conductivity, WSA, infiltration rate, Atterberg's limit, soil organic carbon and CEC).

2.2 Long-term effect of fertilizers and amendments on cation exchange capacity and soil organic carbon

Benbi et al. (1998) reported that long-term application of FYM significantly increased the soil organic carbon content. While studying the influence of organic and inorganic fertilizers on soil fertility under soybean-wheat cropping systems in Jabalpur (MP), Tiwari et al. (2002) observed that applying FYM (10 t ha^{-1}) along with the recommended dose of fertilizers improved organic carbon, N, P, K, and S content over the initial soil status in Vertisols.

While studying the soil properties, Debuyser and Tessier (2004) at Versailles reported that the organic matter content declined in all treatments except those which

were treated with manure. The use of ammonical fertilizers strongly decreased the cation exchange capacity, whereas, basic amendments increased the cation exchange capacity of the soil. Under maize-wheat system, Chakraborty et al. (2010) found soil organic content significantly higher (6.8 g kg^{-1}) with manure. Alike this experiment, Du et al. (2009) found that the application of crop residue plus mineral fertilizers enhanced the soil organic carbon content.

Hati et al. (2008) conducted a field experiment to study the impact of long-term application of inorganic fertilizer, manure and lime on organic carbon content of an acidic Alfisol (Typic Haplustalf) under soybean-wheat crop rotation and they reported that SOC content reduced from initial levels in all the treatments, but the reduction was considerably less in NPK + Manure and NPK + Lime treatments than that in sole N fertilization treatment.

To understand the effect of integrated nutrient management on soil properties, a study was conducted by Verma et al. (2010). After 9 years of continuous intensive cropping under various fertilizer and manurial treatments, resulted in improved cation exchange capacity (CEC). Application of 20 t FYM ha^{-1} and combined use of NPK and 10 t FYM ha^{-1} recorded significant differences in the soil properties

Hemalatha and Chellamuthu (2013) studied the effect of continuous fertilization on soil nutrient status after 36 years of cropping on Inceptisol of Coimbatore (Tamil Nadu) and they reported that the CEC, organic carbon and NPK status of soil significantly increased in treatment having 100 per cent NPK + FYM.

2.3 Long-term effect of fertilizers and amendments on nutrient uptake and crop productivity

Ali et al. (2002) conducted an experiment at Malakandher research farm, Peshawar (Pakistan) to study the effect of different levels of N and P on maize. Results revealed that the different levels of N and P significantly affected the grain yield. Plots treated with fertilizer combination of 150 and 90 kg ha^{-1} N and P, respectively, resulted in maximum grain yield. The effect of combined application of FYM and nitrogen (N) on rice-wheat system in Uttarakhand mid-hill soils was evaluated by Ghosh and Singh (2003) and the results revealed that the grain and straw yield of both the crops increased with increasing rates of FYM and N fertilizer. The highest yields were obtained with 15 t ha^{-1} FYM + $60/80 \text{ kg ha}^{-1}$ N. The productivity

of rice-wheat cropping system cannot be sustained over the years even with the use of recommended dose of NPK (120:80:20) (Katyial et al. 2003).

Mehta et al. (2005) carried out a field study to examine the effect of sulphur (S), P and FYM on yield of maize at Udaipur (Rajasthan). They found that the seed, stover yields, N, P, S and Fe uptake by maize increased significantly with the successive increment in S up to 60 kg S ha⁻¹. Application of 40 kg P ha⁻¹ significantly increased the seed and stover yield. Application of 10 t FYM ha⁻¹ enhanced yield significantly over control. The continuous addition of 100 per cent N (urea) gave no yield in maize and wheat, whereas, application of FYM and lime along with recommended NPK sustained higher grain yield as compared to sole use of NPK fertilizers in an acid Alfisol of Palampur Subehia and Sharma (2005)

Jiang et al. (2006) examined the long-term effects of manure and fertilizers on yield of maize in the soils of Jiangsu province (China) and concluded that integrated use of manure and fertilizers resulted in significantly higher yield of maize over the sole use of NPK. In sandy clay loam soils of Udaipur (Rajasthan), Verma et al. (2006) studied the effect of integrated nutrient supply on productivity and nutrient uptake by maize-wheat cropping system. The results revealed that the highest grain and stover yield of maize was obtained with application of NPK @ 150 per cent of recommended dose. Furthermore, balanced and integrated nutrient supply to maize recorded significantly higher uptake of NPK.

In a long-term experiment at Ludhiana (Punjab), Dhaliwal et al. (2007), found that the application of 100 per cent NPK + FYM resulted in the highest yields of maize and wheat followed by 100 per cent NPK + Zn. To study the effect of integrated use of manure and fertilizers on maize, a field study was carried out by Abunyewa et al. (2007) at Nyankpala (Ghana). They found that the application of manures along with fertilizers significantly increased the maize yield over the control. The combined application of manure and fertilizers also recorded the highest sustainability index (0.62) than other treatments.

From a field experiment in an acidic red loam soil of Ranchi (Jharkhand) Mishra et al. (2008) concluded that continuous application of organic manures alone or in combination with inorganic fertilizers increased the grain yield of both maize

and wheat. The highest yield was recorded in 100 per cent NPK + lime which was at par with NPK + FYM. The uptake of N, P, K and S by maize was significantly higher under NPK + lime and NPK + manure over 100 per cent NPK alone. A similar study was conducted in an acid Alfisol of Jharkhand to study the influence of integrated nutrient management on productivity of maize-wheat cropping system by Prasad et al. (2010). The results revealed that grain yield of maize increased significantly with the application of NPK. The maximum yield, N, P and K uptake was recorded in plots which received 50 per cent N through FYM plus 50 per cent N through inorganic fertilizers.

Mahesh et al. (2010) conducted a field experiment in a sandy loam soil of Mandya (Karnataka) to assess the effect of INM on growth and yield of maize. The study revealed that the application of recommended dose of NPK + FYM @ 10 t ha⁻¹ recorded significantly higher maize grain yield and this treatment was at par with the application of 75 per cent recommended N through chemical fertilizers + 25 per cent recommended N through poultry manure. At Faisalabad (Pakistan) Ghaffari et al. (2011) conducted an experiment to evaluate the effect of integrated use of nutrients on growth and yield of maize. The results revealed that the recommended dose of NPK along with single spray of multi-nutrients improved all growth parameters and enhanced macronutrient use efficiency up to 11.5 per cent which resulted in significant increase in maize grain yield as compared to control as well as the treatment where recommended dose of NPK was applied alone.

A field study was carried out by Tatarwal et al. (2011) in a clayey soil of Jhalawar (Rajasthan) to evaluate the effect of INM on productivity and nutrient uptake by maize. They concluded that application of NPK @ 150 per cent of recommended dose of fertilizers recorded maximum grain and biological yield of maize. The highest N, P and Zn uptake by maize was recorded with an application of 150 per cent of recommended dose of fertilizers.

Thakur et al. (2011) studied the impact of continuous use of inorganic fertilizers and organic manure on productivity of soybean-wheat cropping sequence in Vertisols of Jabalpur (Madhya Pradesh). The results revealed that the application of recommended dose of NPK with FYM @ 15 t ha⁻¹ resulted in significant increase in

soybean and wheat yield over the control. They further reported that highest uptake of NPK was recorded in the treatment comprising 100 per cent NPK + FYM @ 12 t ha⁻¹. In a long-term experiment, Sathish et al. (2011) studied the effect of organic manures and inorganic fertilizers on yield and uptake of nutrients in rice-maize cropping system in a sandy clay soil at Kathalagere (Karnataka). The results revealed that the highest grain yield and nutrient uptake was recorded in treatment receiving 50 per cent N through FYM and 50 per cent NPK through inorganic fertilizers in *kharif* followed by 75 per cent NPK through inorganic fertilizers, which might be due to slow release of nutrients in FYM applied treatments. A field experiment was conducted on a sandy loam soil of New Delhi to study the effect of conjoint use of value-added manures and chemical fertilizers on crop productivity and N uptake under maize-wheat cropping system by Basak et al. (2012) concluded that the application of 100 per cent NPK as well as integrated use of value added manures like vermicompost, compost, FYM @ 5 t ha⁻¹ along with 50 per cent NPK gave significantly higher yield and N uptake in both crops over control.

Joshi et al. (2013) found that the significantly higher grain and stover yield of maize was recorded with conjoint application of recommended dose of NPK + 10 t FYM ha⁻¹ compared to either inorganic fertilizer alone or organic sources in a sandy clay loam soil of Udaipur (Rajasthan).

Sepat and Rai (2013) evaluated the effect of different phosphorus levels and sources on productivity, nutrient uptake of maize-wheat cropping system in a sandy loam soil at New Delhi. They recorded significant improvement in grain and straw/stover yield with the application of single super phosphate and biofertilizers. Application of P increased N and P uptake in maize significantly. They further concluded that P increased N and P concentration in grain and stover by providing balanced nutrition.

In a silt clay loam soil of Shaanxi (China), Yang et al. (2014) studied trends of yield in a long-term experiment on use of manure and fertilizers in wheat-maize system. They reported that the grain yield of maize was significantly higher in NPK + manure treatment than untreated control.

Endris and Dawid (2015) studied the yield response of maize to integrated soil fertility management on an acidic Nitosol of south western Ethiopia and found that the application of 50 per cent recommended NP and compost gave the highest grain yield of maize as compared to the control which recorded the lowest yield. It was further concluded that the integrated use of inorganic fertilizers and organic sources of plant nutrients demonstrated potential for efficient nutrient supply in maize-based cropping system. In a long-term experiment on maize-wheat system at Tianjin (China), Yang et al. (2015) revealed that the treatment receiving combined application of N along with organic manure recorded significantly highest maize yield which was at par with the treatment receiving only NPK fertilizers.

Brar et al. (2015) from a long-term field experiment in a sandy loam soil of Ludhiana (Punjab) to assess the effect of continuous use of FYM and inorganic fertilizers on productivity of maize-wheat rotation revealed that the maize grain yield increased significantly when fertilizer application was increased from 50 per cent to 100 per cent NPK, but further increase to 150 per cent NPK showed non-significant effect on yield. The highest maize grain yield was recorded in treatment with 100 per cent NPK + FYM and the lowest in control showing favorable effects of manure on crop productivity. The NPK uptake was significantly higher in all fertilizer treatments as compared to control. The N and P uptake was highest in 100 per cent NPK + FYM treatment but K uptake was highest in 150 per cent NPK which was at par with K uptake in 100 per cent NPK + FYM. Similar study was carried out by Sindhi et al. (2016) to investigate the impact of integration of organic manures and chemical fertilizers on maize yield and NPK uptake in maize-green gram sequence in a clayey soil of Navsari (Gujarat). The results revealed that the highest grain (56.0 q ha^{-1}) and stover yield (64.5 q ha^{-1}) and uptake of N ($127.39 \text{ kg ha}^{-1}$), P (24.99 kg ha^{-1}) and K (88.95 kg ha^{-1}) was recorded in the plots receiving recommended dose of NPK along with FYM @ 5 t ha^{-1} . The increase in yield and N uptake was attributed to the enhanced nutrient availability and better root development which ultimately improved uptake of nutrients.

In Kandic Paleustalf soils of Abeokuta (Nigeria), Ogundijo et al. (2017) studied the effect of INM on yield and nutrient uptake by maize. It was reported that the application of poultry manure @ 10 t ha^{-1} and $120 \text{ kg NPK ha}^{-1}$, sole application of $10 \text{ t poultry manure ha}^{-1}$, combined application of $5 \text{ t poultry manure ha}^{-1}$ and $120 \text{ kg NPK ha}^{-1}$, sole application of 5 t ha^{-1} poultry manure and sole application of 120

kg NPK ha⁻¹ significantly increased grain yield over the control. Furthermore, the combined application of 10 t ha⁻¹ poultry manure and 120 kg ha⁻¹ NPK fertilizer enhanced the uptake of N, P and K significantly over other treatment combinations. Wailare and Kesarwani (2017) found that grain and stover yield of maize was significantly higher under INM as compared to 100 per cent NPK alone.

Majhi et al. (2018) while investigating the effects of fertilizer use on maize productivity in a sandy loam soil of Ranchi (Jharkhand) found that the balanced fertilization resulted in the maximum grain yield of maize. Continuous application of N alone for more than 30 years drastically reduced the maize grain yield. From a similar study, Shambhavi et al. (2018) reported that the highest yield of maize and wheat was obtained with 100 per cent NPK + FYM treatment which was at par with 100 per cent NPK + lime. The uptake of micronutrients (Fe, Zn, Mn and Cu) was also highest in same treatments, whereas, the continuous application of N alone for 36 years had the most deleterious effect on crop productivity. Balanced application of NPK fertilizers positively influenced the yield sustainability of crops which was confirmed from a study conducted by Choudhary et al. (2018). Gai et al. (2018) also reported the superiority of combined application of manure and chemical fertilizers over chemical fertilizers alone w.r.t. crop yield, from a long-term experiment on maize and wheat in China. Similar results were reported by Zhang et al. (2018) in China.

A field experiment was conducted by Thakur et al. (2021) to study the maize grain quality as influenced by 46 years' continuous application of fertilizers, FYM, and lime in an *Alfisol* of North-western Himalayas. According to them, higher crop yield and better nutritional quality can be achieved with a balanced application of NPK fertilizers along with FYM and lime.

It can be concluded that with the balanced application of NPK along with FYM increased the crop output, nutrient uptake and improve the nutrient quality.

2.4 Relationship of soil physical properties with nutrient uptake and crop yield

Hati et al. (2007) from a long-term experiment on the impact of fertilizer and manure application in a soybean–wheat–maize (fodder) crop rotation found that using

a balanced rate of fertilizers along with organic manure, improved the physical environment of the soil in the surface layer and sustained higher crop productivity under this intensive cropping system.

Under Maize (*Zea mays*)–Mustard (*Brassica campestris*) cropping sequence in Acidic soils, Saha et al. (2010) studied the effect of INM on soil physical properties and crop productivity and the results revealed that the integrated use of balanced inorganic fertilizers in combination with lime and organic manure maintained soil conditions that are superior for enhancing crop productivity in intensive farming systems in northeastern India's hilly ecology.

A study was conducted by Nandapure et al. (2011) to assess the long-term effect of fertilizers and FYM on soil physical properties and crop productivity in sorghum-wheat cropping sequence in Vertisol of Akola (Maharashtra). The results indicated a significant negative correlation ($r=-0.47$) between yield and bulk density. At Mymensingh (Bangladesh), Sarker et al. (2012) found that the rice grain yield was negatively correlated with the bulk density which indicated that the grain yield would decrease with the increase of bulk density.

Arriaga et al. (2003) studied the soil physical properties and crop productivity of an eroded soil amended with cattle manure and concluded that the long-term manure application is a possible management alternative for improving physical qualities and crop productivity of degraded soils.

Brar et al. (2015) studied the effect of long-term application of inorganic and organic fertilizers on soil organic carbon and physical properties in maize-wheat rotation and reported that the infiltration rate, MWD and crop yields were positively correlated with soil organic carbon.

Zaid et al. (2017) studied the relationship between soil quality parameters and crop productivity in the soil of Cairo (Egypt) and found non-significant relationship between wheat productivity, physical and chemical parameters such as coarse sand, slowly drainable pores and total nitrogen content.

In a long-term experiment at Palampur, Singh et al. (2017) concluded that the yield of maize and wheat were negatively correlated with bulk density of soil.

Long-term effect of crop residues incorporation on yield and soil physical properties under rice - wheat cropping system in calcareous soil was studied by Kumari et al. (2018) and the results revealed that the correlations of water holding capacity (WHC) and MWD of water stable aggregates with different plant parameters were positive and highly significant, thus, indicating synergistic relationship, i.e. higher the water holding capacity and MWD of water stable aggregates higher is the crop yield and Zn utilization by crops.

While studying the impact of forty-seven years of long-term fertilization and liming on soil health, yield of soybean and wheat in an acidic Alfisol, Vishwanath et al. (2022) found that application of NPK + FYM significantly enhanced the soil cation exchange capacity as compared to NPK. Fertilization of FYM/lime with NPK recorded higher crops yield as compared to NPK. In general, it improved soil health and crop yield. Thakur et al. (2022) studied the effect of 46 years' application of fertilizers, FYM and lime on physical, chemical and biological properties of soil under maize-wheat system in an acid Alfisol of northwest Himalayas. They reported that at 0–15 cm soil depth, bulk density was least, porosity and water holding capacity were greatest in 100% NPK + FYM, corresponding to the largest organic carbon content (13.93 g/kg). Microbial biomass C and dehydrogenase activity in 100% NPK + FYM were 42% and 13.7% greater than 100% NPK, respectively. Available nutrients were significantly higher with 100% NPK + FYM and 100% NPK + lime than control and other fertilizer treatments. At 15–30 cm depth, the effect of various treatments was comparable to the surface layer. Grain yield declined by 55% and 53% in 100% NPK(-S) and 100% NP, respectively, as compared to 100% NPK, whereas, 100% N as urea alone eventually led to crop failure. Soil porosity recorded the greatest positive correlation ($r = .933$), whereas, bulk density recorded a negative significant correlation ($r = -.942$) with grain yield.

3. MATERIALS AND METHODS

The present study entitled “**Effect of long-term application of fertilizers and amendments on soil physical quality and crop productivity in an acid Alfisol**” was carried out in an on-going long-term fertilizer experiment started during *rabi* 1972-73 at the experimental farm of the Department of Soil Science, College of Agriculture, Chaudhary Sarwan Kumar Himachal Pradesh Krishi Vishvavidyalaya, Palampur. The present investigation was carried out on maize crop (*kharif* 2021).

The details of field experiment and methodology adopted during the course of investigation have been described under the following heads:

3.1 General description of the study area

3.2 Experimental details

3.3 Field studies

3.4 Laboratory studies

3.5 Statistical analysis

3.1 General description of the study area

3.1.1 Experimental site

The experimental farm is situated at 32°6' N latitude and 76°3'E longitude at an altitude of about 1290 meters above mean sea level. The site is situated in the Palam valley of Kangra district in the foothills of *Dhauladhar* ranges and falls under mid hills, sub humid agro-climatic zone of Himachal Pradesh.

3.1.2 Climate and weather

The climate of the study area is characterized by mild summers and severe winters. The area receives an average annual rainfall ranging from 2500-3000 mm. In general, a major portion of rainfall (about 75%) is received during the monsoon period from June to September. During the crop growth period, total rainfall of 1989 mm ranging from 6.2 mm to 559 mm was received in different standard weeks. The weekly relative humidity varied from 51.1 to 97.6 percent. The minimum and maximum temperatures of 14.9 °C and 31.1 °C were observed during the crop growth period.

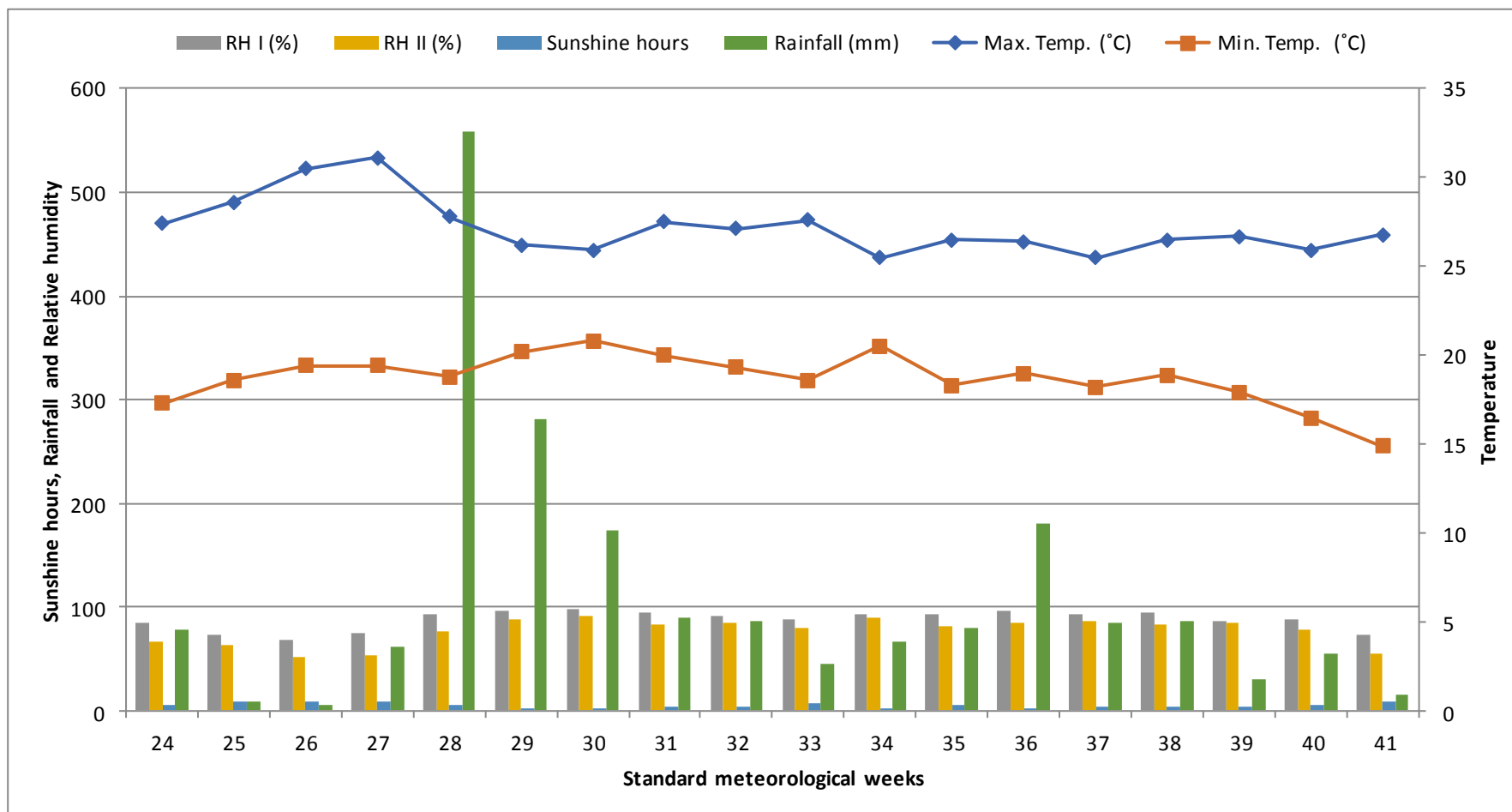


Fig. 3.1 Mean weekly weather data at Palampur (HP) *kharif* 2021

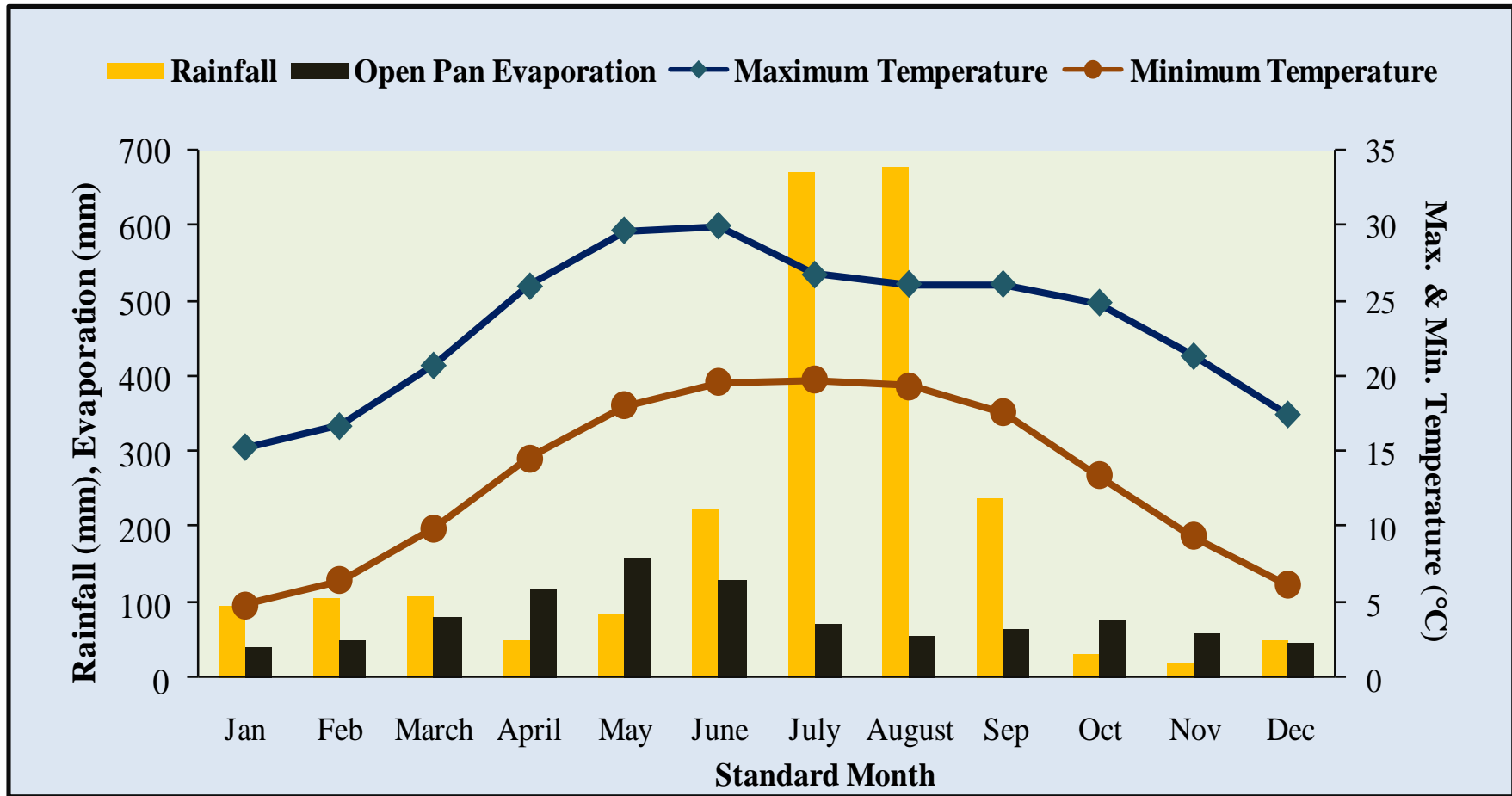


Fig. 3.2 Mean monthly rainfall (mm), open pan evaporation (mm) and air temperature (°C) for the period 1974-2020

The mean weekly meteorological data recorded at the meteorological observatory of CSK Himachal Pradesh Krishi Vishvavidyalaya, Palampur during the crop duration are illustrated in Fig 3.1 and presented in Appendix I. The mean monthly rainfall, temperature, and open pan evaporation for the period 1974 to 2020 have been presented in Fig. 3.2 and appended in Appendix II.

3.1.3 Soil characteristics

Taxonomically, the soils of the study area fall in the order “Alfisol” and sub-group “Typic Hapludalf” (Soil Survey Staff 1975; Verma 1979). Some important physico-chemical characteristics of the surface soil (0-0.15 m) at the initiation of the experiment are given in table 3.1.

Table 3.1 Initial (1972) physico-chemical characteristics of the surface soil

Soil property	Characteristic
Bulk Density (Mg m^{-3})	1.31
Permeability	Moderately rapid
Mechanical separates (%)	
Sand	29.5
Silt	46.8
Clay	23.7
Textural class	Silt loam
Soil reaction	Acidic (pH 5.8)
Organic carbon (g kg^{-1})	7.9
Available nutrients (kg ha^{-1})	
N	736.0
P	12.0
K	194.2
Exchangeable cations $\{\text{c mol (p}^+) \text{ kg}^{-1}\}$	
Ca	5.30
Mg	1.30
DTPA extractable micronutrients (mg kg^{-1})	
Fe	26.0
Mn	24.3
Zn	1.9
Cu	0.4
Taxonomic classification	<i>Typic Hapludalf</i>

3.2 Experiment details

3.2.1 Treatment details

The field experiment was conducted on a pre-established long-term fertilizer experiment which comprised of ten treatments up to 1980-81. The eleventh treatment, consisting of 100 per cent NPK (-S) was introduced during *kharif*, 1981.

Treatments

The experiment comprised of eleven treatments. The detail of treatments is given below:

Treatment No.	Treatment Details
T1	: 50% NPK (sub optimal dose)
T2	: 100% NPK (optimal dose) *
T3	: 150% NPK (super optimal dose)
T4	: 100% NPK + Hand Weeding (HW)
T5	: 100% NPK+ Zn @ 25 kg ha ⁻¹ through ZnSO ₄
T6	: 100% NP
T7	: 100% N
T8	: 100% NPK + FYM @ 10t ha ⁻¹ (to maize crop only)
T9	: 100% NPK (-S), P through DAP
T10	: 100% NPK + Lime @ 900 kg ha ⁻¹
T11	: Control

Replications : Three

Design : Randomized Block Design

Crop : Maize

Plot size : 5 m x 3 m = 15 m²

*100 per cent NPK application rate corresponds to the state level recommendation for respective nutrients (i.e. 120 kg N and 60 kg P₂O₅ ha⁻¹ to both maize and wheat and 40 and 30 kg K₂O ha⁻¹ to maize and wheat, respectively).

Due to marked buildup of available P, the original treatment structure was slightly modified from *kharif* 2011, optimal and super optimal doses of P were reduced by 50 per cent and in case of sub optimal dose (i.e. 50 % NPK), addition of FYM @ 5 t ha⁻¹ on dry weight basis to maize crop only was also included. In T₈, FYM was added @ 5 t ha⁻¹ on dry weight basis.

Maize (Kanchan Gold hybrid) was taken as the test crop. The recommended dose for maize crop is 120 kg N, 60 kg P₂O₅ and 40 kg K₂O ha⁻¹. The sources of N, P and K were urea, single super phosphate and muriate of potash, respectively. In 100 per cent NPK (-S), P was applied through diammonium phosphate (DAP) to assess the effect of 'S' free high analysis P fertilizer in crop production. Half dose of N and full doses of P and K were applied at the time of sowing in maize. The remaining half N was top dressed in two equal splits at knee high and pre-tasseling stage of maize. Zinc was applied in T₅ as zinc sulphate @ 25 kg ha⁻¹ every year to both the crops till *rabi* 2010-11. Application of FYM was made @ 5 t ha⁻¹ on dry weight basis to maize crop only. The FYM applied contained 60 per cent moisture and its average nutrient content during the period of experimentation on dry weight basis was 1.03, 0.28 and 0.38 per cent of N, P and K, respectively. Lime was added in T₁₀ @ 900 kg ha⁻¹ to maize crop only as marketable lime (CaCO₃) passed through 100 mesh sieve. Lime application continued till the soil pH increased to about 6.5. Lime application in the subsequent years was restored only when the soil pH declined to about 6.3.

The maize crop was sown on 12th June, 2021. One pre-sowing irrigation was given for the field preparation. Thereafter, the crop met its water requirement through rainfall, which was very high during the crop growth period. Chemical weed control measures were followed using Atrazine @ 1.125 kg ha⁻¹ (as pre-emergence) except in T₄ (100% NPK + hand weeding), where weeds were removed manually and incorporated in the same plot. Standard package of practices was followed for raising the crop. After attaining maturity, the crop was harvested on 6th October, 2021.

3.2.2 Layout

As mentioned earlier there were eleven treatments which were replicated thrice. The layout plan of the experiment has been shown in fig. 3.2.

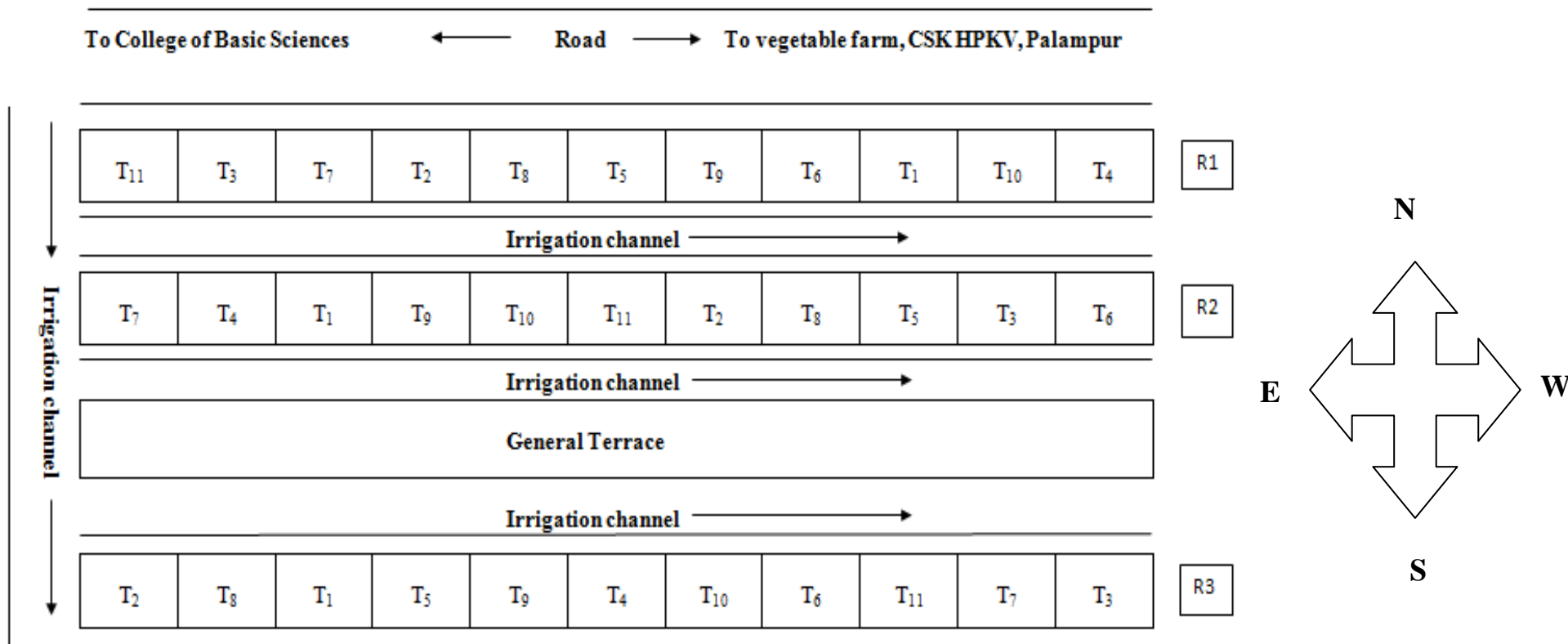


Fig. 3.3 Layout plan of the long-term fertilizer experiment

T₁ = 50% NPK

T₄ = 100% NPK + HW

T₇ = 100% N

T₁₀ = 100% NPK + lime

T₂ = 100% NPK

T₅ = 100% NPK + Zn

T₈ = 100% NPK + FYM

T₁₁ = Control

T₃ = 150% NPK

T₆ = 100% NP

T₉ = 100% NPK (-S)

(Plot Size = 5m x 3m)

3.3 Field studies

After the harvest of maize (*kharif 2021*), data on grain and stover yield was recorded on dry weight basis.

3.4 Laboratory studies

3.4.1 Soil studies

3.4.1.1 Collection and preparation of soil samples

After maize harvest (*kharif 2021*), soil samples were collected from a depth of 0 - 0.15 and 0.15 - 0.30 m from each plot. The samples were air dried and ground in a wooden pestle and mortar to pass through 2 mm sieve and subsequently stored in polyethylene bags for further analysis. The undisturbed soil samples were used for estimating aggregate size distribution. Air dried undisturbed soil samples were passed through a set of 4 and 8 mm sieves and the soil aggregates retained on 4 mm were used for estimating aggregate size distribution by wet sieving method (Yoder 1936). The processed soil samples were stored in polyethylene bags at room temperature until the analysis was carried out.

Table 3.2 Methods used for soil analysis

Soil Property	Parameter	Reference
Physical	Bulk Density	Singh (1980)
	Particle Density	Gupta and Dhakshinamoorthy (1980)
	Porosity	Gupta and Dhakshinamoorthy (1980)
	Water holding capacity	Piper (1950)
	Mean weight diameter	Yoder (1936)
	Water stable aggregates	Yoder (1936)
	Saturated hydraulic conductivity	Klute (1965)
	Infiltration rate	Hillel 1982
	Atterberg's Limit	Raina et al. (2007)
Chemical	CEC	Jackson (1973)
	Organic Carbon	Walkley and Black (1934)

3.4.1.2 Analysis of soil samples

The processed soil samples were analyzed for various physical and chemical parameters. The procedures followed for analysis are listed in table 3.2.

3.4.2 Plant studies

3.4.2.1 Collection, processing and analysis of grain and stover samples

The grain and stover samples of maize were dried in an oven at 60°C. The dried grain samples were then ground in a mixer grinder, passed through 1 mm sieve and were stored in air-tight plastic bags. The stover samples were ground in Wiley mill fitted with stainless steel parts and were then kept in paper bags for subsequent analysis.

Table: 3.3 Analytical methods used for plant analysis

S. No	Parameter	Method	Reference
1	Nitrogen	Micro Kjeldahl	Jackson (1973)
2	Phosphorus	Colorimetry	Jackson (1973)
3	Potassium	Flame photometry	Black (1965)
4	Sulphur	Turbidimetry	Chesnin and Yein (1950)
5	Calcium	Flame photometry	Jackson (1973)
6	Magnesium	Atomic absorption spectrophotometry	Jackson (1973)
7	Micronutrients (Fe, Zn, Cu, Mn)	Atomic absorption spectrophotometry	Jackson (1973)

Nutrient uptake

The nutrient uptake was calculated by multiplying per cent concentration of a particular nutrient with grain and stover yields. The uptake of the nutrients obtained in respect of grain and stover yield was summed up in order to compute the amount of total nutrients removed by the crop.

$$\text{Nutrient uptake (kg ha}^{-1}\text{)} = \text{Nutrient content (\%)} \times \text{yield (q ha}^{-1}\text{)}$$

$$\text{Total uptake} = \text{uptake by grain} + \text{uptake by straw}$$

3.5 Statistical analysis

The data obtained from field and laboratory studies were subjected to statistical analysis. The technique of analysis of variance for randomized block design was used for the interpretation of results. Relationship of crop yield and nutrients' uptake with soil properties was worked out by computing simple correlation coefficients. Statistical analysis was done by the standard procedure as described by Gomez and Gomez (1984).

4. RESULTS AND DISCUSSION

The present study entitled “**Effect of long-term application of fertilizers and amendments on soil physical quality and crop productivity in an acid Alfisol**” was carried out in the ongoing “Long-term Fertilizer Experiment” laid out at the experimental farm of the Department of Soil Science, CSK Himachal Pradesh Krishi Vishwavidyalaya, Palampur (HP). The results obtained from this investigation have been presented and discussed in this chapter under the following subheads:

- 4.1 Effect of long-term application of fertilizers and amendments on soil physical properties
- 4.2 Effect of long-term application of fertilizers and amendments on soil chemical properties
- 4.3 Effect of long-term application of fertilizers and amendments on nutrient uptake and productivity of maize
- 4.4 Relationship of soil physical properties with crop yield and nutrient uptake

4.1 Effect of long-term application of fertilizers and amendments on soil physical properties

The soil samples were taken from 0-0.15 and 0.15-0.30 m depth after the harvest of maize (*kharif* 2021). The samples were then examined for various soil physical properties and the results are presented in tables 4.1 to 4.8.

4.1.1 Bulk density (BD)

Bulk density is the ratio of the mass of oven dried soil solid particles to the total volume of soil and it is influenced by soil texture, structure, organic matter content and land management practices. Higher the BD more will be the compactness of soil and with addition of organic matter leads to decrease the BD.

According to the findings (Table 4.1), the BD of surface soil (0-0.15 m) ranged from 1.21 Mg m⁻³ under 100 per cent NPK + FYM to 1.40 Mg m⁻³ under 100 per cent N treatment. Except for 100 per cent N, all of the treatments resulted in a considerable reduction in bulk density compared to the control. The highest value of

BD was found in plots that solely received urea as the source of N, which might be due to the low levels of soil organic matter and damage to the soil structure in these plots.

Bulk density decreased from 1.31 Mg m^{-3} to 1.21 Mg m^{-3} under a 100 per cent NPK + FYM treatment after forty-nine cropping cycles. This decrease could be explained by enhanced aggregation and a subsequent rise in macro and micropores. These results are in agreement with the findings of Sharma et al. (2007), Hati et al. (2008) and Sharma et al. (2016). Addition of lime (T₁₀) significantly reduced the BD which might be due to the precipitation of exchangeable Al and resultant reduction in the negative potential on soil colloids and flocculating action of lime (Hynes and Naidu 1998). Long-term application of chemical fertilizers along with FYM for forty-nine cropping cycles caused a significant decrease in the BD of soil which might be due to the addition of organic matter that resulted in an increase in pore space and good soil aggregation (Rasool et al. 2008, Verma et al. 2010 and Khan et al. 2017).

Table 4.1 Effect of long-term application of fertilizers and amendments on soil bulk density (Mg m^{-3})

Treatment	Bulk density	
	0-0.15 m	0.15-0.30 m
T ₁ : 50% NPK	1.26	1.28
T ₂ : 100% NPK	1.28	1.29
T ₃ : 150% NPK	1.29	1.31
T ₄ : 100% NPK+ HW	1.25	1.26
T ₅ : 100% NPK+ Zn	1.27	1.29
T ₆ : 100% NP	1.32	1.36
T ₇ : 100% N	1.40	1.42
T ₈ : 100% NPK+ FYM	1.21	1.23
T ₉ : 100% NPK (-S)	1.30	1.32
T ₁₀ : 100% NPK+ Lime	1.24	1.26
T ₁₁ : Control	1.37	1.39
CD (P= 0.05)	0.02	0.03
Initial	1.31	-

Bulk density values in the sub-surface layer (0.15-0.30 m) ranged from 1.23 Mg m⁻³ in 100 per cent NPK + FYM treated plots to 1.42 Mg m⁻³ in 100 per cent N treated plots. Although the effects of treatments in the sub-surface layer were essentially identical to those in the surface layer, there was an increase in bulk density as soil depth increased, which may be related to the reduced soil organic carbon content in the sub-surface layer.

4.1.2 Particle density (PD)

Particle density is the ratio of total mass of soil solids to total volume of soil solids. It depends on the chemical and mineralogical compositions of soil. The presence of organic matter lowers the value of PD.

Table 4.2 Effect of long-term application of fertilizers and amendments on soil particle density (Mg m⁻³)

Treatment	Particle density	
	0-0.15 m	0.15-0.30 m
T ₁ : 50% NPK	2.40	2.41
T ₂ : 100% NPK	2.41	2.42
T ₃ : 150% NPK	2.41	2.42
T ₄ : 100% NPK+ HW	2.39	2.40
T ₅ : 100% NPK+ Zn	2.42	2.42
T ₆ : 100% NP	2.41	2.43
T ₇ : 100% N	2.42	2.44
T ₈ : 100% NPK+ FYM	2.38	2.39
T ₉ : 100% NPK (-S)	2.39	2.42
T ₁₀ : 100% NPK+ Lime	2.40	2.40
T ₁₁ : Control	2.42	2.41
CD (P= 0.05)	NS	NS

The information on how soil PD was affected by the long-term application of fertilizers and amendments has been shown in table 4.2. The data showed that the fertilizer treatments had no significant impact on soil PD at the surface (0-0.15 m) or sub-surface (0.15-0.30 m) soil. In surface soil, particle density ranged from 2.38 Mg m⁻³ in 100 per cent NPK + FYM to 2.42 Mg m⁻³ in 100 per cent N alone. The particle

density of surface soil was reduced to the extent of 1.7 and 1.2 per cent, respectively by the integrated (100% NPK + FYM) and balanced (100% NPK + HW) fertilizer application over control, but these reductions were not significant.

In comparison to surface soil, sub-surface soil had a significantly higher particle density. Particle density in sub-surface soil (0.15-0.30 m) ranged from 2.39 Mg m^{-3} in 100 per cent NPK + FYM to 2.44 Mg m^{-3} in 100 per cent N. Similar to surface soil, treatment-specific effects on sub-surface soil's PD followed a similar pattern. Nandapure et al. (2011) also reported that the particle density did not show any significant change due to the long-term application of fertilizers and manures at Akola (Maharashtra).

4.1.3 Porosity

It is the ratio of total volume of pore spaces to the total volume of soil. Addition of organic matter increases the porosity of soil which ultimately increase the infiltration rate, hydraulic conductivity and decrease the bulk density.

The data with respect to the effect of continuous fertilization and amendment use on soil porosity have been presented in table 4.3. The long-term application of amendments and fertilizers, resulted in the considerable change in soil porosity (%). Soil porosity varied significantly between different treatments in the 0-0.15 m depth and ranged from 42.27 to 49.44 per cent. The treatment consisting of 100 per cent NPK + FYM resulted in the highest porosity value (49.44%), followed by 100 per cent NPK + HW (47.63%), whereas, 100 per cent N application showed the lowest value (42.27%).

The porosity of soil was enhanced by graded doses of fertilizers from 50 per cent to 150 per cent NPK to the extent of 7.9, 8.7 and 6.9 per cent, respectively, over control, although the variations with the graded doses were not statistically significant.

In sub-surface soil layer (0.15-0.30 m), the per cent porosity ranged from 41.66 under 100 per cent N to 48.89 under 100 per cent NPK + FYM treatment. There was a reduction in the porosity of sub-surface layer as compared to surface layer.

Table 4.3 Effect of long-term application of fertilizers and amendments on soil porosity (%) and water holding capacity (%)

Treatment	Soil porosity		Water holding capacity	
	0-0.15 m	0.15-0.30 m	0-0.15 m	0.15-0.30 m
T ₁ : 50% NPK	46.98	46.46	55.30	51.95
T ₂ : 100% NPK	47.31	46.02	55.55	52.95
T ₃ : 150% NPK	46.53	45.71	54.37	50.44
T ₄ : 100% NPK+ HW	47.63	47.29	58.52	54.92
T ₅ : 100% NPK+ Zn	47.32	46.73	55.07	51.09
T ₆ : 100% NP	45.01	44.10	53.25	49.65
T ₇ : 100% N	42.27	41.66	48.84	46.13
T ₈ : 100% NPK+ FYM	49.44	48.89	60.02	56.99
T ₉ : 100% NPK (-S)	45.68	45.32	54.43	50.58
T ₁₀ : 100% NPK+ lime	48.19	47.36	59.63	56.30
T ₁₁ : Control	43.53	42.10	50.06	47.43
CD (P= 0.05)	2.86	2.30	1.03	1.21

Higher soil porosity observed in the treatment 100 per cent NPK + FYM in both layers as compared to 100 per cent NPK could be attributable to the better soil aggregation, which enhanced soil physical characteristics (Hati et al. 2007). A rise in soil porosity with simultaneous application of fertilizers and organic manure was also reported by Marinari et al. (2000), Celik et al. (2004) and Nandapure et al. (2011).

4.1.4 Water holding capacity (WHC)

Water holding capacity defines the amount of water that a given soil can hold for crop use. WHC shows the direct relationship with addition of organic amendments.

The results depicted in table (Table 4.3) clearly shows that applying chemical fertilizers alone or in conjunction with organic manure or lime greatly boosted the ability of soil to retain water as compared to control. It varied from a minimum value of 48.84 under 100 per cent N to a maximum value of 60.02 per cent under 100 per cent NPK + FYM, which was at par with 100 per cent NPK + lime, in the surface layer (0–0.15 m). Except for 100 per cent N alone, fertilizer application considerably improved soil's ability to retain water as compared to control. This increase could be attributed to better root growth and addition of more plant residues under these treatments.

Further analysis of the data showed that as soil depth increased, water holding capacity declined. Water holding capacity in the sub-surface soil layer (0.15-0.30 m) ranged from 46.13 in 100 per cent N treatment to 56.99 per cent in 100 per cent NPK + FYM treatment. The highest water holding capacity recorded under 100 per cent NPK + FYM was at par with 100 per cent NPK + lime. The water holding capacity under 100 per cent NPK + lime and 100 per cent NPK + HW were significantly higher over 100 per cent NPK alone (T_2). 100 per cent NPK + FYM, 100 per cent NPK + lime and 100 per cent NPK + HW treatments showed improvement in WHC as compared to the other treatments. The addition of organic matter or lime may have encouraged aggregation and improved soil structure (Hati et al. 2008). These findings are in agreement with those made by Selvi et al. (2005), Katkar et al. (2012) and Amipara and Jadhav (2017).

4.1.5 Saturated hydraulic conductivity (SHC)

Saturated hydraulic conductivity is the ease with which pores of a saturated soil transmit water. It affects by soil bulk density, size and configuration of the soil pores, organic matter, soil structure etc.

The information on how long-term application of fertilizers and amendments affects the SHC of soil has been shown in table 4.4. The results revealed that the SHC varied between 2.52 and 5.46 cm hr^{-1} in the surface layer (0-0.15 m) and between 2.48 and 4.31 cm hr^{-1} in the sub-surface layer (0.15-0.30 m).

In the surface layer, 100 per cent NPK+ FYM recorded the highest SHC (5.46 cm hr^{-1}), followed by 100 per cent NPK+ Lime (4.14 cm hr^{-1}), both of which were

significantly greater than all other treatments, while the lowest SHC (2.52 cm hr^{-1}) was recorded in 100 per cent N. The highest value of SHC under 100 per cent NPK+ FYM treatment could be attributed to high organic carbon content in soil which might have enhanced soil aggregation, decreased bulk density and increased porosity. Under 50, 100 and 150 per cent NPK treatments increasing the NPK level increased SHC by 17.6, 18.7 and 23.9 per cent, respectively, over control.

Table 4.4 Effect of long-term application of fertilizers and amendments on saturated hydraulic conductivity (cm hr^{-1})

Treatment	Saturated hydraulic conductivity	
	0-0.15 m	0.15-0.30 m
T ₁ : 50% NPK	3.14	2.76
T ₂ : 100% NPK	3.17	3.03
T ₃ : 150% NPK	3.31	3.24
T ₄ : 100% NPK+ HW	3.62	3.45
T ₅ : 100% NPK+ Zn	3.44	3.37
T ₆ : 100% NP	2.81	2.52
T ₇ : 100% N	2.52	2.48
T ₈ : 100% NPK+ FYM	5.46	4.31
T ₉ : 100% NPK (-S)	3.46	3.22
T ₁₀ : 100% NPK+ Lime	4.14	3.82
T ₁₁ : Control	2.67	2.50
CD (P= 0.05)	0.14	0.53

Application of 100 per cent NPK increased the SHC significantly by 12.8 and 25.7 per cent over 100 per cent NP and 100 per cent N, respectively. In all of the treatments, the SHC was lower in sub-surface layer than the surface layer, possibly because deeper layers were more compacted (Ali 2011). Other reason could be a higher organic matter content in surface layers prevented the compaction and resulted in easy movement of water. Overall, the treatment effect of SHC at subsurface layer was similar to that in surface layer.

4.1.6 Mean weight diameter (MWD)

Mean weight diameter express the stability of soil aggregates. The data on the long-term effect of chemical fertilizers and amendments on MWD has been presented in table 4.5. The MWD values in the surface layer (0-0.15 m) varied from a minimum of 0.92 mm to a maximum value of 4.89 mm. 100 per cent NPK+ FYM had the highest MWD followed by 100 per cent NPK+ Lime and 100 per cent NPK+ HW with the values of 4.89, 3.74 and 2.45 mm, respectively. MWD was lowest (0.92 mm) in 100 per cent N and increased significantly in all the treatments over control.

Table 4.5 Effect of long-term application of fertilizers and amendments on mean weight diameter (mm)

Treatment	Mean weight diameter	
	0-0.15 m	0.15-0.30 m
T ₁ : 50% NPK	1.71	1.55
T ₂ : 100% NPK	2.12	2.03
T ₃ : 150% NPK	1.60	1.48
T ₄ : 100% NPK+ HW	2.45	2.15
T ₅ : 100% NPK+ Zn	1.67	1.52
T ₆ : 100% NP	1.56	1.45
T ₇ : 100% N	0.92	0.81
T ₈ : 100% NPK+ FYM	4.89	3.82
T ₉ : 100% NPK (-S)	1.61	1.42
T ₁₀ : 100% NPK+ Lime	3.74	3.32
T ₁₁ : Control	1.09	0.99
CD (P= 0.05)	0.16	0.13

The MWD considerably increased over the control (1.09 mm) by 43.1 and 94.4 per cent under 100 per cent NP and 100 per cent NPK respectively. Verma and Sharma (2007) and Brar et al. (2015) have also reported similar results. The addition of FYM along with inorganic fertilizer might have increased the amount of organic matter in the soil which acting as a binding agent might have enhanced aggregate stability (Hati et al. 2006; Brar et al. 2015). In contrast to the application of 100 per cent N alone, balanced fertilization of NPK along with hand weeding (T₄) increased

aggregate stability by the insertion of more biomass in the soil in the form of crop root residues (Hati et al. 2008). In T₇, low pH conditions might have caused ferrolysis, which ultimately might have increased the fraction of clay by breaking down sand particles (Chaudhary et al. 2012).

The increase in MWD with application of lime could be ascribed to the advantageous action of calcium ions, which might have helped in flocculating soil particles and enhancing aggregate stability. Liming also increased the pH of the soil, which stimulated an increase in microorganism activity and the production of a variety of organic compounds that might have aided in binding the aggregates.

Mean weight diameter varied from 0.81 mm in 100 per cent N to 3.82 mm in 100 per cent NPK+ FYM treated plots in the sub-surface soil (0.15–0.30 m). Both the surface and the sub-surface layers showed the same trend in the increase of MWD. These outcomes are in line with those of Hati et al. (2008).

4.1.7 Atterberg's limits

Atterberg was a Swedish soil scientist who established three limits of soil consistency based on the moisture content of the soil, that is liquid limit, plastic limit and plasticity index. The plastic limit is the moisture content that defines where the soil changes from a semi-solid to a plastic (flexible) state. The liquid limit is the moisture content that defines where the soil changes from a plastic to a viscous fluid state. The plasticity index is the difference between moisture contents of the soil at its upper plastic limit and lower plastic limit.

The data on atterberg's limit of soil as affected by long-term application of fertilizers and amendments have been presented in table 4.6. In the surface layer (0-0.15 m), it is evident from the results that all the soil consistency limits, *viz.*, liquid limit, plastic limit and plasticity index were affected significantly with the long-term application of fertilizers and amendments. The moisture content at liquid limit increased by 28.09 and 18.73 per cent and the corresponding values of per cent moisture content increase at plastic limit were 31.75 per cent and 22.31 per cent, under 100 per cent NPK + FYM and 100 per cent NPK + HW, respectively, over control. The data showed that the increase in moisture content at liquid limit was

relatively more than at plastic limit. It resulted into significant increase in plasticity index except for the treatment 100 per cent N (T₇).

Table 4.6 Effect of long-term application of fertilizers and amendments on Atterberg's limit (%) of soil

Treatment	SOIL MOISTURE CONTENT (%)					
	Liquid Limit		Plastic Limit		Plasticity Index	
	Soil depth (m)		Soil depth (m)		Soil depth (m)	
	0-0.15	0.15-0.30	0-0.15	0.15-0.30	0-0.15	0.15-0.30
T ₁ : 50% NPK	36.3	35.2	26.2	25.9	10.1	10.2
T ₂ : 100% NPK	35.7	35.4	25.4	24.8	10.3	10.6
T ₃ : 150% NPK	34.3	34.2	24.9	24.2	9.4	10.0
T ₄ : 100% NPK + HW	39.3	38.7	28.5	27.7	10.7	11.0
T ₅ : 100% NPK + Zn	38.4	37.4	27.9	27.2	10.5	10.2
T ₆ : 100% NP	33.5	33.1	23.6	23.5	9.8	9.6
T ₇ : 100% N	32.1	32.0	22.6	23.2	9.5	8.8
T ₈ : 100% NPK + FYM	42.4	41.5	30.7	30.2	11.6	11.3
T ₉ : 100% NPK (-S)	34.6	34.6	24.1	24.32	10.5	10.3
T ₁₀ : 100% NPK + lime	40.5	39.9	29.9	29.8	10.6	10.1
T ₁₁ : Control	33.1	32.7	23.3	23.4	9.8	9.3
CD (P = 0.05)	0.52	0.83	1.11	1.18	1.20	1.30

The data further revealed that atterberg's limit decreased with an increase in soil depth. This could be due to low soil organic carbon content, low root biomass and more compaction in the sub-surface soil (Kumar et al. 2015).

The highest plasticity index recorded under 100 per cent NPK + FYM was at par with 100 per cent NPK + HW. The plasticity index under 100 per cent NPK + FYM and 100 per cent NPK + HW were significantly higher over control. This could be attributed to the high water holding capacity and surface area of organic matter. Similar findings were reported by Baver (1930). Under 100 per cent NPK + HW the increase in plasticity index was probably due to the incorporation of weed biomass which resulted in improved physical condition of soil and the lowest was recorded under 100 per cent N which may be attributed to the deterioration of soil structure by continuous addition of nitrogenous fertilizer only. All the value lies in medium plastic range and similar findings was reported by Jumikis (1967).

4.1.8 Water stable aggregates

Water stable aggregates refers to the ability of soil aggregates to resist disruption when outside forces (usually associated with water) are applied.

The data recorded on soil aggregate distribution as influenced by long term use of fertilizers and amendments has been depicted in table 4.7 and table 4.8. Soil aggregate distribution was significantly affected by long-term application of inorganic fertilizers alone or in combination with FYM. The data revealed that an aggregate fraction of 0.5-0.25 mm made up the largest, whereas, 0.1-0.062 mm fraction made the least contribution in total water stable aggregate percentage. The aggregate soil mass in different size classes varied from 6.10-10.77, 5.97-10.93, 13.94-18.82, 17.96-24.00, 17.91-23.29 and 1.67-4.12 per cent in 4-2 mm, 2-1 mm, 1-0.5 mm, 0.5-0.25 mm, 0.25-0.1 mm and 0.1-0.062 mm aggregate size classes, respectively. The data from table showed that the treatment 100 per cent NPK + FYM recorded the highest percentage (91.93) of total water stable aggregates and the lowest (63.55) was in 100 per cent N (T₇). The highest proportion of water stable aggregates in organic amended plots can be attributed to the regular addition of organic matter through organics and additional root biomass added to soil, resulting in increased carbon availability and improved microbial activity, which might have resulted in aggregate binding. These results are in agreement with the results of Hati et al. (2007), Tripathi et al. (2014), Mazumdar et al. (2015) and Bhagwatrao et al. (2019). Application of FYM alone or in combination with inorganic fertilizers may have significantly improved the formation of macroaggregates due to secretion of mucilaginous compounds from FYM decomposition which might have resulted in the binding of soil particles into micro and macroaggregates (Tripathi et al. 2014; Mazumdar et al. 2015). The lowest value for water stable aggregates was recorded in the treatment 100 per cent N which may be attributed to the deterioration of soil structure by addition of nitrogenous fertilizer only.

The treatment effect on water stable aggregates at 0.15 – 0.30 m soil depth was almost similar to that in the surface layer but there was significant decrease in water stable aggregates with the increase in the depth. This might be due to low soil organic carbon content, low root biomass and more compaction in the sub-surface soil (Kumar et al. 2015).

Table 4.7 Effect of long-term application of fertilizers and amendments on water stable aggregates (%) (0-0.15m)

Treatment	Soil aggregates distribution (%)						Total WSA (%)
	4-2 mm	2-1 mm	1-0.5 mm	0.5-0.25 mm	0.25-0.1 mm	0.1-0.062 mm	
T ₁ : 50% NPK	8.97	9.1	16.22	20.78	19.68	2.26	77.01
T ₂ : 100% NPK	9.43	9.62	17.52	21.37	20.50	2.58	81.02
T ₃ : 150% NPK	9.70	9.94	17.00	21.48	20.92	2.50	81.54
T ₄ : 100% NPK+ (HW)	9.97	10.35	17.98	21.99	21.58	2.95	84.82
T ₅ : 100% NPK+ Zn	8.90	9.14	17.43	21.46	20.68	2.69	80.30
T ₆ : 100% NP	7.56	7.74	14.93	19.74	19.27	2.61	71.85
T ₇ : 100% N	6.10	5.97	13.94	17.96	17.91	1.67	63.55
T ₈ : 100% NPK+ FYM	10.77	10.93	18.82	24.00	23.29	4.12	91.93
T ₉ : 100% NPK (-S)	8.98	8.96	18.55	21.64	20.90	2.77	81.80
T ₁₀ : 100% NPK+ Lime	10.31	10.48	18.76	23.50	22.95	3.58	89.58
T ₁₁ : Control	6.68	6.82	13.95	19.35	18.59	1.65	67.04
CD (P = 0.05)	-	-	-	-	-	-	1.43

Table 4.8 Effect of long-term application of fertilizers and amendments on water stable aggregates (%) (0.15-0.30 m)

Treatment	Soil aggregates distribution (%)						Total WSA (%)
	4-2 mm	2-1 mm	1-0.5 mm	0.5-0.25 mm	0.25-0.1 mm	0.1-0.062 mm	
T ₁ : 50% NPK	8.87	8.9	16.12	20.58	19.28	2.07	75.82
T ₂ : 100% NPK	9.43	9.52	17.42	21.17	19.7	2.27	79.51
T ₃ : 150% NPK	9.50	9.74	16.80	21.28	20.82	2.42	80.56
T ₄ : 100% NPK+ (HW)	9.77	10.15	17.78	21.79	21.48	2.91	83.88
T ₅ : 100% NPK+ Zn	8.60	9.04	17.23	21.26	20.58	2.60	79.31
T ₆ : 100% NP	7.36	7.54	14.73	19.54	19.17	2.57	70.91
T ₇ : 100% N	6.00	5.37	13.84	17.86	17.71	1.45	62.33
T ₈ : 100% NPK+ FYM	10.37	10.43	18.62	23.50	23.09	4.08	90.09
T ₉ : 100% NPK (-S)	8.78	8.87	18.35	21.44	20.70	2.67	80.81
T ₁₀ : 100% NPK+ Lime	10.11	10.28	18.66	23.50	22.85	3.55	88.85
T ₁₁ : Control	6.38	6.62	13.55	19.15	18.29	1.56	65.55
CD (P = 0.05)	-	-	-	-	-	-	1.23

4.1.9 Infiltration rate

Infiltration refers to ‘the process of entry of water into soil’ and infiltration rate refers to the ‘volume of water entering into soil per unit surface area per unit time’. Infiltration rate depends upon soil aggregate stability, texture, structure, organic matter, bulk density, saturated hydraulic conductivity etc.

The data on the long-term effect of chemical fertilizers and amendments on infiltration rate and cumulative infiltration is depicted in figure 4.1 and 4.2, respectively. The infiltration rate and cumulative infiltration was recorded maximum under the treatment of 100 per cent NPK + FYM and the minimum was recorded under treatment 100 per cent N. This increase in infiltration rate and cumulative infiltration might be due to decrease in BD and an increase in micropores and macropores in the soil resulting from better aggregation by cementing of soil particles together due to higher organic matter and favourable living conditions for soil organisms.

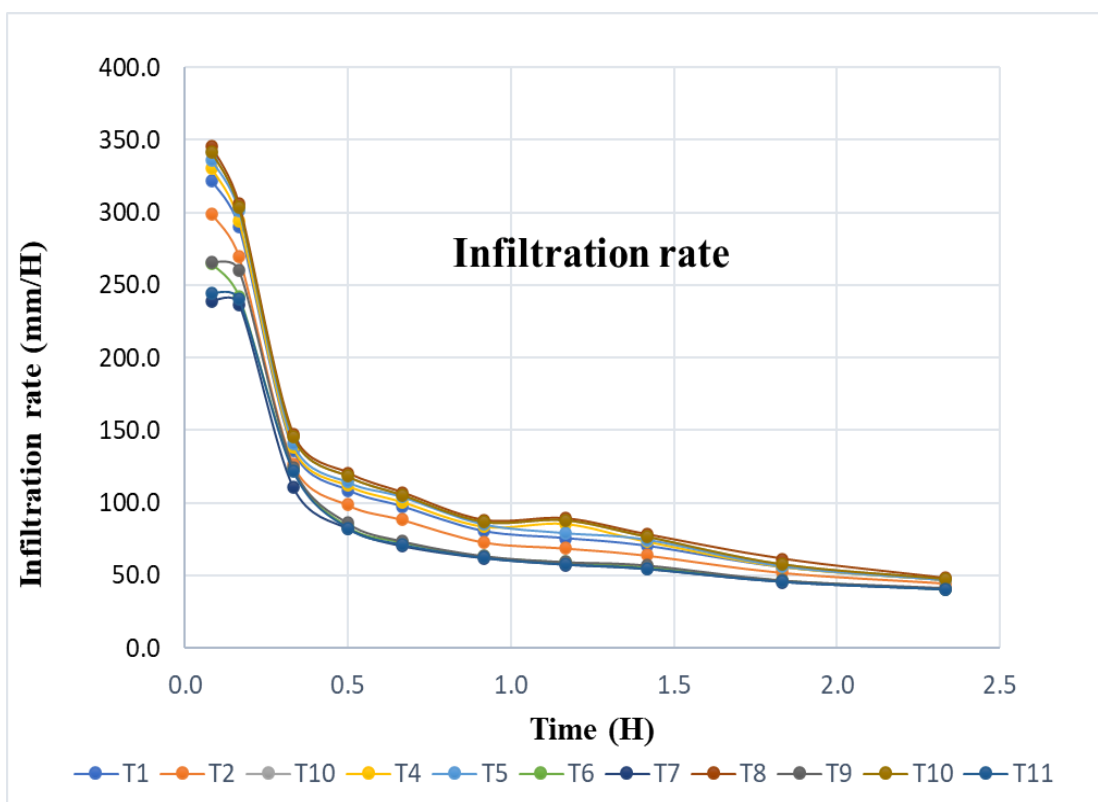


Fig 4.1 Effect of long-term application of fertilizers and amendments on infiltration rate (mm/h)

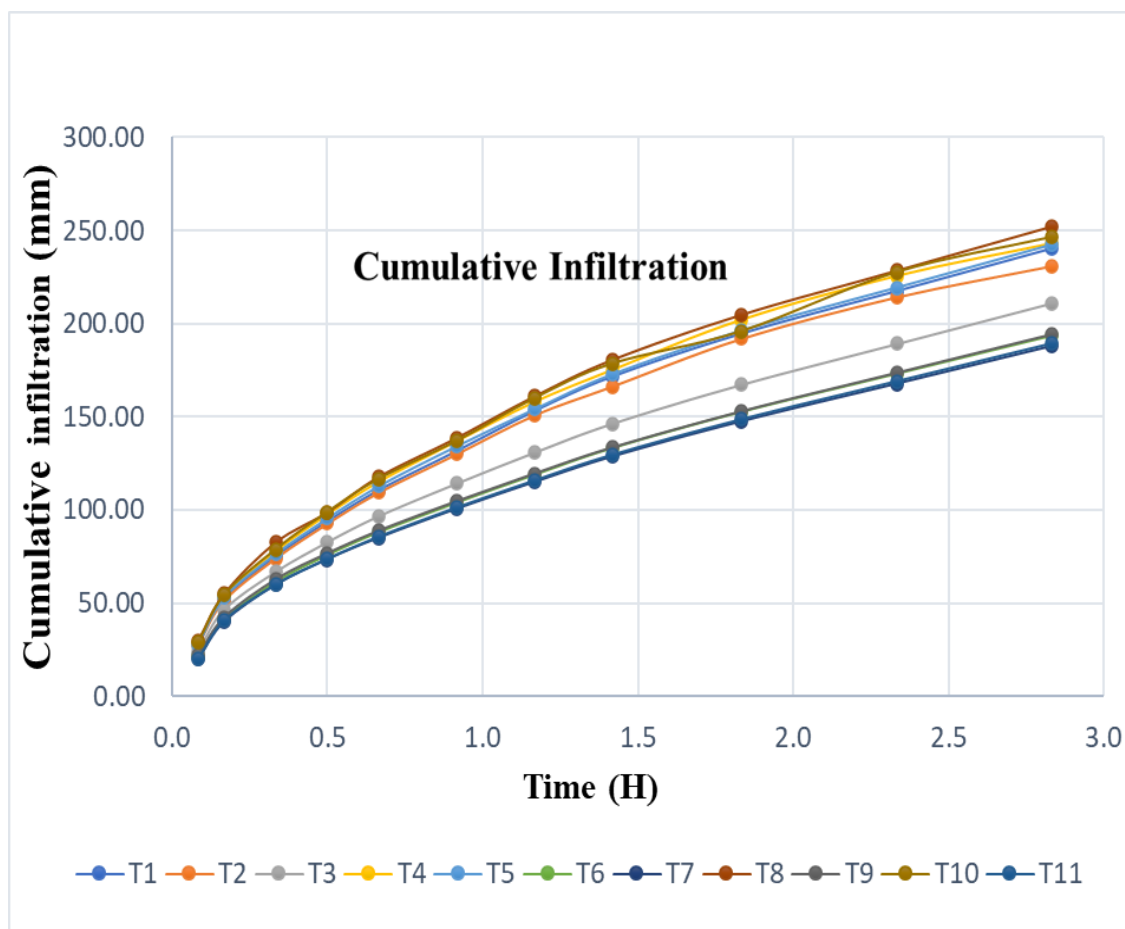


Fig 4.2 Effect of long-term application of fertilizers and amendments on cumulative infiltration (mm)

Other reason could be the to increase in soil organic matter, rooting density and improvement in aggregation and soil structure resulting in higher porosity and pore continuity. Bhattacharya et al. (2007) reported similar results that the infiltration rate under NPK + FYM was higher than that in unfertilized plot. The minimum infiltration rate and cumulative infiltration recorded in 100 per cent N might be attributed to an increase in BD and decrease in porosity resulting in the destruction of soil structure due to the sole use of urea.

4.2 Effect of long-term application of fertilizers and amendments on soil chemical parameters

4.2.1 Cation exchange capacity (CEC)

The effect of long-term application of fertilizers and amendments on CEC has been presented in table 4.9. The results, revealed that the CEC ranged from the lowest value of 6.20 c mol (p+) kg⁻¹ in 100 per cent N treated plots to the maximum value of 12.39 c mol (p+) kg⁻¹ in 100 per cent NPK + FYM treated plots in surface layer. In

general, the CEC values decreased in almost all the treatments in comparison to the initial value except 100 per cent NPK + FYM and 100 per cent NPK + lime treatments.

The 100 per cent NPK + FYM and 100 per cent NPK + lime plots had significantly higher cation exchange capacities than the 100 per cent NPK treatment.

The CEC for the sub-surface layer (0.15–0.30 m) varied from 5.92 c mol (p+) kg⁻¹ under 100 per cent N to 11.03 c mol (p+) kg⁻¹ under 100 per cent NPK + FYM. With increasing soil depth, CEC decreased. In 0.15-0.30 m soil depth, the impact of treatment on CEC was essentially identical to that in the surface layer.

Table 4.9 Effect of long-term application of fertilizers and amendments on cation exchange capacity {c mol (p⁺) kg⁻¹}

Treatment	CEC	
	0-0.15 m	0.15-0.30 m
T ₁ : 50% NPK	10.13	9.38
T ₂ : 100% NPK	10.41	9.37
T ₃ : 150% NPK	10.26	9.19
T ₄ : 100% NPK+ HW	11.25	9.68
T ₅ : 100% NPK+ Zn	10.10	8.22
T ₆ : 100% NP	9.11	7.52
T ₇ : 100% N	6.20	5.92
T ₈ : 100% NPK+ FYM	12.39	11.03
T ₉ : 100% NPK (-S)	9.22	8.27
T ₁₀ : 100% NPK+ lime	12.13	10.67
T ₁₁ : Control	8.43	6.26
CD (P= 0.05)	0.75	0.71
Initial	12.1	

The CEC of soils is a function of negative charges developed on the broken edges of clay minerals. The decline in CEC value was observed in plot T₇ due to prolonged soil acidification brought on by continuous usage of urea fertilizer, which may have contributed to the low pH values of these plots. Only the permanent charges of the clays and a small percentage of the charges of organic colloids are capable of holding ions that can be exchanged by cations at such low pH values (Brady 1990). It may also be due to the formation of non-exchangeable hydroxyl-Al complexes in the interlayer region of the clays. Similar findings have also been reported by Barak et al. (1997) and Ogbodo (2013) from their experiment conducted at south central Winconsin and Ebonyi state of South Nigeria.

The CEC of the soil was improved by using chemical fertilizers either alone or in combination with FYM. This increase might be caused by the production of more humus as a result of the inclusion of organic materials, which served as a storage facility for exchangeable cations (Dhiman 2007). The significant increase in soil organic matter content may also be used to explain the rise in CEC brought on by higher fertilizer levels. The present results are in agreement with the findings of Sharma et al. (2001), Phogat et al. (2004) and Nkechi et al. (2013). Moreover, the increase in CEC with the addition of FYM or lime can be attributed to an increase in root biomass and crop residue production and their incorporation into the soil. Similar findings were reported by Prasad et al. (1996) and Sharma (2004). Lime can enhance pH and contribute Ca through it, which may explain its beneficial effects on CEC. Irrespective of treatments, the CEC dropped with depth. This could be explained by a lower organic carbon concentration in the deep layer than in the surface layer.

4.2.2 Soil organic carbon (SOC)

In surface layer of soil (0-0.15 m), the SOC content varied from 7.75 in control plots to 13.97 g kg⁻¹ in 100 per cent NPK + FYM plots (Table 4.10). There was an increase in SOC content in all the treatments, except in control. A marked buildup of organic carbon was noticed under integrated use of fertilizers and manure i.e. 100 per cent NPK + FYM treatment. The lime application increased soil organic carbon content significantly over 100 per cent NPK alone. Significantly higher values of organic carbon were recorded with manual weed control (T₄) over the chemical weed

control (T₂). The omission of potassium (T₆) decreased the SOC content significantly as compared to 100 per cent NPK. Sole application of N at optimal level (T₇) recorded significantly lower organic carbon content (8.27 g kg⁻¹) in comparison to the plots receiving 100 per cent NPK (9.83 g kg⁻¹).

At 0.15-0.30 m soil depth, the organic carbon content varied from 5.92 in control to 9.93 g kg⁻¹ in 100 per cent NPK + FYM treatment. The treatment wise effect in sub-surface layer was almost similar.

Table 4.10 Effect of long-term application of fertilizers and amendments on soil organic carbon (g kg⁻¹)

Treatment	Soil organic carbon	
	0-0.15 m	0.15-0.30 m
T ₁ : 50% NPK	10.02	7.67
T ₂ : 100% NPK	9.83	7.48
T ₃ : 150% NPK	9.67	7.32
T ₄ : 100% NPK+ HW	11.83	8.88
T ₅ : 100% NPK+ Zn	9.63	7.28
T ₆ : 100% NP	8.97	6.62
T ₇ : 100% N	8.27	6.02
T ₈ : 100% NPK+ FYM	13.97	9.93
T ₉ : 100% NPK (-S)	9.57	7.01
T ₁₀ : 100% NPK+ lime	10.92	8.06
T ₁₁ : Control	7.75	5.92
CD (P= 0.05)	0.89	0.69
Initial	7.9	

In general, over time, extensive cropping reduces SOC, but here, the organic carbon content improved in fertilized plots due to regular carbon addition through the root, crop residues and rhizo-decomposition, confirming the findings of Kundu et al. (2002) and Hati et al. (2007). Also, slow rate of organic matter decomposition in wet

temperate zone could be another reason for buildup of SOC Sharma and Manohar (2002) and Verma et al. (2012). Substantial increase in organic carbon (76.8%) was registered in the plots receiving 100 per cent NPK + FYM over initial value. It may be partly due to the continuous addition of carbon manure and partly due to the fact that FYM addition along with fertilizers resulted in better crop growth which, in turn, added more organic materials in the form of decaying roots, litter and crop residues in these plots. These results are in conformity with those of Mishra et al. (2008), Yang et al. (2011) and Brar et al. (2015).

Significantly higher SOC content in the plots where manual weeding was done (T₄) in comparison to the treatment involving chemical weed control (T₂) might be attributed to the continuous recycling of weed biomass in these plots. The beneficial effects of recommended dose of balanced fertilizer application (T₂) in terms of SOC over control, 100 per cent N, 100 per cent NP and 100 per cent NPK (-S) could be attributed to better crop growth along with more root biomass generation and higher amount of leftover surface plant residues (Christensen 1988).

4.3 Effect of long-term application of fertilizers and amendments on nutrient uptake and productivity of maize

The data pertaining to nutrient uptake and yield by maize crop (*khariif* 2021), as influenced by the long-term application of fertilizers and amendments for forty-nine years have been presented in tables 4.11 to 4.21.

4.3.1 Productivity of maize

The data pertaining to maize productivity (*khariif* 2021) have been presented in table 4.11. It is evident from the data that the yield of maize was significantly affected by long-term application of fertilizers and amendments for forty-nine years. Barring T₇ (100 % N alone), maize grain and stover yield ranged between 8.35 and 64.02 q ha⁻¹ and 14.22 and 103.21 q ha⁻¹, respectively.

Application of FYM along with 100 per cent NPK recorded the highest grain (64.02 q ha⁻¹) and stover yield (103.21 q ha⁻¹) after 49 cropping cycles. The grain (59.87 q ha⁻¹) and stover yield (96.66 q ha⁻¹) obtained in 100 per cent NPK + lime was at par with 100 per cent NPK + FYM. It is clear from the data that use of manure or lime as an amendment along with recommended dose of NPK resulted in significantly

higher yield of maize over rest of the treatments. Hand weeding (T₄) treatment increased biological maize yield by 19.42 per cent over chemical weed control (T₂). It is noteworthy that the application of 150 per cent of recommended NPK did not show any beneficial effect on maize productivity, rather it declined the biological productivity by 6.21 per cent as compared to recommended dose of NPK (T₂).

Table 4.11 Effect of long-term application of fertilizers and amendments on productivity of maize

Treatment	Productivity (q ha ⁻¹)		
	Grain	Stover	Biological (Grain + Stover)
T ₁ : 50% NPK	43.75	72.44	116.19
T ₂ : 100% NPK	39.23	64.67	103.90
T ₃ : 150% NPK	36.77	60.67	97.44
T ₄ : 100% NPK + HW	46.97	77.11	124.08
T ₅ : 100% NPK + Zn	37.67	62.22	99.89
T ₆ : 100% NP	15.12	25.11	40.23
T ₇ : 100% N	0.00	0.00	0.00
T ₈ : 100% NPK + FYM	64.02	103.21	167.23
T ₉ : 100% NPK (-S)	14.32	23.78	38.1
T ₁₀ : 100% NPK + lime	59.87	96.66	156.53
T ₁₁ : Control	8.35	14.22	22.57
CD (P=0.05)	5.35	7.96	13.31

Application of Zn did not show any beneficial effect on productivity of maize. The data further revealed that omission of S and K from fertilization schedule significantly reduced the maize yield. The biological yield of maize recorded in plots under 100 per cent NPK (-S) and 100 per cent NP (-K) was 38.10 and 40.23 q ha⁻¹, which was 63.33 and 61.28 per cent lower than 100 per cent NPK, respectively. The

plots receiving no fertilizer or manure for last forty-nine years (T_{11}) recorded a significant decline in grain and stover yield of maize, the decrease was 78.71 and 78.01 per cent as compared to 100 per cent NPK, respectively.

Increased grain and stover yield in 100 per cent NPK + FYM might be attributed to the insertion of FYM resulted in the addition of organic matter which in turn improved the soil structure, aggregation, water infiltration, storage, decomposition and nutrient release. Soil with higher organic matter acts like a sponge holding more water and nutrients. The balanced and sufficient supply of nutrients from FYM and chemical fertilizers, improved physical, chemical and biological properties of the soil which might have augmented root system and promoted higher nutrient and water absorption, thus, better plant growth which led to higher crop productivity (Hazarika et al. 2016). These results are in line with the findings of Thakur et al. (2011), Brar et al. (2015) and Singh et al. (2019). Application of lime improved maize productivity which might be due to amelioration of soil pH that might have improved the availability of P, Ca and Mg, combatted the Al toxicity and improved the overall soil health. These findings corroborate with the findings of Caires et al. (2006) and Buni (2015). The increase in maize yield under 100 per cent NPK + HW treatment over 100 per cent NPK might be due to the increased organic matter content in the plots under this treatment as a result of recycling of weed biomass, leading to improvement in the physical properties and microbial processes in the soil. This might also be due to release of nutrients particularly micronutrients on decomposition of weed biomass as there is no other external source of micronutrients was applied.

Continuous cropping without addition of fertilizers and manure for last forty-nine years caused mining of nutrients and deterioration of physical and biological properties of soil and hence resulted in poor soil productivity in control plots. Long-term application of N alone through urea (T_7) resulted in zero productivity. Continuous cropping and addition of only urea resulted in deterioration of soil structure and sharp decline in soil pH which might have increased the concentration of Al ions to toxic levels, caused nutrient imbalance and thus, created unfavourable conditions for crop growth. Deleterious effects of use of N alone on crop production

have also been reported by a number of workers in the country (Mahajan et al. 2007; Majhi et al. 2018).

Application of P along with N at optimum level (T_6) recorded higher yield in comparison to control and 100 per cent N, which might be attributed to the favourable effect of P on plant root system and hence consequential better nutrient absorption. But omission of K in this treatment resulted in lower yield as compared to 100 per cent NPK. Absence of K from fertilization schedule resulted in K deficiency in soil. Since K plays an important role in activation of various enzymes and translocation of photosynthates in plant system, its deficiency in soil led to the decreased maize yield (Chaudhary et al. 2017).

Significant decline in maize yield was recorded in the treatment where recommended dose of P was applied through DAP (S-free fertilizer) in place of SSP, which led to the depletion of S reserves in the soil over the years (Kundu et al. 2016). This corroborates with the findings of Varavipour et al. (1999), Sharma and Manohar (2002) and Brar et al. (2015). Application of 150 per cent NPK reduced the yield over 100 per cent NPK which might be because of the reason that super optimal application of NPK removed secondary and micro nutrients from the soil in large amount and hence resulted in the imbalance of nutrients in the soil (Das et al. 2012).

4.3.2 Nutrient uptake

The data pertaining to the uptake of nutrients by maize crop (*khariif* 2021) during the 49th cropping cycle have been presented in tables 4.12 to 4.21. Application of 100 per cent N recorded zero yield hence, nutrient uptake in these plots was nil.

4.3.2.1 Nitrogen uptake

The data pertaining to N uptake by maize have been presented in table 4.12. The highest N uptake (99.91 kg ha^{-1}) by maize grain was recorded under 100 per cent NPK + FYM treatment followed by 100 per cent NPK + lime with N uptake of 88.79 kg ha^{-1} . These two treatments were found to be significantly superior over rest of the treatments. 100 per cent NPK + FYM and 100 per cent NPK + lime recorded 79.56 and 59.57 per cent higher N uptake, respectively as compared to 100 per cent NPK. The treatment comprising 100 per cent NPK + HW was significantly superior over

100 per cent NPK, whereas, 100 per cent NPK + Zn was statistically at par with 100 per cent NPK. Omission of K (T₆) and S (T₉) recorded significantly lower N uptake by maize grain than optimal dose of NPK, the decrease being 67.48 and 69.39 per cent, respectively.

The data further revealed that in case of maize stover, N uptake ranged from 5.35 kg ha⁻¹ in control to 74.39 kg ha⁻¹ in 100 per cent NPK + FYM treatment. FYM (T₈) and lime (T₁₀) amended plots recorded significantly higher N uptake over rest of the treatments. Absence of either S (T₉) or K (T₆) resulted in significantly lower N uptake by maize stover in comparison to 100 per cent NPK.

The total N uptake by maize varied from 14.75 kg ha⁻¹ in control to 174.30 kg ha⁻¹ in 100 per cent NPK + FYM treated plots. Long-term application of FYM (T₈) or lime (T₁₀) in combination with 100 per cent recommended dose of NPK increased the N uptake by maize crop significantly over rest of the treatments. The total N uptake in 100 per cent NPK + FYM and 100 per cent NPK + lime treated plots was 85.48 and 57.30 per cent higher over 100 per cent NPK, respectively. Hand weeding treatment (T₄) with total N uptake value of 112.31 kg ha⁻¹ was significantly superior over 100 per cent NPK. Treatments *viz.*, 50 per cent NPK, 100 per cent NPK, 150 per cent NPK and 100 per cent NPK + Zn were statistically alike. Omission of S (T₉) and K (T₆) led to 68.50 and 66.68 per cent reduction as compared to the 100 per cent NPK treatment.

Nutrient uptake is a function of yield and nutrient concentration in plant. Hence, the trend of nutrient uptake resembled very well with the yield of different treatments. The highest N uptake under balanced application of FYM and inorganic fertilizers might be due to the improvement in soil physical properties *viz.*, bulk density, porosity, soil structure and aggregates, and improvement in SOC concentration. Higher availability of native and applied nutrients, improved physiological and metabolic functions in plants which might be responsible for better uptake and yield in 100 per cent NPK + FYM treated plots (Manjhi et al. 2014). These findings are similar to those of Pathak et al. (2005), Kalhapure et al. (2014) and Chaudhary et al. (2017). Higher uptake of N in lime treated plots might be ascribed to

increased removal of N due to improvement in physical, chemical and biological environment of soil.

Table 4.12 Effect of long-term application of fertilizers and amendments on nitrogen uptake by maize

Treatment	Uptake (kg ha ⁻¹)		
	Grain	Stover	Total
T ₁ : 50% NPK	51.86	37.57	89.43
T ₂ : 100% NPK	55.64	38.33	93.97
T ₃ : 150% NPK	51.83	35.78	87.61
T ₄ : 100% NPK + HW	67.92	44.39	112.31
T ₅ : 100% NPK + Zn	53.60	36.04	89.64
T ₆ : 100% NP	18.09	13.22	31.31
T ₇ : 100% N	0.00	0.00	0.00
T ₈ : 100% NPK + FYM	99.91	74.39	174.30
T ₉ : 100% NPK (-S)	17.03	12.57	29.60
T ₁₀ : 100% NPK + lime	88.79	59.03	147.82
T ₁₁ : Control	9.40	5.35	14.75
CD (P=0.05)	11.01	11.68	14.16

As long-term application of N alone led to degradation of soil, the productivity in these plots (T₇) declined to zero, hence, no uptake was recorded. Continuous cropping without the use of nutrients led to poor crop growth in control plots (T₁₁) which resulted in low N uptake in these plots. Except 100 per cent N, higher N uptake by maize crop was recorded in rest of the treatments over control due to the supply of N through external inputs. Continuous omission of S (T₉) and K (T₆) from plant nutrition declined the crop yield drastically and thereby, resulted in marked reduction in N uptake by maize.

4.3.2.2 Phosphorus uptake

A cursory look into the data (Table 4.13) indicated that P uptake by maize grain varied from 1.54 in control to 23.79 kg ha⁻¹ in 100 per cent NPK + FYM. Significantly higher value of P uptake was recorded under 100 per cent NPK + FYM treatment over rest of the treatments. P uptake by maize grain in 100 per cent NPK + Zn, 100 per cent NPK, 150 per cent NPK and 50 per cent NPK was statistically alike. Control, 100 per cent NP and 100 per cent NPK (-S) treatments registered 83.89, 70.50 and 62.65 per cent reduction in P uptake by maize grain in comparison to 100 per cent NPK, respectively. The P uptake by maize grain recorded under 100 per cent NPK + HW (24.79 kg ha⁻¹) was significantly higher than 100 per cent NPK.

Table 4.13 Effect of long-term application of fertilizers and amendments on phosphorus uptake by maize

Treatment	Uptake (kg ha ⁻¹)		
	Grain	Stover	Total
T ₁ : 50% NPK	9.11	4.35	13.46
T ₂ : 100% NPK	9.56	4.58	14.14
T ₃ : 150% NPK	10.64	6.26	16.90
T ₄ : 100% NPK + HW	11.93	7.00	18.93
T ₅ : 100% NPK + Zn	8.50	4.17	12.67
T ₆ : 100% NP	2.82	2.36	5.18
T ₇ : 100% N	0.00	0.00	0.00
T ₈ : 100% NPK + FYM	23.79	11.36	35.15
T ₉ : 100% NPK (-S)	3.57	2.67	6.23
T ₁₀ : 100% NPK + lime	18.69	7.74	26.43
T ₁₁ : Control	1.54	0.55	2.09
CD (P=0.05)	6.74	1.31	3.01

In case of maize stover, the P uptake ranged from 0.55 in control to 11.36 kg ha⁻¹ in 100 per cent NPK + FYM treatment. As observed in case of maize grain, long-term application of FYM along with 100 per cent NPK (T₈) resulted in significantly higher P uptake by maize stover over rest of the treatments. The treatment *viz.*, 100 per cent NPK + HW recorded significantly higher P uptake (52.83%) than 100 per cent NPK. A significant reduction in P uptake was recorded under the treatments where either K (T₆) or S (T₉) were excluded from fertilization schedule in comparison to the treatment receiving balanced dose of fertilizers (T₂) without FYM, decrease being 48.47 and 41.70 per cent, respectively.

The total P uptake by maize varied from 2.09 in control to 35.15 kg ha⁻¹ in 100 per cent NPK + FYM treated plots. The treatment consisting of 100 per cent NPK + FYM and 100 per cent NPK + lime were significantly superior over other treatments. Control plots recorded the lowest value of total P uptake.

Higher P uptake with addition of FYM (T₈) might be due to improvement in soil physical properties such as improved soil structure, increased porosity and WHC and reduction in bulk density which in turn may have increased the ability of roots to move towards nutrient and the ability of water to move throughout the profile to supply nutrients to the root system. This may also be attributed to solubilization of native P and release of P during the mineralization of organic P (Sharma et al. 2016). Similar results have been reported by Dwivedi et al. (2007), Das et al. (2010) and Manjhi et al. (2014). The higher P uptake under 100 per cent NPK + lime might be ascribed to the rise in soil pH and precipitation of Al ions due to lime application and hence increased availability of P to the crop (Rajneesh et al. 2017). These results confirm the findings of Sathish et al. (2011), Sepat and Rai (2013) and Verde et al. (2018). Significantly higher P uptake under hand weeding treatment (T₄) might be due to higher organic carbon which encouraged better root and crop growth. Continuous cropping without addition of nutrients in control plots led to decreased P reserves in soil and poor crop growth which ultimately reduced the P uptake.

4.3.2.3 Potassium uptake

Potassium uptake by maize grain varied from 1.54 in control to 23.15 kg ha⁻¹ in 100 per cent NPK + FYM (Table 4.14). The increase in K uptake by maize grain

under 100 per cent NPK + FYM and 100 per cent NPK + lime was to the extent of 100.95 and 44.44 per cent respectively over 100 per cent NPK alone. The exclusion of K and S from fertilization schedule led to 70.65 and 72.74 per cent reduction in K uptake by maize grain in comparison to 100 per cent NPK, respectively.

Potassium uptake by maize stover ranged between 5.63 in control and 78.52 kg ha⁻¹ in 100 per cent NPK + FYM. Application of FYM along with balanced application of chemical fertilizers (T₈) recorded significant increase in K uptake over other treatments. Furthermore, application of lime as an amendment (T₁₀) recorded significantly higher K uptake than rest of the treatments except 100 per cent NPK + FYM.

Table 4.14 Effect of long-term application of fertilizers and amendments on potassium uptake by maize

Treatment	Uptake (kg ha ⁻¹)		
	Grain	Stover	Total
T ₁ : 50% NPK	11.01	38.87	49.88
T ₂ : 100% NPK	11.52	40.27	51.79
T ₃ : 150% NPK	12.33	40.50	52.83
T ₄ : 100% NPK + HW	12.87	48.91	61.78
T ₅ : 100% NPK + Zn	9.58	37.02	46.60
T ₆ : 100% NP	3.38	9.70	13.09
T ₇ : 100% N	0.00	0.00	0.00
T ₈ : 100% NPK + FYM	23.15	78.52	101.67
T ₉ : 100% NPK (-S)	3.14	12.40	15.54
T ₁₀ : 100% NPK + lime	16.64	62.90	79.54
T ₁₁ : Control	1.54	5.63	7.17
CD (P=0.05)	5.37	12.90	14.17

The highest value of total K uptake by maize crop ($101.67 \text{ kg ha}^{-1}$) was recorded in 100 per cent NPK + FYM, which was statistically superior over all other treatments, followed by 100 per cent NPK + lime (79.54 kg ha^{-1}). The trend of effect of different treatments on total K removal by maize was similar to that observed in case of K uptake in grain and stover. Application of 100 per cent NP (-K), 100 per cent NPK(-S) and control plots recorded significantly lower K uptake as compared to 100 per cent NPK.

The low uptake in control plots was the outcome of complete exhaustion of native nutrient pool of soil as a result of continuous nutrient removal by crops, or there was addition of nutrients from any external source. Exclusion of K (T_6) and S (T_9) from fertilization schedule resulted in low yield because of K and S deficiency and hence less K uptake was recorded in these treatments. Moreover, mining of native K reserves since last forty-nine years in the absence of K in 100 per cent NP treatment reduced the availability of K in soil and hence low uptake was recorded.

Sharma et al. (2014) and Chaudhary et al. (2017) also reported significant effect of K fertilization on K uptake by maize. Addition of FYM in conjunction with 100 per cent NPK resulted in the highest K uptake which could be attributed to the improvement in soil physical properties *viz.*, reduction in BD, increase in porosity, stable aggregates and improved structure which lead to easy mobility of water through soil profile and easy proliferation of roots leading to better crop growth. Furthermore, there was additional supply of K through FYM in addition to fertilizers. Similar effects of integrated use of fertilizers and manures on K uptake have earlier been reported by Pathak et al. (2005), Thakur et al. (2011) and Das et al. (2012). Positive influence of liming on K uptake might be attributed to the improved soil environment and subsequently higher crop yield.

4.3.2.4 Sulphur uptake

A critical examination of the data (Table 4.15) revealed that S uptake by maize grain varied from 0.51 to 16.75 kg ha^{-1} . The highest S uptake by maize grain was recorded under 100 per cent NPK + FYM (16.75 kg ha^{-1}), followed by 100 per cent NPK + lime (12.45 kg ha^{-1}) and the lowest was in control (0.51 kg ha^{-1}). Sulphur

uptake by maize grain in 100 per cent NPK (-S) was at par with control. Absence of S (T₉) from fertilization schedule resulted in significant decrease in S uptake by maize grain (73.71%) over to 100 per cent NPK. Graded doses of NPK resulted in increase in uptake of S, nevertheless, the increase was non-significant.

Sulphur uptake by maize stover varied from 0.55 in control to 13.42 kg ha⁻¹ in 100 per cent NPK + FYM. Addition of FYM along with 100 per cent NPK (T₈) resulted in 195.5 per cent increase in S uptake by maize stover over 100 per cent NPK alone. Whereas, use of lime as an amendment (T₁₀) increased the S uptake by 70.70 per cent over 100 per cent NPK alone. Use of S-free fertilizers in 100 per cent NPK (-S) significantly decreased the S uptake by maize stover (59.69 %) in comparison to 100 per cent NPK.

Total S uptake by maize crop ranged from 1.06 in control to 30.17 kg ha⁻¹ in 100 per cent NPK + FYM. The total S uptake by maize crop recorded under 100 per cent NPK + FYM was significantly higher (165.5 %) than 100 per cent NPK. The total S uptake recorded in control plots was numerically lower than 100 per cent NPK (-S).

Lower S uptake in plots under 100 per cent NPK (-S) and control might be due to the depletion of S reserves in soil under intensive cropping over the years in absence of addition of sulphur from any external source (Sime and Ram 2012; Das et al. 2012; Kundu et al. 2016). An increase in S uptake was recorded in plots under 100 per cent NP treatment over control and 100 per cent NPK (-S) which might be ascribed to the addition of S through SSP and also the synergistic interaction between P and S (Islam et al. 2006). FYM application in combination with 100 per cent NPK brought about a significant increase in S uptake over 100 per cent NPK which could be due to the addition of organic matter and beneficial effects of FYM on soil physical properties which improved soil structure, aggregation, water infiltration, storage, decomposition and nutrient release.

Table 4.15 Effect of long-term application of fertilizers and amendments on sulphur uptake by maize

Treatment	Uptake (kg ha ⁻¹)		
	Grain	Stover	Total
T ₁ : 50% NPK	5.33	2.89	8.22
T ₂ : 100% NPK	6.81	4.54	11.36
T ₃ : 150% NPK	7.33	3.64	10.98
T ₄ : 100% NPK + HW	9.11	6.14	15.24
T ₅ : 100% NPK + Zn	5.87	4.39	10.25
T ₆ : 100% NP	2.06	1.26	3.33
T ₇ : 100% N	0.00	0.00	0.00
T ₈ : 100% NPK + FYM	16.75	13.42	30.17
T ₉ : 100% NPK (-S)	1.79	1.83	3.62
T ₁₀ : 100% NPK + lime	12.45	7.75	20.20
T ₁₁ : Control	0.51	0.55	1.06
CD (P=0.05)	4.01	1.25	2.21

Soil with higher organic matter acts like a sponge holding more water and nutrients. It could also be attributed to the addition S and other nutrients through FYM and improvement in soil conditions which might have had positive effect on root development (Arisha et al. 2003). Lime application (T₁₀) reduced the soil acidity, increased the nutrient availability and hence recorded the higher yield and uptake.

4.3.2.5 Calcium uptake

A perusal of the data (Table 4.16) revealed that Ca uptake by maize grain varied from 1.21 in control to 13.87 kg ha⁻¹ in lime amended plots (T₁₀). The calcium uptake in 100 per cent NPK + lime (T₁₀) was at par with 100 per cent NPK + FYM. Addition of either FYM (T₈) or lime (T₁₀) along with recommended dose of NPK increased the Ca uptake by maize grain to the extent of 111.7 and 135.8 per cent over

100 per cent NPK, respectively. Graded doses of NPK were statistically at par with each other. Application of 100 per cent NP was at par with control.

The data further revealed that Ca uptake by maize stover varied from 2.62 to 46.52 kg ha⁻¹. The plots under 100 per cent NPK + lime recorded highest Ca uptake by maize stover (46.52 kg ha⁻¹) which was at par with 100 per cent NPK + FYM (39.57 kg ha⁻¹).

Table 4.16 Effect of long-term application of fertilizers and amendments on calcium uptake by maize

Treatment	Uptake (kg ha ⁻¹)		
	Grain	Stover	Total
T ₁ : 50% NPK	4.89	21.08	25.97
T ₂ : 100% NPK	5.88	22.49	28.37
T ₃ : 150% NPK	5.29	21.47	26.76
T ₄ : 100% NPK + HW	7.06	28.09	35.15
T ₅ : 100% NPK + Zn	5.48	21.52	27.00
T ₆ : 100% NP	1.37	6.69	8.06
T ₇ : 100% N	0.00	0.00	0.00
T ₈ : 100% NPK + FYM	12.45	39.57	52.02
T ₉ : 100% NPK (-S)	1.10	6.15	7.25
T ₁₀ : 100% NPK + lime	13.87	46.52	59.40
T ₁₁ : Control	1.21	2.62	3.83
CD (P=0.05)	3.37	8.70	3.27

In case of total Ca uptake, the minimum value (3.83 kg ha⁻¹) was recorded in control plots, whereas, maximum value (59.40) was recorded in 100 per cent NPK + lime plots. Hand weeded plots (T₄) registered an increase of 23.89 per cent in total Ca uptake over 100 per cent NPK.

Very low Ca uptake in control plots could be attributed to continuous removal of all the essential nutrients including Ca under intensive cropping from these plots without addition of nutrients from any external source which led to the decline in the soil fertility in these plots. Other treatments registered an increase in the Ca uptake by maize crop over control due to the addition of Ca through SSP, which was used as a source of P. The plots under 100 per cent NPK + lime recorded significantly highest Ca uptake over 100 per cent NPK because lime itself is a source of Ca and also, it raised the soil pH towards neutrality, that resulted in increased Ca availability to the crop. The application of FYM along with 100 per cent NPK (T₈) recorded higher Ca uptake in maize crop which might be attributed to the improved synchronization between release of nutrients and their uptake in plants. Kumar et al. (2009) also reported encouraging effects of liming and FYM application on Ca uptake.

It may also be possible due to improvement in soil structure, aggregation, water infiltration, storage, decomposition, and nutrient release by adding organic matter and taking advantage of beneficial impacts of FYM on soil physical qualities. As the higher organic matter in soil behaves like a sponge, able to hold more nutrients and water.

4.3.2.6 Magnesium uptake

The data on Mg uptake by maize as affected by the long-term application of fertilizers and amendments have been presented in table 4.17. A perusal of data revealed that Mg uptake by maize grains ranged from 0.57 kg ha⁻¹ in control (T₁₁) to 8.88 kg ha⁻¹ in 100 per cent NPK + FYM (T₈). Magnesium uptake by maize grain in FYM (T₈) and lime amended (T₁₀) plots was significantly higher over all other treatments under study. Graded doses of fertilizers (T₁ to T₃) and 100 per cent NPK + Zn (T₅) were statistically at par with each other.

Magnesium uptake by maize stover varied from 0.81 kg ha⁻¹ in control (T₁₁) to 11.48 kg ha⁻¹ in the plots receiving FYM along with 100 per cent NPK (T₈). Lime (T₁₀) and FYM amended plots (T₈) recorded significant increase in Mg uptake as compared to rest of the treatments. Graded doses of fertilizer from 50 to 150 per cent NPK resulted in Mg uptake of 5.78, 5.51 and 6.13 kg ha⁻¹, respectively, and these were statistically alike.

Further glance at the data indicated that total Mg uptake by maize varied from 1.38 kg ha⁻¹ in control plot to 20.37 kg ha⁻¹ under FYM amended plots. Total Mg uptake in 100 per cent NPK was statistically at par with sub optimal and super optimal dose of fertilizers. Further, the total Mg uptake in 100 per cent NP and 100 per cent NPK (-S) was 2.72 and 2.91 kg ha⁻¹, respectively, which were significantly lower than 100 per cent NPK.

Table 4.17 Effect of long-term application of fertilizers and amendments on magnesium uptake by maize

Treatment	Uptake (kg ha ⁻¹)		
	Grain	Stover	Total
T ₁ : 50% NPK	3.80	5.78	9.58
T ₂ : 100% NPK	3.89	5.51	9.40
T ₃ : 150% NPK	4.60	6.13	10.73
T ₄ : 100% NPK + HW	5.34	6.35	11.69
T ₅ : 100% NPK + Zn	3.54	4.45	7.99
T ₆ : 100% NP	1.26	1.46	2.72
T ₇ : 100% N	0.00	0.00	0.00
T ₈ : 100% NPK + FYM	8.88	11.48	20.37
T ₉ : 100% NPK (-S)	1.30	1.60	2.91
T ₁₀ : 100% NPK + lime	7.79	9.30	17.09
T ₁₁ : Control	0.57	0.81	1.38
CD (P=0.05)	1.06	1.09	1.34

Control plot resulted in lower total Mg uptake. This could be attributed to low yields as continuous cropping without any external inputs might have decreased the native Mg supply. Application of FYM along with NPK recorded the highest Mg uptake which might be due to the improvement in soil physical characteristics, such as improved soil structure, increased porosity, WHC, and decreased BD, which in

turn might have increased the ability of roots to move toward nutrients and the ability of water to move throughout the profile to deliver nutrients to the root system, the favourable conditions for crop growth in these plots and supply of macro and micronutrients through FYM in addition to chemical fertilizers. With the application of lime, the increase in Mg uptake might be ascribed to the liming effect which raised the pH of soil as pH has a direct effect on soil nutrient availability. Magnesium uptake in 100 per cent N (T₇) was zero as long-term application of N alone has led to degradation of soil and the productivity in these plots has declined to zero. The application of FYM along with recommended NPK (T₈) resulted in the highest Mg uptake by maize crop which could be attributed to increased exchangeable Mg content of soil due to release of Mg from added FYM. Also, organic acids released after the decomposition of organic matter might have released Mg from exchangeable sites thus increased the Mg availability to the crop (Kumar 2014). Improved Mg uptake under 100 per cent NPK + lime treatment might be attributed to increased biomass production, addition of Mg to the soil by lime application and amelioration of soil acidity (Kumar et al. 2009; Shambhavi et al. 2018).

4.3.2.7 Iron uptake

The data in table 4.18 clearly indicated that Fe uptake by maize grain ranged from 34.4 to 507.5 g ha⁻¹. The Fe uptake recorded in FYM amended plots (T₈) was significantly higher than other treatments. The treatment consisting 100 per cent NPK + HW was found to be significantly superior over 100 per cent NPK in terms of Fe uptake by maize grain, the increase being 21.9 per cent. Imbalanced use of fertilizers (T₆ and T₉) recorded significantly lesser Fe uptake by maize grain in comparison to balanced fertilizer application (T₂).

Further examination of the data (Table 4.18) revealed that Fe uptake by maize stover varied from 126.1 in control to 1942.6 g ha⁻¹ in 100 per cent NPK + FYM. Addition of FYM increased the Fe uptake by maize stover by 72.18 per cent, whereas, lime application improved the Fe uptake by 32.10 per cent over sole use of 100 per cent NPK. Kher and Minhas (1991) and Ghosh et al. (2001) reported similar findings.

It is evident from the data that the total Fe uptake by maize crop followed the same trend as maize grain and stover. The lowest uptake (160.5 g ha^{-1}) was recorded in control and the highest (2450.1 g ha^{-1}) was recorded in 100 per cent NPK + FYM, followed by 100 per cent NPK + lime (1880.9 g ha^{-1}). The treatments consisting of 50 per cent, 150 per cent NPK and 100 per cent NPK + Zn were at par. Manually weeded plots (T₄) recorded significantly higher Fe uptake than 100 per cent NPK. Significant reduction in total Fe uptake was recorded under 100 per cent NP and 100 per cent NPK (-S) treatments over 100 per cent NPK.

Table 4.18 Effect of long-term application of fertilizers and amendments on iron uptake by maize

Treatment	Uptake (g ha^{-1})		
	Grain	Stover	Total
T ₁ : 50% NPK	244.4	859.9	1104.3
T ₂ : 100% NPK	275.5	1128.2	1403.8
T ₃ : 150% NPK	258.0	970.0	1228.0
T ₄ : 100% NPK + HW	336.1	1174.1	1510.2
T ₅ : 100% NPK + Zn	266.0	932.9	1198.9
T ₆ : 100% NP	80.5	315.4	395.9
T ₇ : 100% N	0.0	0.0	0.0
T ₈ : 100% NPK + FYM	507.5	1942.6	2450.1
T ₉ : 100% NPK (-S)	79.1	294.4	373.5
T ₁₀ : 100% NPK + lime	390.5	1490.4	1880.9
T ₁₁ : Control	34.4	126.1	160.5
CD (P=0.05)	41.3	113.6	170.9

Low values of Fe uptake were recorded in the treatments in which low biomass yield was recorded. Significant increase in Fe uptake by maize crop with the application of recommended NPK dose could be ascribed to better development of

root system under balanced nutrient application, hence resulting in more absorption of water and nutrients. The increased uptake of Fe due to FYM application is probably due to the role of organic matter in supplying micronutrients and improvement in soil health (Dadhich and Somani 2007).

4.3.2.8 Manganese uptake

Table 4.19 presents data with respect to the Mn uptake by maize (*kharif* 2021). The Mn uptake in maize grain is 23.3 g ha⁻¹ in control and 329.1 g ha⁻¹ under 100 per cent NPK + FYM, respectively. Addition of organic manure along with recommended NPK (T₈) increased the Mn uptake by maize grain and stover by 82.6 and 107.1 per cent over 100 per cent NPK, respectively. Manganese uptake by maize grain and stover was recorded lowest in control, apart from zero uptake under 100 per cent N.

Table 4.19 Effect of long-term application of fertilizers and amendments on manganese uptake by maize

Treatment	Uptake (g ha ⁻¹)		
	Grain	Stover	Total
T ₁ : 50% NPK	165.9	412.9	578.9
T ₂ : 100% NPK	180.2	435.8	616.0
T ₃ : 150% NPK	173.9	415.0	588.9
T ₄ : 100% NPK + HW	228.5	551.2	779.7
T ₅ : 100% NPK + Zn	194.9	478.2	673.1
T ₆ : 100% NP	58.2	146.7	204.9
T ₇ : 100% N	0.0	0.0	0.0
T ₈ : 100% NPK + FYM	329.1	902.4	1231.5
T ₉ : 100% NPK (-S)	53.9	144.1	198.0
T ₁₀ : 100% NPK + lime	275.6	728.2	1003.8
T ₁₁ : Control	23.3	54.1	77.4
CD (P=0.05)	23.7	53.1	117.2

Further study of the data revealed that the highest total Mn uptake (1231.5 g ha⁻¹) by maize was recorded in plots receiving 100 per cent NPK + FYM, followed by 100 per cent NPK + lime and 100 per cent NPK + HW. Application of 100 per cent NPK + FYM recorded significantly higher Mn uptake over rest of the treatments.

The higher Mn uptake recorded under 100 per cent NPK + FYM could be ascribed to improvements in soil physical attributes, such as decrease in BD, increase in porosity, stable aggregates, and enhanced structure, which allow for easier water movement through the soil profile and easier root growth, leading to greater crop growth and nutrient uptake. The release of micronutrients during decomposition of FYM into the soil solution, chelation of micronutrients to prevent their losses and prolific root growth resulting in better nutrient uptake. Das et al. (2012), Thangasamy et al. (2017) and Shambhavi et al. (2018) reported similar findings. Higher Mn uptake in lime treated plots (T₁₀) and those under hand weeding (T₄) was possibly due to high organic matter content and better nutrient availability in these plots leading to increased biomass production and higher uptake over 100 per cent NPK.

4.3.2.9 Zinc uptake

The data recorded on the effect of long-term application of fertilizers and amendments on Zn removal by maize (grain, stover and total) have been presented in table 4.20. Zinc uptake by maize grain ranged from 14.2 in control to 208.9 g ha⁻¹ in 100 per cent NPK + FYM. The highest Zn uptake by maize grain was recorded under 100 per cent NPK + FYM (208.9 g ha⁻¹) followed by 100 per cent NPK + Zn (173.1 g ha⁻¹). Application of either FYM (T₈) and Zn (T₅) with recommended NPK dose increased the Zn uptake by maize grain by 95.4 and 61.9 per cent over sole use of 100 per cent NPK. The control plots recorded lowest uptake (14.2 g ha⁻¹), while 100 per cent NP (-K) and 100 per cent NPK (-S) were at par with control.

In case of maize stover, Zn uptake varied from 33.9 in control to 445.8 g ha⁻¹ in 100 per cent NPK + FYM. Application of 100 per cent NPK + FYM was significantly superior over all other treatments but at par with 100 per cent NPK + Zn (436.5 g ha⁻¹) and 100 per cent NPK + lime (422.0 g ha⁻¹).

The data in table 4.20 also depicted that total Zn uptake by maize ranged from 48.1 in control to 654.7 g ha⁻¹ in 100 per cent NPK + FYM. Application of FYM

along with recommended dose of NPK recorded significantly higher Zn uptake over rest of the treatments. The treatments comprising 100 per cent NPK + Zn and 100 per cent NPK + lime were at par. Deletion of either K (T₆) or S (T₉) from fertilization schedule decreased the Zn uptake by 70.5 and 69.2 per cent, respectively, in comparison to the balanced fertilization (T₂).

Table 4.20 Effect of long-term application of fertilizers and amendments on zinc uptake by maize

Treatment	Uptake (g ha ⁻¹)		
	Grain	Stover	Total
T ₁ : 50% NPK	102.8	259.3	362.1
T ₂ : 100% NPK	106.9	277.2	384.1
T ₃ : 150% NPK	105.9	259.4	365.3
T ₄ : 100% NPK + HW	134.0	334.7	468.7
T ₅ : 100% NPK + Zn	173.1	436.5	619.6
T ₆ : 100% NP	31.3	82.0	113.3
T ₇ : 100% N	0.0	0.0	0.0
T ₈ : 100% NPK + FYM	208.9	445.8	654.7
T ₉ : 100% NPK (-S)	30.9	87.2	118.1
T ₁₀ : 100% NPK + lime	172.5	422.0	594.5
T ₁₁ : Control	14.2	33.9	48.1
CD (P=0.05)	29.1	57.3	64.4

The highest Zn uptake by maize crop in 100 per cent NPK + FYM could be attributed to the improvement of soil physical properties, specifically a reduction in BD, enhanced porosity, stable aggregates, and improved structure that allowed for easy water movement through the soil profile and easy root multiplication, ultimately, that resulted in better crop growth and nutrient uptake and the release of micronutrient from FYM and increased biomass yield of maize. Furthermore, FYM application might have increased the availability of native micronutrients through chelation (Gupta 1995). These results are in conformity with those of Das et al.

(2012), Thangasamy et al. (2017) and Shambhavi et al. (2018). Significantly higher Zn uptake by maize was recorded in 100 per cent NPK + Zn plots possibly due to marked increase in available Zn content after the addition of Zn fertilizers.

4.3.2.10 Copper uptake

A detailed examination of the data (Table 4.21) revealed that Cu uptake in maize grain varied from 12.2 in control to 209.6 g ha⁻¹ in 100 per cent NPK + FYM. The Cu uptake by grain in the treatment comprising 100 per cent NPK + FYM and 100 per cent NPK + lime was significantly higher than other treatments. Compared to 100 per cent NPK, 100 per cent NPK + FYM treatment recorded higher Cu uptake. Lime amendment along with application of recommended NPK recorded 77.2 per cent higher Cu uptake by maize grain than 100 per cent NPK. Graded doses of NPK (T₁, T₂, and T₃) were statistically at par.

Table 4.21 Effect of long-term application of fertilizers and amendments on copper uptake by maize

Treatment	Uptake (g ha ⁻¹)		
	Grain	Stover	Total
T ₁ : 50% NPK	89.5	198.8	288.3
T ₂ : 100% NPK	97.4	244.4	341.8
T ₃ : 150% NPK	96.6	240.1	336.7
T ₄ : 100% NPK + HW	129.3	328.7	458.0
T ₅ : 100% NPK + Zn	97.0	227.7	324.7
T ₆ : 100% NP	33.2	72.7	105.9
T ₇ : 100% N	0.0	0.0	0.0
T ₈ : 100% NPK + FYM	209.6	535.0	744.6
T ₉ : 100% NPK (-S)	29.9	65.6	95.5
T ₁₀ : 100% NPK + lime	172.6	403.9	576.5
T ₁₁ : Control	12.2	36.0	48.2
CD (P=0.05)	16.8	34.7	39.2

Regarding the Cu uptake by maize stover, the values ranged between 36.0 g ha⁻¹ in control and 535.0 g ha⁻¹ in 100 per cent NPK + FYM. The treatments comprising 100 per cent NPK + FYM, 100 per cent NPK + lime and 100 per cent NPK + HW recorded significantly higher Cu uptake than 100 per cent NPK. Total Cu uptake by maize ranged from 48.2 g ha⁻¹ in control to 744.6 g ha⁻¹ in 100 per cent NPK + FYM. Treatment wise trend of total Cu uptake was similar to that of grain and stover.

Higher Cu uptake in treatment 100 per cent NPK + FYM could be ascribed to improvement in soil's physical attributes, such as reduction in bulk density, improvement in porosity, mean weight diameter, infiltration rate, stable aggregates and an enhanced structure, which allowed for easier water movement through the soil profile and easier root growth, leading to greater crop growth and the highest nutrient uptake.

Depletion of inherent fertility of soil under intensive cropping might be the reason behind poor biomass productivity and low Cu uptake in control plots. Balanced use of NPK either alone or in combination with FYM or lime recorded higher Cu uptake over control because of the higher soil nutrient status thus resulting in increased productivity and Cu uptake. FYM amended plots (T₈) recorded the highest Cu uptake, which could be ascribed to the release of micronutrient cations after organic matter decomposition, increased nutrient availability to plants and increased biomass production (Ghosh et al. 2001; Das et al. 2012; Thangasamy et al. 2017).

4.4 Relationship of soil physical properties with crop yield and nutrient uptake

The relationships of various physical properties with crop yield and nutrient uptake were worked out through simple correlation. The data on coefficient of correlation between soil physical properties with maize yield and nutrient uptake have been presented in table 4.22 and 4.24 and have been described in this section.

4.4.1 Relationship of soil physical properties with nutrient uptake

A cursory look into the data presented in table 4.24 indicated that all soil physical properties correlated significantly with nutrient uptake. Among different soil physical properties, porosity, MWD, WHC, water stable aggregates, SHC and plasticity index correlated significantly and positively with N, P, K, S, Ca, Mg, Fe,

Mn, Cu and Zn uptake, whereas, BD was negatively correlated. The highest correlation coefficient was recorded with WHC in case of Mn ($r = 0.920^{**}$) and lowest with S ($r = 0.795^{**}$). In case of porosity, the highest correlation coefficient was recorded with N ($r = 0.755^{**}$) and lowest with S ($r = 0.582^{**}$). In case of MWD, the highest correlation coefficient was recorded with Cu ($r = 0.895^{**}$) and the lowest with Zn ($r = 0.787^{**}$).

Water stable aggregates, the highest correlation coefficient was recorded with Mn ($r = 0.880^{**}$) and the lowest with S ($r = 0.778^{**}$). In case of SHC, the highest correlation coefficient was recorded with Cu ($r = 0.860^{**}$) and the lowest with Zn ($r = 0.793^{**}$), the plasticity index showed the highest correlation coefficient with Cu ($r = 0.463^{**}$) and the lowest with Ca ($r = 0.355^{**}$).

Table 4.22 Relationship of soil physical properties with nutrient uptake

Parameters	N	P	K	S	Ca	Mg	Fe	Mn	Cu	Zn
BD	-0.826**	-0.782**	-0.814**	-0.667**	-0.690**	-0.784**	-0.834**	-0.834**	-0.799**	-0.795**
Porosity	0.755**	0.653**	0.708**	0.582	0.655**	0.691**	0.739**	0.741**	0.716**	0.726**
MWD	0.860**	0.867**	0.848**	0.868	0.835**	0.883**	0.866**	0.870**	0.895**	0.787**
WHC	0.907**	0.829**	0.878**	0.795	0.839**	0.887**	0.909**	0.920**	0.913**	0.853**
WSA	0.875**	0.836**	0.856**	0.778	0.818**	0.866**	0.875**	0.880**	0.873**	0.836**
SHC	0.822**	0.835**	0.821**	0.843	0.801**	0.848**	0.841**	0.839**	0.860**	0.793**
Plasticity index	0.435*	0.378*	0.382*	0.371*	0.355*	0.410*	0.431*	0.448**	0.463**	0.394*

4.4.2 Relationship of soil physical properties with maize yield

A cursory look into the data presented in table 4.22 indicated that all soil physical properties of surface layer (0-0.15 m) correlated significantly with maize grain and stover yield. Among different physical soil properties, porosity, mean weight diameter, water holding capacity, water stable aggregates, saturated hydraulic conductivity and plasticity index correlated significantly and positively with grain yield ($r = 0.744^{**}$, $r = 0.809^{**}$, $r = 0.915^{**}$, $r = 0.863^{**}$, $r = 0.768^{**}$ and $r = 0.395^{**}$ respectively), whereas, bulk density was negatively correlated $r = (-0.834^{**})$. The highest correlation coefficient of maize stover yield was recorded with water holding capacity ($r = 0.916^{**}$) followed by water stable aggregates ($r = 0.862^{**}$) and negative coefficient of correlation was found with bulk density having 'r' value of -0.839^{**} . A negative correlation between bulk density and yield has been reported earlier by Aragon et al. (2000); Nandapure et al. (2011) and Singh et al. (2017).

Table 4.23 Relationship of soil physical properties and maize yield (0-0.15 m)

Parameters	Grain Yield	Stover Yield
Bulk density	-0.834 ^{**}	-0.839 ^{**}
Porosity	0.744 ^{**}	0.747 ^{**}
MWD	0.809 ^{**}	0.800 ^{**}
WHC	0.915 ^{**}	0.916 ^{**}
WSA	0.863 ^{**}	0.862 ^{**}
SHC	0.768 ^{**}	0.761 ^{**}
Plasticity Index	0.395 ^{**}	0.391 ^{**}

* Significant at 5 per cent level of significance

** Significant at 1 per cent level of significance

Similar pattern was followed in the sub-surface layer (0.15-0.30 m). All soil physical properties of sub-surface layer were correlated significantly with maize grain and stover yield. The highest positive correlation coefficient of maize grain and stover yield was recorded with water holding capacity ($r = 0.910^{**}$ and $r = 0.909^{**}$) followed by water stable aggregates ($r = 0.862^{**}$ and $r = 0.861^{**}$) and negative coefficient of correlation was found with BD having 'r' value of -0.876^{**} and ' $r = -0.880^{**}$ '.

Table 4.24 Relationship of soil physical properties and maize yield (0.15–0.30 m)

Parameters	Grain Yield	Stover Yield
Bulk density	-0.876^{**}	-0.880^{**}
Porosity	0.810^{**}	0.815^{**}
MWD	0.848^{**}	0.842^{**}
WHC	0.910^{**}	0.909^{**}
WSA	0.862^{**}	0.861^{**}
SHC	0.748^{**}	0.745^{**}
Plasticity Index	0.620^{**}	0.621^{**}

* Significant at 5 per cent level of significance

** Significant at 1 per cent level of significance

5. SUMMARY AND CONCLUSIONS

The present study entitled “**Effect of long-term application of fertilizers and amendments on soil physical quality and crop productivity in an acid Alfisol**” was carried out on maize crop (*khariif* 2021) in an on-going “Long-term Fertilizer Experiment” which was in operation since *rabi* 1972-73 at the experimental farm of Department of Soil Science, College of Agriculture, CSK Himachal Pradesh Krishi Vishvavidyalaya, Palampur. The experiment was laid in randomized block design with eleven treatments replicated thrice. The objectives of the study were:

1. To evaluate the effect of fertilizers and amendments on soil physical properties and crop productivity and
2. to work out the relationships of soil physical properties with crop yield and nutrient uptake.

The soils of the experimental site have been taxonomically classified as “*Typic Hapludalf*” (Sub-Group). The soil was acidic in reaction with a pH value of 5.8 at the start of the experiment in *rabi* 1972. Soil samples were collected after maize (*khariif*, 2021) harvest from the surface (0-0.15 m) and subsurface (0.15-0.30 m) layers from each plot. Soil samples were analyzed for various physical and chemical parameters using standard methods. The grain and stover yield of maize was recorded after the crop harvest. The concentration of nutrients (N, P, K, Ca, Mg, S, Fe, Mn, Zn and Cu) was determined in grain and stover samples of maize and their uptake was calculated. Relationship of soil physical properties with maize yield and nutrient uptake was worked out through simple correlation analysis. The salient findings that emerged from the present investigation are summarized as under:

5.1 Effect of fertilizers and amendments on soil physical properties

5.1.1 Bulk density

- In surface layer (0-0.15 m), the lowest BD (1.21 Mg m^{-3}) was recorded under 100 per cent NPK + FYM treatment and the highest (1.40 Mg m^{-3}) was recorded under 100 per cent N treatment. The respective values in sub surface

layer (0.15-0.30 m) were 1.23 Mg m^{-3} and 1.42 Mg m^{-3} . In general, BD of soil increased with increase in soil depth.

5.1.2 Particle density

- Particle density varied from 2.38 to 2.42 Mg m^{-3} in the surface and 2.39 Mg m^{-3} to 2.44 Mg m^{-3} in the sub-surface soil layer. However, continuous use of chemical fertilizers and amendments did not affect the PD significantly.

5.1.3 Porosity

- The highest value of soil porosity (49.44%) in surface layer (0-0.15 m) was recorded under 100 per cent NPK + FYM and the lowest (42.27%) was under 100 per cent N treatment. Similarly, in sub-surface layer, 100 per cent NPK + FYM treatment recorded the highest value (48.89%) and the lowest (41.66%) value was recorded under 100 per cent N treatment.

5.1.4 Water holding capacity

- The highest value of WHC (60.02 %) was recorded under 100 per cent NPK + FYM, which was at par with 100 per cent NPK + lime (59.63%). Application of 100 per cent N alone recorded the lowest WHC (48.84%). Furthermore, WHC decreased with increase in soil depth.

5.1.5 Saturated hydraulic conductivity

- The highest value of SHC (5.46 cm hr^{-1}) was recorded in treatment 100 per cent NPK+ FYM, followed by 100 per cent NPK+ Lime (4.14 cm hr^{-1}). Application of 100 per cent N alone recorded the lowest SHC (2.52 cm hr^{-1}). Saturated hydraulic conductivity decreased with increase in soil depth.

5.1.6 Mean weight diameter

- In surface layer (0-0.15 m), maximum MWD (4.89 mm) was recorded under 100 per cent NPK + FYM treatment and the minimum (0.92 mm) was recorded under 100 per cent N treatment. The respective values in sub surface layer (0.15-0.30 m) were 3.82 mm and 0.81 mm. In general, MWD of soil decreased with increase in soil depth.

5.1.7 Atterberg's limit

- All the soil consistency limits, viz., liquid limit, plastic limit and plasticity index were affected significantly by the continuous application of fertilizers and amendments. In surface layer (0-0.15 m), the moisture content, maximum and minimum at liquid limit, plastic limit and plasticity index varied from 42.4, 30.7 and 11.6 under 100 per cent NPK + FYM treatment to 32.1, 22.6 and 9.5 under 100 per cent N treatment alone, respectively. The highest plasticity index recorded under 100 per cent NPK + FYM (11.6) was at par with 100 per cent NPK + HW (10.7). Atterberg's limit decreased with increase in soil depth.

5.1.8 Water stable aggregates

- In surface layer (0-0.15 m), the treatment 100 per cent NPK + FYM recorded significantly higher percentage (91.93) of total WSA and 100 per cent N treatment recorded the lowest (63.55). In general, there was significant decrease in WSA with the increase in the depth.

5.1.9 Infiltration rate

- The infiltration rate and cumulative infiltration was recorded maximum under of 100 per cent NPK + FYM and minimum under 100 per cent N treatment.

5.2 Effect of fertilizers and amendments on soil chemical properties

5.2.1 Cation Exchange Capacity

- The CEC in the surface layer (0–0.15 m) ranged from a minimum value of 6.20 c mol (p+) kg⁻¹ under 100 per cent N to a maximum value of 12.39 c mol (p+) kg⁻¹ under 100 per cent NPK + FYM. CEC decreased with increase in soil depth.

5.2.2 Soil organic carbon

- The highest value of SOC (13.97 g kg⁻¹) was recorded under 100 per cent NPK + FYM treatment and the lowest (7.75 g kg⁻¹) under control. Application of 100 per cent NPK + lime and 100 per cent NPK with hand weeding recorded significantly higher organic carbon content than 100 per cent NPK

alone. Soil organic carbon content in sub surface layer was lower than the surface layer.

5.3 Effect of continuous use of fertilizers and amendments on nutrient uptake and productivity of maize

- Combined application of FYM and recommended dose of NPK (T_8) recorded the highest maize grain (64.02 q ha^{-1}) and stover (103.21 q ha^{-1}) yield which was at par with 100 per cent NPK + lime with grain and stover yield of 59.87 and 96.66 q ha^{-1} , respectively.
- Hand weeding along with 100 per cent NPK (T_4) recorded significantly higher (19.7%) grain yield over chemical weed control (T_2).
- 100 per cent NPK + FYM recorded significantly higher grain and stover yield of maize by 63.19 and 59.59 per cent, respectively, in comparison to balanced fertilization (T_2).
- Omission of S {100 % NPK (-S)} and K (100 % NP) reduced the grain yield of maize by 63.4 and 61.4 per cent, respectively, in comparison to balanced fertilization (T_2).
- Continuous application of fertilizers and amendments significantly influenced the nutrient uptake by maize crop (N, P, K, Ca, Mg, S, Fe, Mn, Cu and Zn) and followed almost similar trend as that of yield. In general use of FYM (T_8) or lime (T_{10}) along with recommended dose of chemical fertilizers recorded significantly higher uptake as compared to rest of the treatments.
- Continuous application of 100 per cent N alone had the most deleterious effect on maize productivity and led to nil productivity. Apart from this, maize productivity was lowest under control treatment.

5.4 Relationship of soil physical properties with nutrient uptake and maize yield

- A positive and significant correlation was found between different soil physical properties (porosity, MWD, WHC, WSA, SHC and plasticity index) with uptake of nutrients (N, P, K, S, Ca, Mg, Fe, Mn) except for BD. Bulk density was found to be negatively and significantly correlated with nutrient uptake.

- A positive and significant correlation was found between different soil physical properties (porosity, MWD, WHC, WSA, SHC and plasticity index) with grain and stover yield of maize except BD. Bulk density was found to be negatively and significantly correlated with maize grain and stover yield.

Conclusions:

- Balanced fertilization along with FYM improved the soil physical properties (BD, porosity, MWD, WHC, WSA, SHC, infiltration rate and Atterberg's limit).
- Imbalanced use of fertilizers (100% N, 100% NP, 100% NPK (-S)) had the most deleterious effect on maize productivity and soil physical properties.
- Nutrient uptake (N, P, K, S, Ca, Mg, Fe, Mn, Zn and Cu) by maize was also significantly influenced by the application of fertilizers and amendments.
- Integrated use of inorganic fertilizers and manure enhanced the productivity of maize significantly.
- The soil was rendered almost barren (zero yield) with the sole use of N because of the deleterious effect of continuous use of urea which ultimately resulted in zero nutrient uptake.
- Different soil physical parameters *viz.*, porosity, MWD, WHC, WSA, SHC and plasticity index showed a positive and significant correlation, while, BD showed a negative and significant correlation with grain and stover yield as well as nutrient uptake by maize.

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APPENDIX

Appendix –I

Mean weekly rainfall, air temperature, sunshine hours and relative humidity during the crop period (June 2021 to October 2021)

Standard week	Rainfall (mm)	Temperature (⁰ C)		Sunshine Hours (hr day ⁻¹)	Relative Humidity (%)	
		Max.	Min.		RH 1	RH 2
24	77.8	27.4	17.3	6.2	84.3	67.1
25	9.2	28.6	18.6	8.6	73.9	63.6
26	6.2	30.5	19.4	9.6	68.9	51.1
27	62.2	31.1	19.4	8.7	74.7	52.7
28	559	27.8	18.8	4.9	93	75.9
29	281.8	26.2	20.2	2.1	96.1	88.1
30	174.4	25.9	20.8	1.3	97.6	91
31	89.2	27.5	20	3.9	94.4	83.1
32	85.6	27.1	19.3	4.1	90.6	85.4
33	45	27.6	18.6	6.6	87.9	80.6
34	66.4	25.5	20.5	2	92.6	88.9
35	80.4	26.5	18.3	5	93	82
36	180.6	26.4	19	3	96.3	85.1
37	85.2	25.5	18.2	4	93.1	87
38	86.4	26.5	18.9	4.6	94.9	83.4
39	29.8	26.7	17.9	4.4	85.9	84.7
40	55	25.9	16.5	4.9	88.7	77.9
41	15	26.8	14.9	8.4	73	55.3

Appendix –II

Mean monthly rainfall (mm), air temperature (°C) and open pan evaporation (mm) for the period 1974-2020

Month	Rainfall	Temperature		Open pan evaporation
		Maximum	Minimum	
January	94.2 ± 69.7	15.2 ± 1.4	4.8 ± 0.9	41.1 ± 8.7
February	103.5 ± 70.1	16.7 ± 1.9	6.4 ± 1.3	47.7 ± 9.5
March	107.7 ± 80.3	20.7 ± 2.3	9.9 ± 1.5	80.3 ± 19.8
April	50.5 ± 43.4	26.0 ± 1.8	14.5 ± 1.5	117.6 ± 20.6
May	82.9 ± 59.2	29.6 ± 1.8	18.0 ± 1.3	157.3 ± 36.1
June	223.4 ± 132.6	30.0 ± 1.4	19.6 ± 0.9	130.3 ± 33.7
July	669.6 ± 291.4	26.8 ± 0.9	19.8 ± 0.5	69.6 ± 25.3
August	676.1 ± 177.2	26.1 ± 0.7	19.4 ± 0.4	56.3 ± 15.1
September	239.2 ± 139.2	26.1 ± 0.7	17.5 ± 1.1	64.8 ± 12.9
October	31.5 ± 40.7	24.8 ± 0.9	13.4 ± 0.8	76.7 ± 13.9
November	19.5 ± 26.8	21.4 ± 1.4	9.3 ± 0.9	59.2 ± 8.3
December	49.6 ± 54.1	17.4 ± 1.5	6.1 ± 0.9	45.4 ± 7.8

*Open pan evaporation = Evaporation × 0.75 (Muller 1982)

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10+2	March	2015	Kendriya Vidyalaya Mandi (H.P)	86.6 %	1 st
B.Sc. (Hons.) Agriculture	August	2020	CSK HPKV, Palampur (H.P)	7.71 OGPA	1 st
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Scientific Popular Articles: Nil

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