EFFECTS OF DIFFERENT FACTORS AND MANAGEMENT PRACTICES ON NITRATE DYNAMICS IN SOILS

Thesis
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IN
SOIL SCIENCE (Soil Chemistry and Fertility)
(Minor Subject : Chemistry)

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Dedicated

To

My

Revered Parents

19 8 93. Dean/Head Deptt. of Soils, PAU, LDH,

CERTIFICATE I

This is to certify that the thesis entitled, "**Effects of different factors and management practices on nitrate dynamics in soils**", submitted to Punjab Agricultural University, Ludhiana, in partial fulfilment of the requirements for the degree of Master of Science in the subject of Soil Science (Soil Chemistry and Fertility) [Minor subject : Chemistry], is a bonafide research work carried out by **Mr.Kuldip Singh** (L-90-A-94-M) under my supervision and that no part of this thesis has been submitted for any other degree.

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

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CERTIFICATE II

This is to certify that this thesis entitled. "**Effects of different factors and management practices on nitrate dynamics in soils**", submitted by **Mr.Kuldip Singh** (L-90-A-94-M) to the Punjab Agricultural University, Ludhiana, in partial fulfilment of the requirements for the degree of Master of Science in the subject of Soil Science (Soil Chemistry and Fertility) [Minor subject : Chemistry], has been approved by the student's Advisory Committee after an oral examination on the same in collaboration with an External Examiner.

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ABSTRACT

Laboratory and field experiments were conducted with soils from different agro-climatic regions of North-Western India to study nitrification and nitrate accumulation/depletion in soil as influenced by soil texture, soil pH, crop residues varying in C/N ratio, and different nitrification inhibitors (NIs), with or without fertilizer N in upland (60% water-filled pore space) and flooded (120% WFPS) soil conditions. Effects of green manuring and fertilizer N in wetland rice was also studied in terms of nitrate dynamics in soil, N uptake and crop yield. Most of the applied NH_4^+-N was nitrified within 10 d of incubation at 60% WFPS in the three soils investigated. At similar gravimetric water contents, rates of nitrification differed greatly in soils of varying texture, but when varying water holding capacity and bulk density were accounted for using WFPS, all soils behaved similarly at 60% WFPS. But under impeded aeration (flooded conditions) substantial differences were observed; the highest rate of nitrification in fine-textured Chamror silty clay followed by Habowal loam and the smallest rate in Tolewal sandy loam-I soil.

Soil pH had a distinct effect on nitrification. Under upland conditions the neutral soil was biologically most active in nitrifying the applied NH_4^+-N. The rate of nitrification was

highest in neutral Tolewal soil (7 mg N kg^{-1} d^{-1}), modest in alkaline Sodhi Nagar soil (3 mg N $kg^{-1}d^{-1}$) and was lowest in Andretta acidic soil. Under flooded conditions, rate of nitrification was relatively low, but followed the same trend. Nitrification of the applied fertilizer NH_4^+-N strictly followed the first-order kinetics and first order rate constants were highest in the neutral soil as compared to other two soils under both upland and flooded conditions.

Incorporation of wider C/N ratio residues of wheat (C/N=111) and soybean (C/N=37) resulted in drastic N immobilization. Apparent net immobilization of fertilizer N in 30 d period was 18 and 37 mg N kg^{-1}, respectively. In contrast, significant accumulation of NO_3^--N occurred due to incorporation of narrow C/N ratio residues of moongbean (C/N=21) and cowpea (C/N=14). The apparent recovery of added moongbean N was 11 and 17% in without and with fertilizer N treatments, respectively. The corresponding recovery of cowpea N was 13 and 29%. Under flooded conditions, the NO_3^--N content disappeared quickly presumably through denitrification and traces of NO_3^--N were observed throughout the incubation period. Accumulation of NH_4^+-N in flooded soil was maximum due to incorporated cowpea followed by moongbean, soybean and wheat.

Of the three nitrification inhibitors used, encapsulated calcium carbide was found to be most effective nitrification inhibitor upto 10 d in upland condition, and throughout incubation under flooded condition. For prolonged incubation under upland condition, 4-amino-1,2,4-triazole was most effective. Dicyandiamide was least effective under both aerobic and anaerobic soil conditions.

Application of fertilizer N and incorporation of 25 and 50 t ha^{-1} of fresh cowpea green manure (GM) resulted in small temporal changes in the soil profile with respect to content of NO_3^-, NH_4^+ and mineral-N, throughout the rice growing period. Grain yield and N uptake by rice were substantially higher with the combined application of 60 kg N ha^{-1} and 25 t GM biomass ha^{-1} than with individual application of 120 kg fertilizer N ha^{-1} or green manure. Grain yield decreased when 25 t GM ha^{-1} was applied in conjunction with high dose of 120 kg N ha^{-1}. Comparable rice yields were obtained with 120 kg fertilizer N ha^{-1} and 25 t GM ha^{-1}, exhibiting efficiency of green manure-N equal to that of fertilizer-N. Green manure N was more effective when applied alone or with low rate of fertilizer N (60 kg N ha^{-1}).

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Chapter I

INTRODUCTION

Nitrogen (N) is a major essential plant nutrient. In the past 20 years, world fertilizer N consumption has increased from 2.1 million metric tons to 72.7 million metric tons (FAO, 1962-1987) and in 1993 it is expected to exceed 88.5 million metric tons (FAO, 1988). The overall growth rate, on an average, is 5 % but is much higher in developing countries such as India.

Soils of North-Western plains of India including Punjab are generally low in organic matter and hence possess low reserves of nitrogen. Therefore, application of fertilizer N is a rule rather than exception to meet the N-requirements of growing plants and to obtain optimum yields. Unfortunately, the efficiency of fertilizer N-use by most crops ranges from 20-60% and commonly averages below 50% (Allison, 1955; Rekhi et al., 1982; Katyal et al., 1985; Yadvinder-Singh et al., 1989). A substantial portion of the applied fertilizer N is lost by denitrification, leaching and/or volatilization (Yadvinder-Singh et al., 1989; Aulakh et al., 1992).

Ammonium-based fertilizers such as urea, ammonium sulphate, ammonium-nitrate, calcium ammonium nitrate, diammonium phosphate and anhydrous ammonia, have become the most extensively used sources of fertilizer-N in the world (Harre and Bridges, 1988). After application to the soil, these fertilizers undergo nitrification, a two step oxidative process in which ammonium

(NH_4+) is biologically oxidized to nitrite (NO_2^-) and nitrate (NO_3^-) mainly by chemoautotrophic bacteria.

At one time NO_3^- was thought to be the preferred form of N for plant growth, and conversion to NO_3^- of NH_4^+ ions released by decomposition was considered desirable. Later on, research revealed that plants can also utilize NH_4^+ and, on an energetic basis, its more reduced nature makes it a more favourable source of N for plants. Results obtained from nutrient solution studies suggest that crop growth will be higher in solution containing an optimum ratio of NH_4^+ to NO_3^- (Cox and Reisanauer, 1973). In addition, positively charged NH_4^+ ions are adsorbed to soil surfaces thereby becoming less susceptible than NO_3^- to leaching. Further, NO_3^- ions are also a substrate for denitrifying organisms resulting into the release of N gases to the atmosphere. Nitrification rates in excess of NO_3^- utilization by plants can also increase the levels of NO_3^- in run-off and ground water (Bijay-Singh and Sekhon, 1978; Keeney et al., 1987; Bijay-Singh et al., 1991a). High NO_3^- levels (> 10 mg NO_3^--N l^{-1} water) can lead to eutrophication and are considered unsafe for human consumption. Inside the body NO_3^- can be reduced to NO_2^- which combines with haemoglobin to form methaemoglobin and interrupts O_2 transfer to the cells of infants (Paul and Clark, 1989).

Presence of NO_3^- in soil is a precursor for denitrification. Similarly, production and accumulation of NO_3^- in soil are subject to leaching beyond plant rooting zone along with percolating water. On the other hand, slow rate of nitrification would result in accumulation of NH_4^+-N which may enhance fertilizer-use-efficiency by reduced denitrification and leaching losses (Banerjee and Mosier, 1989; Banerjee et al., 1990). But if fertilizer N is broadcast on soil surface, reduced nitrification could increase N losses via ammonium volatilization (Freney et al., 1987; Bock and Kissel, 1988). Hence, nitrification acts as a key process in the determination of fertilizer N use efficiency by crops as well as N losses from the soils.

The major factors governing nitrification include soil aeration status (expressed as oxygen or water content), concentration of NH_4^+-N, soil pH, soil texture and temperature (Schmidt, 1982). The soil and climatic conditions prevailing in plains of North-Western India present a wide range of pH (5-9), temperature (5-40°C), moisture regimes, cropping systems and crop residue management practices are expected to result in different rates of nitrification. For instance, arable lands (upland soil systems) provide congenial conditions for nitrification whereas, in flooded rice-growing soils, submergence results in the depletion of oxygen (O_2) and hence nitrification may proceed slowly. However, in coarse textured soils which have been brought under rice cultivation during last decade in the Punjab have high percolation rates, (Katyal et al., 1985, 1987) anaerobic condition do not exist continuously. Thus under alternating aerobic-anaerobic conditions, nitrification could produce enough NO_3^- which may be subsequently lost by denitrification and/or leaching. Therefore, it is pertinent to study the effect of important factors and management practices on nitrification kinetics so that by their manipulation, means and ways can be found to control the rate of nitrification and NO_3^- accumulation in soil. The present study was undertaken with the following objectives:

- To determine the kinetics of nitrification in upland and flooded soils of varying texture.
- To investigate the influence of soil pH on nitrification in upland and flooded soil systems.
- To find out the rate of nitrification and nitrate accumulation in upland and flooded soils amended with crop residues varying in C/N ratio.
- To study the role of applying nitrification inhibitors in affecting the nitrate accumulation in upland and flooded soils.

Chapter II

REVIEW OF LITERATURE

Nitrification takes place virtually in all soils containing NH_4^+-N substrate and wherever favourable conditions exist.

In this chapter, an attempt has been made to review the studies made so far to understand the mechanism involved in nitrification process in soils. Some recent researches made to control the rate of nitrification by manipulating controlling factors and, thereby, increasing the efficiency of nitrogen fertilizers, have also been reviewed.

The literature pertinent to the subject of investigation has been reviewed under the following heads:

- 2.1 **Nitrification and Microorganisms involved**
  - 2.1.1 Autotrophic nitrifiers
  - 2.1.2 Heterotrophic nitrifiers
- 2.2 **Important Factors Affecting Nitrification**
  - 2.2.1 Soil texture
  - 2.2.2 Soil pH
  - 2.2.3 Soil moisture/aeration
  - 2.2.4 Soil temperature
- 2.3 **Management Practices Influencing Nitrification**
  - 2.3.1 Green manuring
  - 2.3.2 Incorporation of crop residues

2.3.3 Rate, method and time of fertilizer N application

2.3.4 Use of nitrification inhibitors

2.1 Nitrification and Microorganisms Involved.

The process whereby NH_4^+ is oxidized to NO_3^- is referred to as nitrification. It is a two step mechanism carried out by two distinctive groups of bacteria. The first converts NH_4^+ to NO_2^-; and the second oxidizes NO_2^- to NO_3^-. Nitrification of NH_4^+ or NH_4^+ producing fertilizers proceeds as follows:

$$NH_3 + H_2O \longrightarrow NH_4^+ + OH^- \quad \text{----} \ [1]$$

$$2NH_4^+ + 3O_2 \longrightarrow 2NO_2^- + 2H_2O + 4H^+ + 65 \text{ Kcal} \quad \text{----} \ [2]$$

$$2NO_2^- + O_2 \longrightarrow 2NO_3^- + 17.8 \text{ Kcal} \quad \text{----} \ [3]$$

By summation of the above equations, it can be seen that the net effect is the production of 1 mole of acid (H^+) for nitrification of every mole of NH_4^+.

2.1.1 Autotrophic nitrifiers

Watson (1974) placed ammonia oxidizers in four genera; namely Nitrosomonas, Nitrosococcus, Nitrosospira and Nitrosolobous. A fifth genus Nitrosovibro, had been added by Harms et al. (1976). Generally, Nitrosomonas have been reported to be dominant genera. However, MacDonald (1979) found that the genus Nitrosolobus was the dominant organism in Rothamsted soil. Bhuiya and Walker (1977) isolated Nitrosospira from acid soils of Sri Lanka and Bangladesh.

Nitrite oxidizers belong to three genera namely Nitrobacter, Nitrospina and Nitrococcus, of which Nitrobacter is the most commonly isolated.

Nitrifying bacteria are gram negative and their major feature is their relatively slow rate of growth. Nitrifying bacteria are chemolithotrophs and obtain all their energy from the oxidation of inorganic compounds, while cellular carbon is obtained principally by the fixation of CO_2. About 1 to $4x10^4$ cells ug N^{-1} of Nitrobacter spp. are produced from the oxidation of NO_2^-. Roughly three times this cell concentration has been shown to be supported from an equivalent amount of NH_4^+-N oxidized by Nitrosomonas spp. (Focht and Verstraete, 1977). Inspite of the above fact, number of ammonium oxidizing bacteria do not always appear to be larger than NO_2^--oxidizers under natural conditions.

2.1.2 Heterotrophic nitrifiers

In addition to autotrophic nitrifying bacteria, many heterotrophic microorganisms convert NH_4^+ to NO_2^-, and NO_2^- and organic nitrogen compounds to NO_3^-. Species capable of such transformations are listed by Focht and Verstraete (1977) and include a wide range of bacteria, actinomycetes and fungi. Heterotrophs can oxidize N but cannot use the exothermic reaction as a sole source of energy for cell synthesis.

Heterotrophic nitrification can be observed by selectively inhibiting the autotrophic nitrifier population and is often a dominant mechanism at temperature, pH values and moisture contents which are unfavourable for the growth of autotrophic nitrifying bacteria (Prosser and Cox, 1983).

2.2 Important Factors Affecting Nitrification

2.2.1 Soil texture

Soil texture may influence the nitrification process in several ways. Exposed soil surfaces provide attachment sites for microbial cells and negatively charged soil colloids may concentrate nutrients on the colloid surface (Focht and Verstraete, 1977). The effect of soil texture on nitrification results from natural differences in capacity of soils to supply NO_3^- and also due to physical variations in soil structure, bulk density, pore size, aggregation and water infiltration rates that affect aeration, water holding or absorption capacity and microenvironment.

Soil texture may have direct or indirect influence on rate of nitrification. Wahhab et al. (1960) showed that less urea was nitrified and more time was required for nitrification in sandy than in sandy loam soils. The rates of nitrification appear to be greater with increasing clay content (Broadbent et al., 1957; Justice and Smith, 1962), probably because less free NH_3 is available through exchange equilibria in sandy soils. However, greatest accumulation of nitrites and less production of nitrates were observed in Yoloclay loam soils of pH 7.7 than sand with pH 6.3 (Chapman and Liebig, 1952). Similarly, Hosny (1979) reported that nitrification was rapid in soil rich in clay minerals and harbouring a denser population of nitrifying bacteria.

Smith (1964) showed that by decreasing cation exchange capacity (CEC) through addition of sand to clay reduced the nitrification of ammonium ion, due to toxicity of nitrobacter by high concentration of NH_4^+ in soil solution. Laubscher and Preez (1991) showed that the maximum nitrification rates of the soils were significantly affected by the nitrifier population and CEC. In their study, Kmax increased logarithmically with increasing CEC.

A number of workers (Lees and Quastel, 1946; Smith and Cook, 1946; Goldberg and Gainey, 1955) have shown that the presence of colloids affect nitrification rate. Lees and Quastel (1946) concluded that adsorbed NH_4^+ is preferentially nitrified to NH_4^+ present in solution. Similar conclusions were made by Macure and Kune (1965) using a continuous flow system.

Kai and Harada (1969) studied the effect of varying amounts of clay minerals using a shaking culture and observed a stimulating effect followed by a depressing effect as the amount of clay minerals in suspension was increased. They concluded that the stimulating effect of cation exchange material was due to (a) lowering the concentration of NH_4^+ in soil solution below the toxic levels to organisms, and/or (b) by having nitrifying organisms and adsorbed NH_4^+ on the surface of materials in close contact. They proposed two possible explanations for the depressing effect viz. (a) NH_4^+ added was small compared to CEC and therefore the concentration in solution was small and relatively more of the adsorbed NH_4^+ was held back in forms not readily available to nitrifying organisms, and (b) there was a few nitrifying organisms compared with the number of clay particles and, therefore, less contact between microorganisms and adsorbed NH_4^+-N.

Nommik (1966) indicated that in soils of low buffering capacity, nitrification of NH_4^+ in the vicinity of large urea granules may be suppressed significantly due to the increased acidity from initial nitrification. Hue (1981) found that clays having a large specific surface area (smectite) and H^+ buffering capacity prolonged the delay period but favoured the high oxidation rate.

Gadkari (1990) study the process of nitrification in the presence of soil particles, sand, alginate beads and agar strands. Except sand,each substance used caused considerable stimulation of nitrification. Ammonium oxidation was more stimulated than NO_2^- oxidation. In the presence of soil, the rate of NH_4^+ oxidation was twice that of control.

Bower (1951) and Allison et al. (1953) reported that NH_4^+ could be fixed in difficulty exchangeable form in soils depending upon their ammonium fixation capacity and hence NH_4^+ may not be readily nitrified. However, later studies have documented that "recently fixed NH_4^+" is not an inert N fraction in the soil, but rather there is a dynamic equilibrium between the fixed NH_4^+ pool, and the exchangeable and soluble N pools. Therefore, "recently fixed NH_4^+" is released and nitrified when concentration of NH_4^+ in soluble and exchangeable forms decline (Juma and Paul, 1983; Aulakh and Rennie, 1984).

2.2.2 Soil pH

Growth and metabolism of autotrophic nitrifying bacteria are optimal in neutral to slightly alkaline range (pH 7-8). The inhibition of nitrification has been observed below pH 6.0, although slow rates of nitrification have been reported at pH values as low as 4.5 (Boer and Laanbroek, 1989). In this respect growth of NH_4^+ oxidizers is auto-inhibitory since two moles of H^+ ions are produced for each mole of NH_3 oxidized (Prosser and Cox, 1983). Another reason could be Al toxicity (Brar and Giddens, 1968).

Nitrification proceeds at soil reaction far below the pH limits observed for nitrifying bacteria in pure culture. Most observations indicate an arbitrary lower limit of nitrification at pH 4.0. Obviously, nitrification is pH-dependent in the pH 4 to 6 range, and pH-independent in the range of 6 to 8 (Morrill and Dawson, 1967; Chase et al., 1968; Sarathchandra, 1978).

Similarly, Dancer et al. (1973) found a 3 to 5-fold increase in the nitrification rate with soil pH increasing from 4.7 to 6.5, which was associated with decrease in the length of delay period and increase in the maximum rate of nitrification.

Bramley and White (1990) studied the effect of pH on the activity of nitrifying organisms in pasture soils ranging in pH from 4.9 to 7.3. The optimum pH for nitrifier activity was generally close to the soil's natural pH, suggesting that the indigenous nitrifier population adjusts to the prevailing soil pH.

Stams and Marnette (1990) study the nitrification of acid and calcareous forest soils and observed that nitrification rates were higher in calcareous soils. In acid soil nitrification was much slower indicating that autotrophic bacteria from acid soil are sensitive to pH increase. In a later study, Stams et al. (1990) reported that after 98 d incubation, 65% of applied $^{15}N\text{-}NH_4^+$ was recovered as NO_3^- in a calcareous soil as compared to only 10% in two acid forest soils.

Nitrification was much slower in five strongly acid soils (pH 4.0-4.3) from tea plantation in Sri-Lanka than in a near neutral grassland soil suggesting that the nitrifiers in these tea soils are close to the lower limit of their pH range. Boer and Laanbrock (1989) have shown that an ureolytic NH_4^+ oxidizing chemolithotrophs belonging to genus Nitrosospira was shown to nitrify at pH 4.5. This study also revealed that in acid soil nitrification by ureolytic NH_4^+-oxidizing chemolithotrophs may not be restricted to microsites otherwise observed in neutral soils.

At a very high pH, nitrite may accumulate (Jones and Hedlin, 1970; Nitant, 1974) as Nitrobacter which oxidizes NO_2^- to NO_3^-, is very sensitive to high pH conditions. Anthonison et al. (1976) found that high concentration of free ammonia (10-150 mg l^{-1}) inhibited both Nitrosomonas spp. and Nitrobacter spp., while, at lower concentration of free ammonia, NH_4^+-N oxidized selectively to NO_2^--N and NO_2^--N oxidation to NO_3^--N was inhibited. Consequently, NO_2^--N accumulates and persists in the environment as has been revealed by several studies (Stojanovic and Alexander, 1958; Aleem and Alexander 1960; Morrill and Dowson, 1967; Anthonison et al., 1976). The accumulation and toxicity of NO_2^- to plants in alkaline soils fertilized with ammonia or urea has been recognized for several decades (Martin et al., 1942; Chapman and Liebig, 1952).

Wetselaar et al. (1972) observed virtually no nitrification when soil pH was 8.0, the osmotic pressure was 1000 KPa or when the NH_4^+-N concentration was above 3000 mg kg^{-1} soil. The NO_2^- accumulated when the pH was between 7 and 8, and NO_3^- accumulated at pH below 7.0. In the environment where pH, NO_3^- and osmotic pressure are high, nitrification may be reduced drastically. Parakasam and Loehr (1972) found that nitrification was unaffected upto pH 11.2 as long as the free NH_3 concentration was

<0.02 mg l^{-1}. In another study, the conversion of NO_2^- to NO_3^- did not start until the pH of the soil came down to threshold value of pH 7.7 ± 0.1 (Chapman and Liebig, 1952). Above this value substantial quantities of NO_2^- accumulated, indicating that the microorganisms responsible for converting ammonia to NO_2^- (<u>Nitrosomonas</u>) are less sensitive to alkaline pH than those involved in the oxidation of NO_2^- to NO_3^- (<u>Nitrobacter</u>) resulting the accumulation of NO_2^- in alkaline soils (Souldies and Clark, 1958).

In summary, the review of literature on effect of soil pH reveals that its inhibitory effects in acidic or alkaline range on rate of nitrification could be due to:-

(a) Toxic effects of HNO_2 in acidic soil on <u>nitrobacter</u> spp.

(b) Auto-inhibitory effects of growth of NH_4^+ oxidizers, since two moles of H^+-ion are produced for each mole of NH_4^+ oxidized.

(c) Free aluminium toxicity in acidic soils.

(d) Toxic effects of free NH_3 in alkaline soil on <u>nitrobacter</u> spp. presumably due to high osmotic pressure.

(e) Higher sensitivity of nitrobacter to high pH resulting into the accumulation of NO_2^- in alkaline soils fertilized with ammonia or urea fertilizers.

2.2.3 Soil moisture/aeration

The amount and composition of the soil water influence nitrification because the O_2 and HCO_3^- needed for nitrification are provided by liquid phase of soil system. A change in moisture content of the soil will affect aeration and hence should affect nitrification. Depletion of O_2 in the soil water is favoured by (a) high soil moisture content, which fills soil pores and restricts recharge of O_2 from the gaseous phase; (b) high soil temperature, which reduces the solubility of O_2 and increases O_2 demand by heterotrophic microorganisms; and (c) oxidizable organic matter, which also increases heterotrophic O_2 demand. Generally, the effect of moderately high moisture level is to enhance nitrification in most soils as long as aeration is adequate (Russell, 1973). Moreover, potential for nitrification in soils is a complex interaction between aeration, nitrate availability, carbon substrate availability and other "intrinsic" soil factors (Firestone, 1982).

Quantification of O_2 availability and related rates of nitrification in soils, however, is complicated by dynamic relationship between aeration potential (O_2 flux) and microbial oxygen use (Greenwood, 1975). While water content, matric potential and water holding capacity all serve as relative predictors of microbial activity in soil, the expression of water content as a volumetric percentage of soil pore space also encompasses the role of water as a barrier to O_2 diffusion and as such is a better measure of factors regulating aeration-dependent microbial processes (Sommers et al., 1981).

As the nitrifying population is aerobic, the optimum percentage of O_2 in the soil air for rapid NO_3^- accumulation was found to be similar to that found in the atmosphere (Amer and Bartholomew, 1951; Grechin and Cheng, 1960). They further reported that Km values for O_2 is 0.3 to 1.0 mg O_2 l^{-1}, which is higher than for heterotrophs.

Nitrates neither form in air-dry soil nor at very low moisture levels (Robbinson, 1957; Slavina, 1961). Seifert (1970, 1972) and Alexander (1977) suggested the optimum moisture content for the greatest NO_3^- accumulation is at one-half to two-third of the maximum water holding capacity of the soil. Justice and Smith (1962) found soil moisture at -30 KPa was the most favourable; this was their maximum moisture treatment though. Later on Sabey (1969), using a wider moisture range from 0 KPa (saturation) to -1500 KPa, observed maximum nitrification at -10 KPa tension. Malhi and McGill (1982) reported that an increase in the relative rate of nitrification with increasing soil moisture tension from -1500 to -33 KPa. Nitrification ceased at 0 KPa soil moisture potential in all three soils used in their study. The negligible rate of nitrification at 0 KPa is attributed to the shortage of O_2 in the soil system. The mean rate of nitrification for three soils treated with 100 mg NH_4^+-N kg^{-1} soil was 3.4, 2.0

and 1.3 mg N kg^{-1} day^{-1} at -33, -700 and -1500 KPa soil moisture tension, respectively.

Doran and his associates (Linn and Doran, 1984a, 1984b; Doran _et_ _al_., 1988, 1990; Aulakh _et_ _al_., 1991a, 1991b) have shown that water filled pore space (WFPS) depicts a better relationship with the rate of nitrification and other aeration-dependent microbial processes in the soil (Fig. 1). Use of WFPS overcomes several problems associated with varying water saturation levels and bulk density for soils differing in texture and tillage regimes. Moreover, WFPS is a more practical index of soil aeration than measurement of oxygen diffusion rates because it requires only a knowledge of gravimetric soil water content and soil bulk density (assuming the particle density of mineral soils = 2.65Mg m^{-3}).

Figure 1 clearly illustrates that the rate of nitrification is limited by soil moisture at low WFPS (<10%) and by aeration at high WFPS (>90%). Therefore, flooded soils, commonly used for rice cultivation, may lack nitrification, and mineralized N often exists mainly as NH_4^+-N (Savant and DeDatta, 1982; Aulakh, 1988). However, under natural conditions nitrification may not be completely inhibited in these soils because NH_4^+ could be oxidized to NO_3^- in the thin O_2-containing surface soil layer and in the overlying water phase of flooded soils (Engler and Patrick, 1974). The so formed NO_3^- in this upper oxidized zone move into the lower anaerobic zone where they are lost via

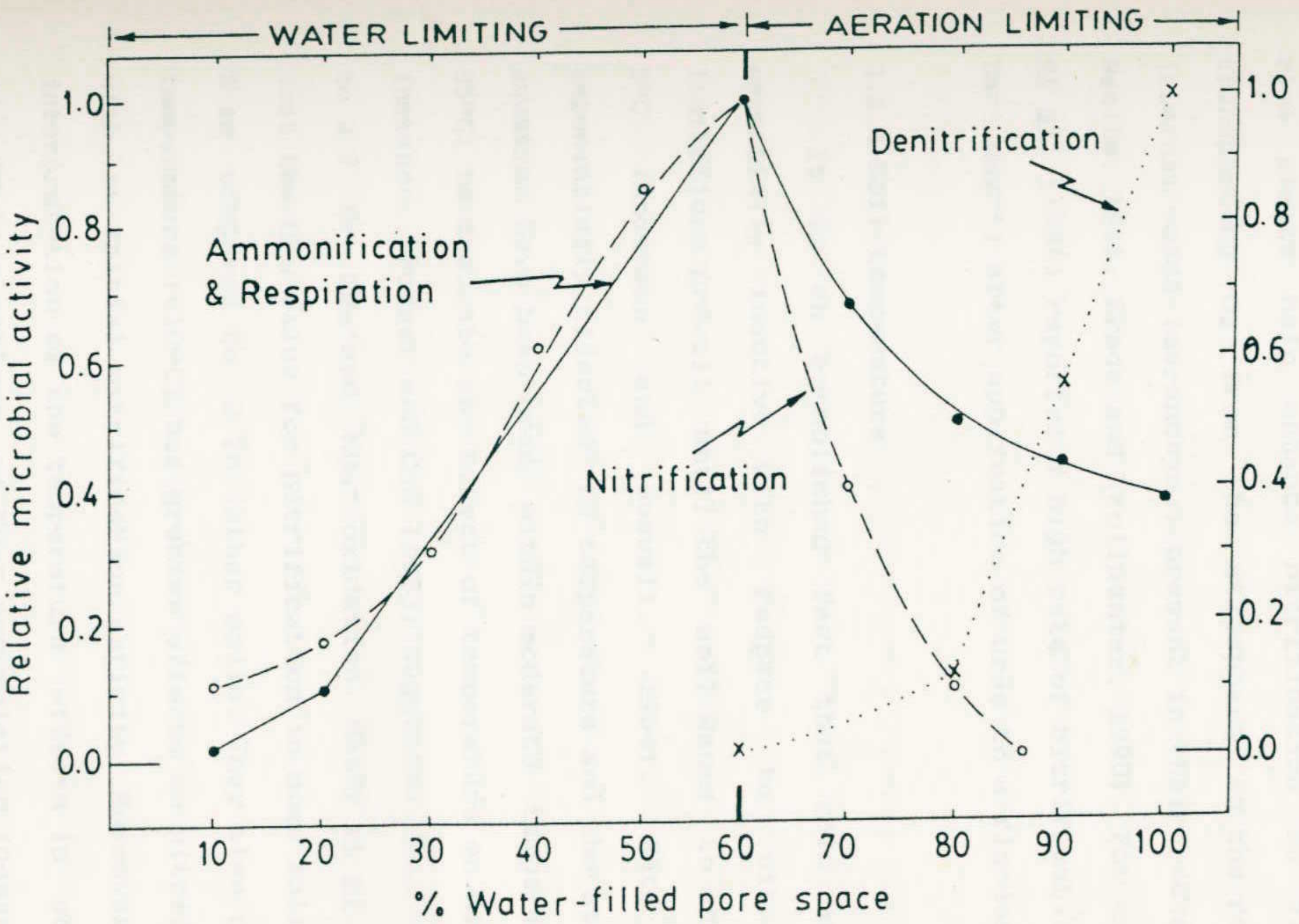


Fig. 1. Relationship between soil water-filled pore space (relative saturation)and the aerobic microbial processes of respiration and nitrification and anaerobic denitrification in soil. (Linn and Doran, 1984a)

denitrification (Tusneem and Patrick, 1971). Furthermore, growing rice plants help enhance nitrification in flooded soils by transporting O_2 from the atmosphere to the root-zone through internal voids (aerenchyma) present in their roots and stems (van Raalte, 1941; Prade and Trolldenier, 1990). For example, Watanabe et al. (1981) reported a high rate of nitrification (1.2 Kg N ha^{-1} day^{-1}) after application of urea to a flooded soil.

2.2.4 Soil temperature

It is an established fact that cold and wet soils are essentially inactive with respect to nitrification. Such limitations prevail until the soil warms to approximately 4 or 5°C (Anderson and Boswell, 1964). Rate processes are exponentially affected by temperature and the standard Arrhenius equation have been used within moderate temperature limits (15-35°C) to describe the effect of temperature on nitrification. For instance, Prosser and Cox (1983) suggested Q_{10} ranging from 1.7 to 2.7 for NH_4^+ and NO_2^- oxidation. Sabey et al. (1959) reported that the Q_{10} value for nitrification in some soils was as high as 5 as compared to 2 in other soils. They also reported that low temperature (<10°C) has greater effects on nitrification in soils with low initial nitrification activity. Moreover, the problem of interpretation of the temperature effects is complicated by the sigmoid-like pattern of NO_3^- accumulation (depending on previous soil treatments), nitrifier populations (Sabey et al., 1956) and soil moisture (Beek and Frissel, 1973; Kowalenko and Cameron, 1976). Sabey et al. (1959) conducted experiments using several soils, with varying soil reactions, rate of N application, number of inoculations with nitrifiers and temperature from 0 to 25°C. The maximum nitrification rates increased from almost nil to 900 mg kg^{-1} $week^{-1}$ and the delay periods decreased from 32 weeks to less than one day, as the temperature was increased from 0 to 25°C.

The above cited studies clearly reveal that the temperature for nitrification appears to vary widely (2° to 60°C) among soils and is influenced by several factors including soil moisture. For instance, Tyler et al. (1959) suggested no minimum temperature for nitrification, since this is governed by the nature of the soil, climatic region and the amount of ammonia concentration. MacLean and McRae (1987) found that nitrification rate increased with temperature from 4 to 18°C. Limited nitrification occurred at 4°C but was extensive at 9°C and above. Evidently nitrification of added urea was complete between 48 and 68 d at 18°C as compared to 90% nitrification in 92 d when temperatures were lower (9 and 13°C).

Mahendrappa et al. (1966) reported maximum nitrification rates at 20-25°C for a group of soils from North-Western United States and at 30-40°C for soils of South-Western United states. Similarly, Malhi and McGill (1982) observed that the optimum temperature for nitrification in 3 soils of Western Canada (where mean annual temperature is 2.5°C) was 20°C and nitrification activity almost ceased at 30°C. The optimum temperature for Iowa (U.S.A.) soils (mean annual temperature 10°C) was 25-30°C (Sabey et al. 1959). In Australian soils where mean annual temperature is 25°C, the optimum temperature obtained for nitrification was 35°C (Myers, 1975). Although there was a rapid decline in nitrification rate over 35°C, measurable nitrification occurred even at 55°C. Similarly, in tropical soils of Ludhiana (mean annual temperature 25°C) the optimum temperature for nitrification was found to be 35°C (Bhupinderpal-Singh et al., 1992). The low temperature optimum and complete lack of nitrification in temperate region soils at high temperature (30-40°C), suggest a climatic selections for nitrifiers having a low temperature optimum and poor heat tolerance than has been reported for soils from warmer areas in which nitrifiers require high temperature optimum.

2.3 **Management Practices Influencing Nitrification**

2.3.1 **Green manuring**

Ever increasing cost of inorganic fertilizers has promoted renewed interest in the recycling of plant nutrients through leguminous green manures (Power, 1987; Yadvinder-Singh et al., 1991) and crop residues (Aulakh, 1988). Raising of leguminous crops and their incorporation into soil at flowering stage (commonly known as green-manuring) or after picking grain pods (e.g. moongbean) or at maturity has been used to partially meet the fertilizer requirement of cereal crops (Bahl et al., 1986; 1988; Yadvinder-Singh et al., 1991). Now a days nutrient recycling through green manuring or crop residues incorporation is widely practiced in several parts of the world to maintain high levels of soil organic matter and productivity.

The benefits of green manuring include increase in organic matter content, available plant nutrients and improvement in the microbiological and physical properties of the soil. Of these, the role of green manures in supplying plant nutrients, particularly N is most prominent. The decomposition and release of N from green manures generally proceed very rapidly during the first few weeks followed by much slower phases thereafter, both under aerobic (Yadvinder-Singh et al., 1988; Wagger, 1989) and anaerobic conditions (Singh et al., 1981; Khind et al., 1985; Beri et al., 1989; Aulakh et al., 1991a). The amount of N released from *Sesbania aculeata* green manure after two weeks of incubation ranged from 12 to 38% under aerobic conditions (Yadvinder-Singh et al., 1988). Gale and Gilmour (1988) observed relatively slow rate of N mineralization from alfalfa residue and apparent net N release was only 12 and 28% in 14 and 30 d after incubation, respectively. Similarly, Aulakh et al. (1991a) observed 36% of N in incorporated vetch residue mineralized in a 35 d incubation study.

Under field conditions, where harbinger and clover were incorporated, 35 to 40% of legume N became available during 8 to 10 months fallow period (Ladd et al., 1981; Aulakh et al., 1983). Similarly, Wilson and Hargrove (1986) and Wagger (1989) observed an exponential N mineralization pattern of legume residues (vetches and crimson clover), under field conditions.

Residue of grain legumes harvested at maturity, which often have a lower N content than that of green manures, also rapidly release mineral N when incorporated into the soil. Nagarajah (1987) determined the net N release for two legume green manures (S. rostrata and Crotolaria juncea) and five legume residues (cowpea, moongbean, groundnut, pigeonpea, and soybean) after a 50 d incubation in flooded fallow soils. Plant N contents ranged from 1.1% for soybean to 2.7% for S. rostrata and C/N ratio ranged from 17 for S. rostrata, cowpea, groundnut to 38 for soybean. Net recovery of plant N as ammonium at 50 d ranged from 16% for soybean to 43% for S. rostrata. It correlated directly with plant N and inversely with C/N ratio.

Similar patterns of N recovery as extractable soil NH_4^+-N have been observed with incorporated cowpea green manure ($N = 2.7\%$, $C/N = 15$) and its residue at maturity ($N=1.3\%$, $C/N=30$) under field conditions in the Philippines (Buresh et al., 1991). In this study, a net N recovery, 15 d after transplanting, was 37% for green manures and 28% for mature residue.

Under flooded soil conditions, NH_4^+-N released during mineralization of added green manures is nitrified in the upper oxidized zone and after transporting into lower anaerobic zone it may be lost via denitrification, as is discussed earlier in section 2.2.3. Therefore, it is rather difficult to study the mineralization of N added through green manures in flooded soils.

2.3.2 **Incorporation of crop residues**

Crop residues varying in C/N ratio could have a pronounced affect on nitrate dynamics. For instance, Patra et al. (1992) in an incubation study with sandy loam soil showed that at 60% of maximum water holding capacity, more nitrates were produced from low C/N ratio cowpea than those from wider C/N ratio wheat crop. Similarly, in a recent study Aulakh et al. (1991a) showed a consistent increase in NO_3^--N content of Nicollet loam soil incubated at 60% WFPS with the incorporation of 2500 mg kg^{-1} of crop residues of wheat, corn and soybean with narrowing C/N ratio.

In a three year field study Rekhi and Meelu (1983) observed that (after picking pods) incorporation of moongbean straw along 60 kg N ha^{-1} produced rice grain yield equivalent to 120 kg fertilizer N ha^{-1}. Dhillon and Dev (1984) did not observe any effect of incorporation or burning of wheat straw on the yield of following rice during the first year of the experiment. However, in the second year, incorporated wheat straw resulted in additional 600 kg ha^{-1} grain yield of rice. Maskina et al. (1987) reported enhanced rice grain yield with burning of wheat straw as compared to no straw treatment.

Broadbent and Nakashima (1970) observed that rice straw containing 0.47% N immobilized additional 0.5% N in flooded soil and another sample of rice straw containing 1.17% N, immobilized 0.43% N.

From a long term experiment Gotoh et al. (1984) found that carbon and total-N contents of soil profile increased by application of residues of rice (90 t ha^{-1}) and rye grass (384 t ha^{-1}) during a period of 16 years. Similarly, incorporation of straw in the soil increase the content of organic carbon, total N, available N and hydrolyzable-N in the soil (Dhillon and Dev, 1984).

Wagger et al. (1985) reported that 12-15% of wheat residue-N was mineralized after one cropping season and about 79% of mineralized wheat residue-N and 82% of mineralized sorghum residue-N were utilized by succeeding wheat and sorghum plants, respectively.

Although several studies are available on the influence of incorporation of crop residues with wider C/N ratio on immobilization/mineralization of N in the soil, their effect on nitrification of applied fertilizer N is rarely documented. One study by Aulakh (1989) where ^{15}N labelled ammonium sulphate was used, illustrates such effect. In this study, the addition of wheat residues (C/N = 60) did not influence the rate of nitrification of added $^{15}NH_4^+$-N in the upland soil (60% WFPS) obviously due to no limitation of O_2 diffusion. But under submerged soil conditions where nitrification occurs only in the flood water and in the oxidized surface soil layer due to restricted O_2 diffusion, the incorporation of successive levels of wheat straw which had relatively higher water holding capacity than soil, progressively decreased the thickness of flood water on the soil surface. As a result of this, the thickness of oxidized surface soil layer was probably increased and helped in enhancing the rate of nitrification. This study very clearly demonstrated that incorporation of crop residue in soil with restricted aeration such as flooded, submerged or wetland paddy soils, could enhance the rate of nitrification of added ammoniacal fertilizer and may produce sufficient NO_3^-.

2.3.3 Rate, method and time of fertilizer N application

(i) Rate of fertilizer N application

Generally speaking rate of nitrification dependents on the substrate (NH_4^+) concentration. Studies have shown that upon addition of ammoniacal fertilizers populations of <u>nitrosomonas</u> spp. may increase from several hundred to several hundred million per gram of soil. For instance, Malhi and McGill (1982) found that at 20°C and -33 KPa soil moisture tension, nitrification rate increased with increasing NH_4^+-N concentration from 50 to

200 mg kg^{-1} soil and the rate of nitrification was 2.5 times greater at 200 mg of NH_4^+-N than at 50 mg NH_4^+-N kg^{-1}, but decreased with further increase in NH_4^+-N concentration presumably due to auto-inhibitory effect as discussed earlier in section 2.2.2

Many workers (Justice and Smith, 1962; Anderson and Boswell, 1964; Malhi and McGill, 1982; Malhi et al., 1992) have reported that higher concentration of NH_4^+ have an adverse effect on nitrification as high ammonium concentrations inhibit both ammonia and nitrite oxidizers, and the later are more sensitive. The maximum tolerable NH_4^+-N concentration in soil appears to vary between 400 mg kg^{-1} (Anderson and Boswell, 1964) to 800 mg kg^{-1} soil (Broadbent et al., 1957). The depressing influence of NH_4^+-N at high concentration on nitrification has been attributed to several factors such as (a) toxic levels of ammonia at high pH (Stojanovic and Alexander, 1958) (b) lowering of pH when ammonium sulphate was added (Justice and smith, 1962), (c) high salt concentration effects, and (d) high osmotic pressure exerted by chloride ion when ammonium chloride is used (Darrah et al., 1985).

(ii) Method of fertilizer N application

Different methods of fertilizer N application are broadcast (surface application), incorporation (mixing with soil of plough layer), banding (drilling in bands) and placement in nests (placed at one central point). It has long been recognized that under some conditions, NH_3 can volatilize from ammoniacal fertilizer applied on the soil surface which could be eliminated by their incorporation or placement below the soil surface (Bock and Kissel, 1988). However, incorporation or subsurface placement are not always practical in several cropping systems.

In a montmorillonite clay, fertilizer ^{15}N utilization and grain yield were highest where the fertilizer was placed at 10 cm depth (DeDatta et al. 1968). Similarly, puddling or placement of fertilizer-N at 5 cm depth increased N utilization and rice yields significantly as compared to basal surface application (Khind and Datta, 1975). Savant et al. (1982) reported that recovery of deep placed ^{15}N increased with increase in placement depth of urea super granules (USG) presumably because of reduction in losses of applied N by ammonia volatilization and nitrification-denitrification. Vachhani (1952) reported that application of urea pellets near the rice plant was superior to broadcast application in Indian soils. Prasad et al. (1970) showed that deep placement of N was superior to broadcast application for both grain yield and N uptake. Craswell et al. (1981) reported higher recovery of deep placed fertilizer N in rice plants than that in surface applied and/or incorporated nitrogen. Cao et al. (1983, 1984) reported that grain yields were the highest with point placement of USG and uniform placement of prilled urea. Grain yield with uniform placement of prilled urea was not significantly better from those obtained with band placement and split application of prilled urea. Moraghan <u>et al</u>. (1984) concluded that rate and method of application of urea greatly affected the plant production and N uptake. Grain yield increased as the rate of soil incorporated urea increased. The split band treatment of urea application was superior to its incorporation in upper 15 cm soil.

Balwinder-Singh (1984) reported that placement of urea produced higher dry matter yield as compared to its broadcast application in two recently reclaimed sodic soils.

Malhi and Nyborg (1992) in four field experiments on barley compared the relative performance of top dressed, incorporated and banded application of fertilizer N (urea or aqua NH_3). Band placement was the most effective whereas top dressing was least effective. The recovery of applied N as NH_4^+-N was markedly higher when the fertilizer was banded or nested. The recovery of applied N as mineral N was even greater with nesting than banding, indicating that N losses were reduced significantly when fertilizer N (urea) was placed in bands or nests.

Hence dilution of fertilizer NH_4^+-N levels within optimum range (as discussed in preceding paragraphs) would help enhance rate of nitrification. On the other hand, the rate of nitrification may be reduced by creating high concentration of NH_4^+ by banding or nesting which consequently results in higher fertilizer-use-efficiency.

(iii) Time of fertilizer N application

Fertilizer N application at a time when crop needs are high, would be expected to reduce the losses of N from the soil and to increase fertilizer N-use-efficiency by plants. As crop needs of N during the initial week or two are likely to be small, single application of fertilizer N at time of sowing often proves less efficient as compared to split application. For instance, application of N in three equal splits at transplanting, tillering and panicle initiation stages of rice proved more efficient in terms of grain yield than in single or two splits irrespective of source of N and type of soil (Meelu et al., 1987). The results also indicated that N application 7 d after transplanting of rice was more beneficial than its application at transplanting. Therefore, improved fertilizer management should aim at concurrent N absorption by growing plants and minimum accumulation of NO_3^--N in the soil.

2.3.4 Use of nitrification inhibitors

Fast rate of nitrification may have undesirable consequences resulting into increased N losses and reduced fertilizer N use efficiency by plants. A great deal of research has, therefore, been devoted to finding chemicals that might be mixed or applied together with ammonium or urea fertilizers to reduce the rate of nitrification in soils. Control of nitrification through nitrification inhibitors (NI) could lead to increased fertilizer-use-efficiency with corresponding improvement in crop growth, yield and quality.

A number of studies have shown that nitrification inhibitors have the potential to increase the efficiency of applied fertilizers through reducing N losses due to denitrification (Malhi and Nyborg, 1979; Keeney and Nelson, 1982; Aulakh and Rennie, 1984) and preventing leaching (Papendick and Engibous, 1980; Aulakh and Rennie, 1984).

Table 1 lists some of the chemicals which are known to be in commercial production and/or are patented as nitrification inhibitors for agricultural use.

Of the number of NIs mentioned in the literature over a period of the past twenty years, only nitrapyrin, DCD and to a lesser extent AM and thiourea have been tested in more details in U.S.A., Canada, Germany and Japan (Ranney, 1978; Slangen and Kerkhoff, 1984).

The literature on nitrification inhibitors suggests that materials such as nitrapyrin are fairly effective in retarding nitrification (Bundy and Bremner, 1973; Aulakh and Rennie, 1984; Wickramasinghe et al., 1985). Increased efficiency of applied urea by use of nitrapyrin have been reported in rice (Rajale and Prasad, 1975; Sahrawat and Mukherjee, 1976; Das and Chatterjee, 1980), Wheat (Huber et al., 1980) and Corn (Warren et al., 1975). A number of reports provide evidence that nitrapyrin is more effective at relative low temperature (Goring, 1962; Bundy and

Table 1. Chemical used and patented as nitrification inhibitors.

Chemical name	Common name or symbol
2-Amino-4-chloro-6-methyl pyridine	AM
4-Amino-4-methyl-6-trichloromethyl triazine	MAST
4-Amino-1,2,4 triazole. HCl	ATC
2-Benzothiazole-sulfanemorpholine	KN, KNE
Carbon disulphide	CS_2
2-chloro-6(trichloromethyl) pyridine	N-serve,Nitrapyrin
Coated calcium carbide,Encapsulated calcium carbide	CaC_2, ECC
Dicyandiamide	DCD, Dicyan, Dd
5-ethoxy-3 trichloromethyl-1	Terrazole
5-ethoxy-3 trichloromethyl-1,2,4 thiadiazole	Etradiazole
Guanylthio urea	ASU
2-Mercapto-benzothiazole	MBT
3-Mercapto-1,2,4-triazole	MT
N-2,5-dichlorophenyl succinamide	DCS
Sulfathiazole	ST
Thiourea	Tu, Thiourea

Bremner, 1973). The decreasing effect of nitrapyrin with rising temperature is due to high degradation and volatilization and activity of nitrifiers.

The inhibitory effect of DCD on nitrification has been known for long a time (Prasad et al., 1971). A large number of chemicals at a concentration of 10 mg kg^{-1} soil were evaluated for nitrification inhibitor of applied urea or anhydrous NH_3 in three soils by Bundy and Bremner (1973). They found that DCD was less effective than nitrapyrin but was better than AM.

The effectiveness of DCD with urea or anhydrous ammonia in inhibiting nitrification has been reported as poor (Bundy and Bremner, 1973) or as effective as nitrapyrin (Ashworth and Rodgers, 1981; Sawyer and Hoeft, 1984) or better than all other nitrification inhibitors (Rodgers, 1983). Yadvinder-Singh and Beauchamp (1987) had shown DCD effectively reduce nitrification. Rodgers (1983) found in the laboratory experiments that application of DCD with urea in soils can inhibit nitrification but in certain soils, benefits obtained from inhibiting nitrification may offset by increased losses of fertilizer nitrogen as NH_3 volatilization.

Under flooded conditions, the application of DCD either with urea or ammonium sulphate diminished N losses by leaching and denitrification remarkably as compared to urea or ammonium sulphate alone (Amberger and Gutser, 1978). Graetz et al. (1984) reported that DCD (5 to 10 mg kg^{-1}) was very effective in inhibiting nitrification for 6 to 8 weeks. Dicyandiamide (5 mg kg^{-1}) increased corn yields significantly when used with a single N application. They concluded that DCD is an effective nitrification inhibitor which can increase corn yields on coarse textured soils. Similarly, Hauck (1984) have shown that DCD is a promising nitrification inhibitor for direct seeded rice in the USA. However, DCD failed to increase grain yield in transplanted, tropical lowland rice (DeDatta, 1985). It suggests that nitrification inhibitors behave differently under varying soil and climatic conditions and management practices.

Malhi and Nyborg (1983) in laboratory and field study have shown that ATC (4-amino-1,2,4 triazole) was most effective in retarding nitrification of NH_4^+-N, closely followed by CS_2 and nitrapyrin. Similarly, Bhupinderpal-Singh et al. (1992) have shown that ATC (5 mg kg^{-1}) was found to be more effective nitrification inhibitor than DCD (10 mg kg^{-1}), even though ATC was used at a low concentration.

Acetylene (C_2H_2) gas is also a potent inhibitor of the nitrification as it inhibits ammonium oxidase, a most sensitive enzyme in nitrification (Suzuki, 1978) and immediately stops nitrification (Hynes and Knowler, 1978; Walter et al., 1979; Berg et al., 1982; Aulakh et al., 1984). However, its use under field conditions is not feasible.

Recently, coated calcium carbide (CaC_2) has been used as a source of C_2H_2 to inhibit nitrification in soil (Banerjee and Mosier, 1989; Mohanty and Mosier, 1990). When calcium carbide is placed in moist soil, it is rapidly hydrolyzed to calcium hydroxide and acetylene:

$$CaC_2 + 2H_2O \longrightarrow Ca(OH)_2 + C_2H_2 \qquad \text{----} \; [4]$$

Therefore, use of CaC_2 granules lightly coated with paraffin prolongs the delivery of C_2H_2 to soil and provides an excellent alternative to the labour intensive maintenance of C_2H_2 levels in the soil through use of diffusion probes.

Banerjee and Mosier (1989) studied the efficacy of the coated or encapsulated calcium carbide (ECC) as a nitrification inhibitor in a series of laboratory and green house column experiments in fallow soils. These results indicate that ECC can effectively inhibit NH_4^+ oxidation under both flooded and non-flooded conditions. Under relatively aerobic soil conditions (-33 KPa), the ECC appeared to limit NH_4^+ oxidation only during the first week of the incubation as after two weeks no NH_4^+ was found in either the control or CaC_2 treatment. After three weeks NO_3^- content in soil did not differ significantly in either treated or control soil. Similarly, Sahrawat et al. (1987) found that CaC_2 is an effective nitrification inhibitor when conditions permit C_2H_2 to remain in the soil system. Even under field conditions Banerjee et al. (1990) found a substantial increase in rice grain yield (1470 kg ha^{-1}) with the use of ECC. Similarly, Bronson et al. (1992) were able to prevent NO_3^- accumulation in a soil under irrigated maize when 20 or 40 kg ECC ha^{-1} was applied in conjunction with fertilizer urea and consequently N_2O losses were reduced.

Chapter III

MATERIALS AND METHODS

The effects of different factors and management practices on nitrate dynamics in soils have been investigated by conducting laboratory and field experiments. The details of various experiments conducted and materials required for this investigation are given under the following heads:

3.1 Collection and preparation of bulk soil samples

3.2 Prepartion of repacked soil-cores and treatments for laboratory experiments

3.3 Effects of varying soil texture

3.4 Effects of varying soil pH

3.5 Effects of crop residues varying in C/N ratio

3.6 Effects of different nitrification inhibitors

3.7 Effects of green manuring and fertilizer N in wetland rice

3.8 Methods used for soil and plant analysis

3.9 Statistical analysis and calculations

3.1 Collection and preparation of bulk soil samples

Seven bulk surface soil (0–15 cm) samples were collected from different agro-climatic regions of North-Western India. The location and important characteristics of these soils used are summarized in Table 2. The characteristics of the soil used for a

Table 2 Some physical and chemical characteristics, nitrate-N and ammoniacal-N of surface (0-15cm) soil samples used in different experiments

Characteristics	Soil						
	Andretta	Sodhi Nagar	Habowal	Chamror	Tolewal-I	Tolewal-II	Tolewal-III
Texture	Loam	Sandy loam	Loam	Silty clay	Sandy loam	Sandy loam	Sandy loam
Taxonomy	Hapludalf	Natric Ustochrept	Typic Ustochrept	Dystric Eutrochrept	Typic Ustipsamment	Typic Ustipsamment	Typic Ustipsamment
Location	Andretta, Palampura, Himachal, Pradesh	Ferozepur, Punjab	Habowal, Ludhiana, Punjab	Chamror, Gurdaspur, Punjab	PAU Farm, Ludhiana, Punjab	PAU Farm, Ludhiana, Punjab	PAU Farm, Ludhiana, Punjab
Particle size distribution							
Sand (%)	35	72	50	9	75	71	71
Silt (%)	40	12	33	40	15	13	15
Clay (%)	25	16	17	51	10	16	14
pH	4.8	9.8	7.7	7.6	7.2	7.4	7.9
EC (dSm^{-1})	0.12	0.53	0.28	0.25	0.15	0.18	0.21
Organic carbon ($g\ kg^{-1}$)	14.0	3.60	6.30	6.20	3.80	4.10	6.40
Total N ($g\ kg^{-1}$)	1.20	0.60	0.48	0.80	0.82	0.70	1.00
NO_3^--N ($mg\ kg^{-1}$)	40.4	12.30	21.91	20.74	15.86	16.00	17.20
NH_4^+-N ($mg\ kg^{-1}$)	20.7	2.05	7.75	33.20	2.02	4.00	2.79

field experiment are also given in Table 2. The soil samples were air dried, ground in a wooden pestle and mortar to pass through 2 mm sieve and then stored in polyethylene bags.

3.2 Preparation of repacked soil-cores and treatments for laboratory experiments

Two weeks before the start of each experiment, selected soils were conditioned by moistening bulk soil samples to 40% water-filled pore space (WFPS) and kept for two weeks at 25°C to re-establish soil biological activity. Water- filled pore space, synonymous with relative saturation, was calculated as follows:

WFPS = [(gravimetric water content x soil bulk density)/ total soil porosity]

where:

$$\text{Soil porosity} = 1 - \frac{\text{soil bulk density}}{\text{soil particle density}}$$

Soil particle density = 2.65 Mg m^{-3}

Number of treatments for each of four laboratory experiments are summarized in Table 3. Some of these were common treatments which are explained here. The details of variable treatments are given in succeeding sections.

In each experiment there were two moisture regimes viz. upland and wetland soil conditions simulated by 60 and 120% WFPS, respectively. At 120% WFPS, a thin layer of free water was visible on the soil surface. Two rates of fertilizer N (0 and 100 mg NH_4^+-N kg^{-1} soil as ammonium sulphate) were used in all four experiments. Each treatment was triplicated in 4 or 6 batches to incubate for variable periods (Table 2). Repacked soil cores were prepared by placing moist pre-conditioned soil (20 g on oven dry basis) in 30 ml "see-through" plastic vials (except in experiment 3 where soil premixed with crop residues was used in required number of vials). Then the soil in each vial was hand compacted to required bulk density which was representative of natural reconsolidation for these soils.

Table 3. Number of various treatments used in different experiments (see text for detail).

Exp. No.	No.of soils used	No.of moist-ure regimes	No.of fert. treat.	No.of bulk den-sity treat.	No.of batches for incuba-tion	No.of repacked cores	No.of other treat-ments
1	3	2	2	3	6	216	–
2	3	2	2	1	4	144	–
3	1	2	2	1	4	240	4 CR^
4	1	2	2	1	6	288	3NI^^

^ CR = Crop Residues   ^^ NI= Nitrification Inhibitors

In half of the vials, 100 mg kg^{-1} of NH_4^+-N was added in solution form. Thereafter, distilled water was added dropwise using fine-jet pipette to obtain 60 and 120% WFPS. Each vial was covered with a perforated polythene sheet using a rubber band to allow diffusion of gases in and out and to restrict the evaporation of moisture. Thereafter, the vials were incubated at 35°C which is an optimum temperature for nitrification (Bhupinderpal-Singh, 1990). Moisture loss through evaporation, if any, was replaced after every 2-d period.

At the termination of incubation period of each batch, the whole soil of each vial was immediately extracted with 2M KCl (1h shaking) followed by filtration. These extracts were analysed for $(NO_3^- + NO_2^-)$-N and NH_4^+-N using a micro-Kjeldahl procedure (Keeney and Nelson, 1982).

3.3 Experiment I: Effects of varying soil texture

Effect of soil texture on nitrification in upland and wetland soil systems was studied using three soils varying in texture viz. sandy loam (Tolewal sandy loam-I), loam (Habowal) and silty clay (Chamror) having the comparable pH, EC and organic carbon (Table 2).

Two soil moisture regimes (upland and wetland soil conditions) and two rates of fertilizer N (0 and 100 mg NH_4^+-N kg^{-1} soil) were given. Two hundred and sixteen repacked soil cores prepared to the bulk density of 1.55, 1.45 and 1.35 Mg m^{-3} for sandy loam, loam and silty-clay soil, respectively, were incubated for 0, 3, 6, 10, 20 and 30 d period sampling.

3.4 Experiment 2: Effects of varying soil pH

Three soils varying in pH from acidic (Andretta, pH=4.8) through neutral (Tolewal-II, pH = 7.4) to alkalinity (Sodhi Nagar, pH = 9.8) were used for this study (Table 2).

Two soil moisture regimes (upland and wetland soil conditions) and two rates of fertilizer N (0 and 100 mg NH_4^+-N kg^{-1} soil) were given. One hundred and fortyfour repacked soil cores prepared to the bulk density of 1.5 Mg m^{-3}, were incubated for 0, 10, 20 and 30 d period sampling.

3.5 Experiment 3: Effects of crop residues varying in C/N ratio

Pre-conditioned Tolewal sandy loam-III soil (section 3.2) was used for this study (Table 2). Experiment treatments consisted of a "no-residue" control and four crop residues (2500 mg crop residue kg^{-1} soil), two moisture regimes (upland and wetland soil conditions) and two rates of fertilizer N (0 and 100 mg NH_4^+-N kg^{-1} soil).

Four crop residues were used in this experiment. Two crop residues (moongbean and cowpea) were collected green from a 45-d old crop, other two crop residues (wheat and soybean) were harvested at maturity (Table 4).

Whole plant samples of all above ground material without seed were used in this study. All crop residues were oven dried at 60°C for 3-d and chopped to 5 to 7 mm size before use. Two

Table 4. Characteristics of crop residues used in Experiment 3.

Residue	N content g kg^{-1}	C/N ratio
Wheat	4.2	111
Soybean	12.4	37
Moongbean	21.4	21
Cowpea	31.6	14

hundred and forty repacked soil cores prepared to the bulk density 1.5 Mg m^{-3}, were incubated for 0, 10, 20 and 30 d period sampling as explained in section 3.2.

3.6 **Experiment 4: Effects of different nitrification inhibitors**

Pre-conditioned Tolewal sandy loam-III soil (section 3.2) was used for this study (Table 2). The nitrification inhibitors used in this study are dicyandiamide (DCD), 4-amino 1,2,4-triazol (ATC), and encapsulated calcium carbide (ECC) obtained as per reported by Banerjee (1989). Experimental treatments consisted of a no-NI control; ATC and DCD @ 10 mg kg^{-1} soil (Wickramasinghe, 1985) applied in fertilizer solution, and ECC @ 5 mg g^{-1} soil (Banerjee, 1989) granules mixed with soil; two moisture regimes (upland and wetland soil condition); and two rates of fertilizer N (0 and 100 mg NH_4^+-N kg^{-1} soil). Two hundred and eighty eight repacked soil cores prepared to the bulk density 1.5 Mg m^{-3} were incubated for 0, 3, 6, 10, 15 and 20 d sampling as explained in section 3.2.

3.7 Effects of green manuring and fertilizer N in wetland rice

A field experiment was established in a semi-arid tropical Tolewal sandy loam-III soil at the Punjab Agricultural University Research Farm, Ludhiana (Table 2). Treatments consisted of three rates of fertilizer N (0, 60 and 120 kg N ha^{-1}) without and with green manure (GM) (25 or 50 t fresh biomass ha^{-1}). Seven treatments (N_0GM_0, $N_{60}GM_0$, $N_{120}GM_0$, N_0GM_{25}, $N_{60}GM_{25}$, $N_{120}GM_{25}$ and N_0GM_{50}) were triplicated in a randomized block design in individual plots of 3x10 m^2 size. Cowpea (Vigna unguiculata) was sown as a green manure crop on May 5,1992 with a basal dose of 15 kg N ha^{-1} as urea. After 45-d crop growth, cowpea was harvested, weighed, and disced into the soil. A representative sample of GM crop was taken at time of its incorporation and moisture was determined by drying it in oven at 60 ± 2°C for 3 days. The N content in GM dry matter was determined as explained in section 3.8.2. Green manure contained 83% moisture (w/w) and 30.1 g N kg^{-1} (on oven dry basis). Then 35 d old seedlings of rice (Oryza sativa L., variety PR 106) were transplanted in the puddled soil with a spacing of 15x15 cm. Nitrogen as urea was applied in three equal splits at 0, 28 and 42 days after transplanting (DAT). Crop was irrigated daily during the first month and thereafter at intervals so as to avoid "dry spells" of more than two days.

Using tube-auger (5 cm inner diameter) soil samples were collected upto 120 cm depth (0-15, 15-30, 30-60, 60-90, 90-120 cm) from all plots (2 to 3 cores taken from each plot were composited) at 0, 7, 14, 21, 28, 42, 63 and 125 DAT. Field moist soil samples were immediately extracted with 2M KCl solution, NH_4^+-N and NO_3^--N were determined in the extracts using steam distillation procedure (Keeney and Nelson, 1982). Simultaneously, soil moisture was also estimated gravimetrically.

At maturity grain and straw yields were recorded and expressed on a 14% moisture and oven-dry basis, respectively. Straw samples were washed, dried in an oven at 60±2°C and then ground in stainless steel blender. Total nitrogen in grain and straw was determined by micro-Kjeldahl's method (Section 3.8.2).

3.8 Methods used for soil and plant analysis

3.8.1 Soil analysis:

(1) **Moisture content**: Soil samples were oven dried in aluminium moisture boxes at 105°C to a constant weight and moisture content was expressed on an oven dry weight basis.

(2) **Mechanical analysis**: Particle size distribution of soil samples was determined using International Pipette method (Day, 1965). The USDA textural triangle was used for determining the textural class.

(3) **Soil pH**: Equilibrium pH of 1:2 soil:water suspension (kept for 30 minutes) was determined using a glass electrode pH meter.

(4) **Electrical conductivity (EC)**: The electrical conductivity of the 1:2 soil:water suspension (kept over night) was measured using a "solubridge".

(5) **Organic carbon (OC)**: The organic carbon was estimated using Walkley and Black (1934) rapid titration method.

(6) **Mineral nitrogen**: Soil was extracted with 2<u>**M**</u> KCl in the ratio 1:5 soil:KCl solution by shaking for 1h followed by filtration. Filtrate was analysed for NH_4^+-N and $(NO_3^- + NO_2^-)$-N by steam distillation using MgO and Devarda's alloy, respectively (Keeney and Nelson, 1982).

3.8.2 **Plant analysis**

A known weight (0.5g) of rice grain (unhusked) and straw was wet digested separately in concentrated H_2SO_4 with digestion mixture consisting of K_2SO_4, $CuSO_4$, Se, and HgO. The extract after digestion was diluted to 50 ml volume. Total N was determined from aliquot taken from digested extracts with steam distillation in alkaline medium (45% NaOH). The ammonium N so released was absorbed in 4% boric acid using bromcresol green and methyl red indicators. Its amount was determined by subsequent titration with N/70 H_2SO_4 (Jackson, 1967).

3.9 Statistical analysis and calculations

(1) The crop yield data were analysed statistically by using Randomized Block Design analysis of variance according to the procedure detailed by Steel and Torrie (1960).

(2) Standard deviation (S.D.) within replicates was calculated and reported as mean ± S.D. and indicated by Φ in figures.

(3) Nitrogen Fertilizer Equivalence (NFE) of green manure N was computed from the quardratic equation ($Y=a+bX+CX^2$) using grain yield (Y) obtained with varying rates of fertilizer N(X) applied without GM. The relative efficiency (RE) of GM nitrogen was calculated as follow :

$$\text{RE } (\%) = 100 \times \frac{\text{NFE}}{\text{Added GM nitrogen (kg N ha}^{-1})}$$

(4) $$\text{Percent nitrification} = \frac{B-C}{A} \times 100$$

Where A = Initial NH_4^+-N concentration in "fertilizer treatment" minus in "control" (mg N kg^{-1} soil)

B = NH_4^+-N concentration at a point of time in "fertilizer treatment" (mg N kg^{-1} soil)

C = NH_4^+-N concentration at a point of time in "control" (mg N Kg^{-1})

(5) First order kinetics of nitrification :

$$\text{Ln } C = \text{LnCo} - kt \qquad \text{----} \ [5]$$

$$k = 1/t \ \text{Ln} \frac{Co}{C} \qquad \text{----} \ [6]$$

Where k = first order rate constant (d^{-1})

t = time (d)

Co= Initial NH_4^+-N concentration in "fertilizer treatment" minus in "control" (mg N kg^{-1} soil)

C = NH_4^+-N concentration at time t in "fertilizer treatment" minus in "control" (mg N kg^{-1} soil)

(6) Percent nitrification inhibition with nitrification inhibitor (NI)

$$= 100 \times \frac{\%\text{ nitrification in "control" soil} - \%\text{ nitrification in "NI treated" soil}}{\%\text{ nitrification in "control" soil}}$$

(7) Apparent recovery of N applied through crop residue (CR)

$$= \frac{\text{Mineral N in "CR amended" soil (mg N kg}^{-1}\text{ soil)} - \text{mineral N in "unamended" soil (mg N kg}^{-1}\text{ soil)}}{\text{Added crop residue N (mg N kg}^{-1}\text{ soil)}}$$

(8) Apparent net mineralization of crop residue N

= Mineral N in "CR amended" soil (mg N kg^{-1} soil) - mineral N in "control" soil (mg N kg^{-1} soil)

Chapter-IV

RESULTS AND DISCUSSION

The results of the present investigation on the effects of different factors and management practices on nitrification and nitrate dynamics in upland and flooded soils are presented and discussed under the following heads:

4.1 **Effects of varying soil texture**

4.2 **Effects of varying soil pH**

4.3 **Effects of crop residues varying in C/N ratio**

4.4 **Effects of different nitrification inhibitors**

4.5 **Effects of green manuring and fertilizer N in wetland rice**

4.1 Effects of varying soil texture

The results obtained on the effects of varying soil texture under upland (60% WFPS) and flooded (120% WFPS) conditions incubated for 30 d period, on the nitrification of added NH_4^+-N are presented in Figures 2, 3, 4 and 5 and Tables 5, 6 and 7.

Under upland soil condition, varying soil texture from coarse (sandy loam) through medium (loam) to fine (silty clay), without or with 100 mg fertilizer NH_4^+-N kg^{-1} soil did not affect the nitrifying capacity of soils (Figs. 2 and 3). Nitrification was faster during the initial period as % nitrification ranged from 31 to 35 after 6 d and 97 to 100 after 10d of incubation. At

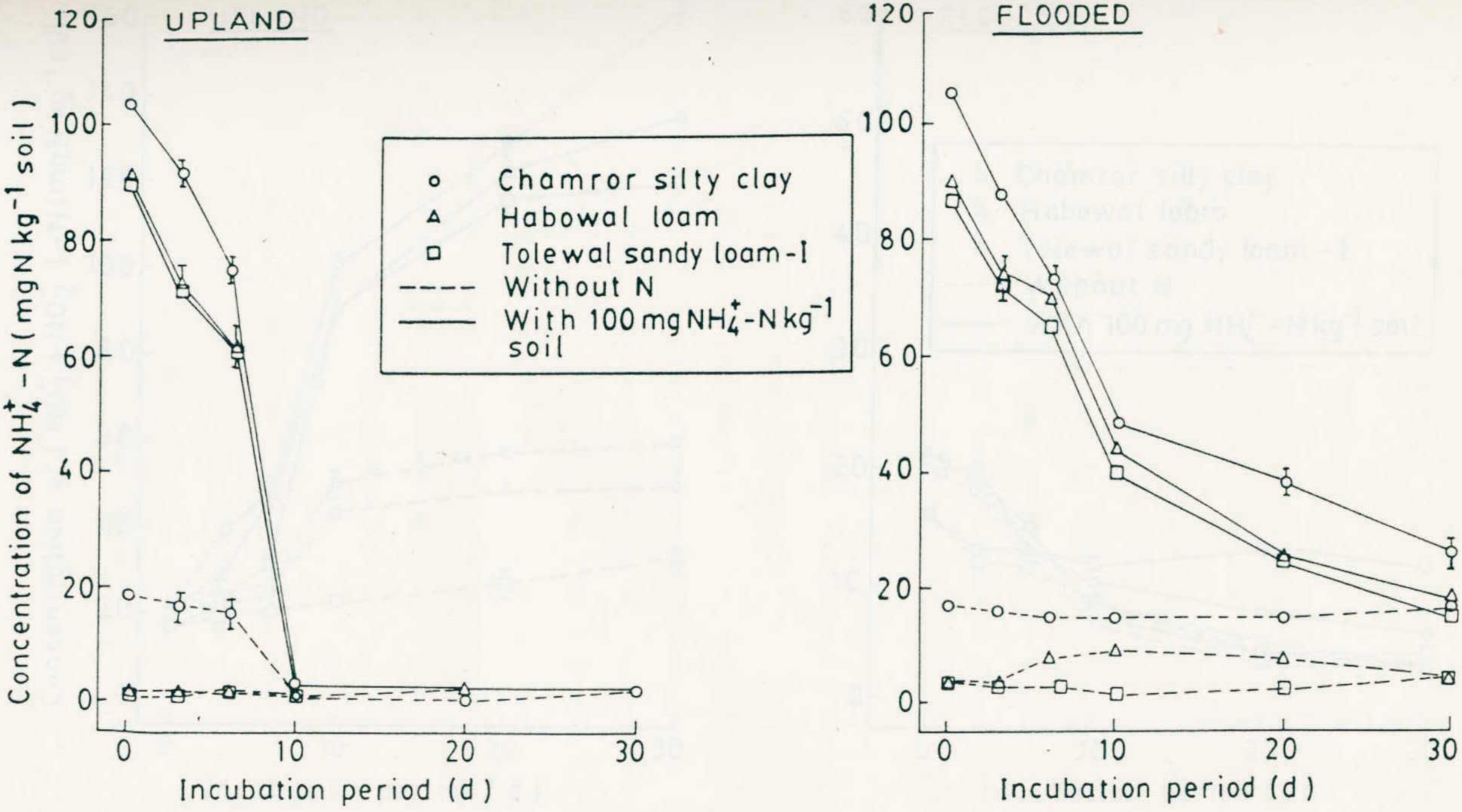


Fig. 2 Kinetics of ammonium-N in sandy loam, loam and silty clay soil incubated with and without 100 mg NH_4^+ – N kg^{-1} soil in upland and flooded conditions. Bars indicate the standard deviation.

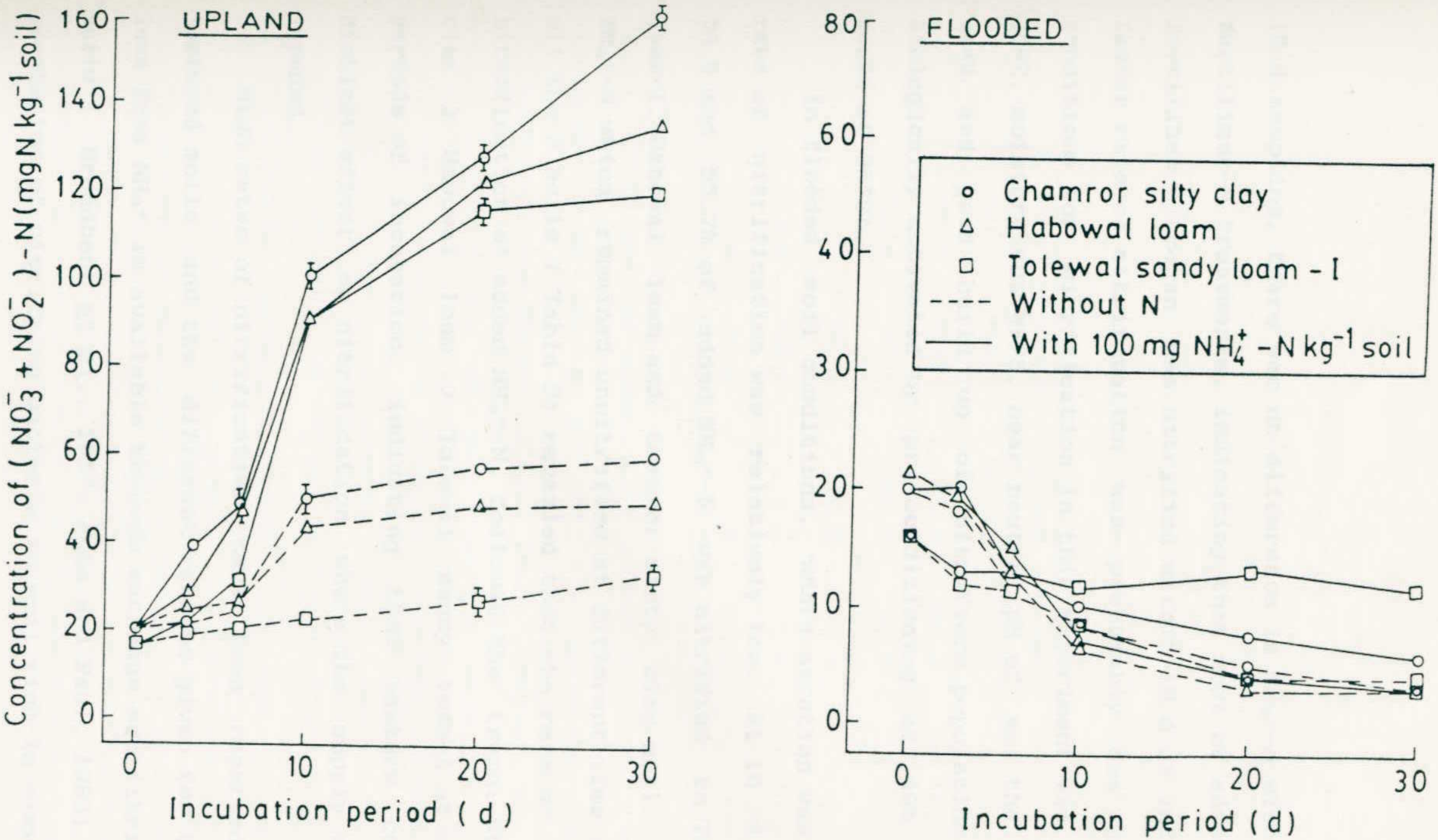


Fig. 3 Kinetics of nitrate-N in sandy loam, loam and silty clay soil incubated with and without 100 mg NH_4^+ -N kg^{-1} soil in upland and flooded conditions. (Note differences in the scale on y-axis) Bars indicate the standard deviation.

10 d sampling, there was no difference in NH_4^+-N with and without fertilizer-N treatments, indicating that most of added ammoniacal fertilizer nitrogen was nitrified within 10 d of incubation. The faster rate of nitrification was presumably due to the ideal conditions for nitrification in this experiment viz. temperature 35°C, moisture 60% WFPS, near neutral pH of all the three soils used and good build up of nitrifiers population (soils were biologically activated by pre-conditioning at 40% WFPS for 2 weeks at 25°C).

In flooded soil conditions, where aeration was restricted, rate of nitrification was relatively low. At 10 d, only 43.4, 54.6 and 55.7% of added NH_4^+-N was nitrified in Tolewal sandy loam-I, Habowal loam and Chamror silty clay soil. Per cent of NH_4^+-N which remained unnitrified at different time intervals in all the 3 soils (Table 5) revealed that the rate of nitrification of added NH_4^+-N followed the trend: Chamror silty clay > Habowal loam > Tolewal sandy loam-I at all the time periods of incubation, indicating that texture could have a distinct effect on nitrification where the supply of oxygen is impeded.

High rates of nitrification have been reported in finer-textured soils and the different reasons given for this are (a) less free NH_4^+ is available through exchange equilibria in sandy soils (Broadbent <u>et</u> <u>al</u>., 1957; Juma and Paul, 1983), (b) denser population of nitrifying bacteria in soil rich in clay minerals

Table 5. Effect of moisture regimes (upland and flooded conditions) on rate of nitrification in sandy loam, loam and silty clay soils.

Incubation period (d)	% ammonium un-nitrified					
	Tolewal sandy loam-I		Habowal loam		Chamror silty clay	
	Upland	Flooded	Upland	Flooded	Upland	Flooded
0	100.0	100.0	100.0	100.0	100.0	100.0
3	87.1	86.2	79.3	85.2	78.5	83.6
6	69.4	77.0	67.5	74.9	67.7	73.8
10	2.5	56.6	0.0	45.4	1.5	44.3
20	3.0	42.4	0.0	25.6	0.0	23.6
30	0.0	16.2	0.0	14.2	0.0	7.2

(Hosny, 1979) and (c) stimulating effect of CEC by lowering the concentration of NH_4^+ in soil solution below the toxic levels to organisms (Kai and Harada, 1969). This, however, may not be due to a direct effect of soil texture because potential for nitrification in soils is a complex interaction between substrate availability, soil structure, bulk density, pore size, aggregation and water infiltration rates that affect aeration, water holding or absorption capacity and micro-environment.

In most of earlier studies on nitrification, soil water content is usually expressed on a gravimetric or volumetric basis or on soils water-holding capacity without consideration of differences in density or porosity for soils of varying textures. Therefore, it has been difficult to obtain conclusive results on the effects of soil texture. The same water content in texturally different soils provide very different conditions of soil aeration and associated nitrification activity. For example, in the present experiment, a water content of 22% (gravimetric) resulted in 60% WFPS (40% air-filled pore space) or aerobic conditions in Chamror silty clay but in near saturated conditions (82% WFPS) in Tolewal sandy loam-I and consequently several-fold lower nitrification rates [Fig. 4(a)]. To integrate the effects of varying soil texture, bulk density and water content with varying management practices, Linn and Doran (1984b) suggested that WFPS was a reliable and relatively simple index of aeration status. In the present study, nitrification in three soils of widely varying texture were better indicated by WFPS rather than gravimetric water content [Fig. 4(b)]. The data clearly illustrate that when % nitrification was plotted against WFPS, there were no differences in nitrification in three soils of varying texture under ideal conditions (60% WFPS). However, substantial differences were observed in nitrification in soils of varying texture under flooded conditions.

Skopp (1985) developed a theoretical model of O_2 uptake and transport in relation to air-water interfacial area (Av). According to this model, at a given WFPS, Av and consequently O_2 flux would be less for sandy than for clay. Thus, soil texture would exhibit some controlling influence on rate of nitrification in O_2 limiting soils. The results of the present study clearly

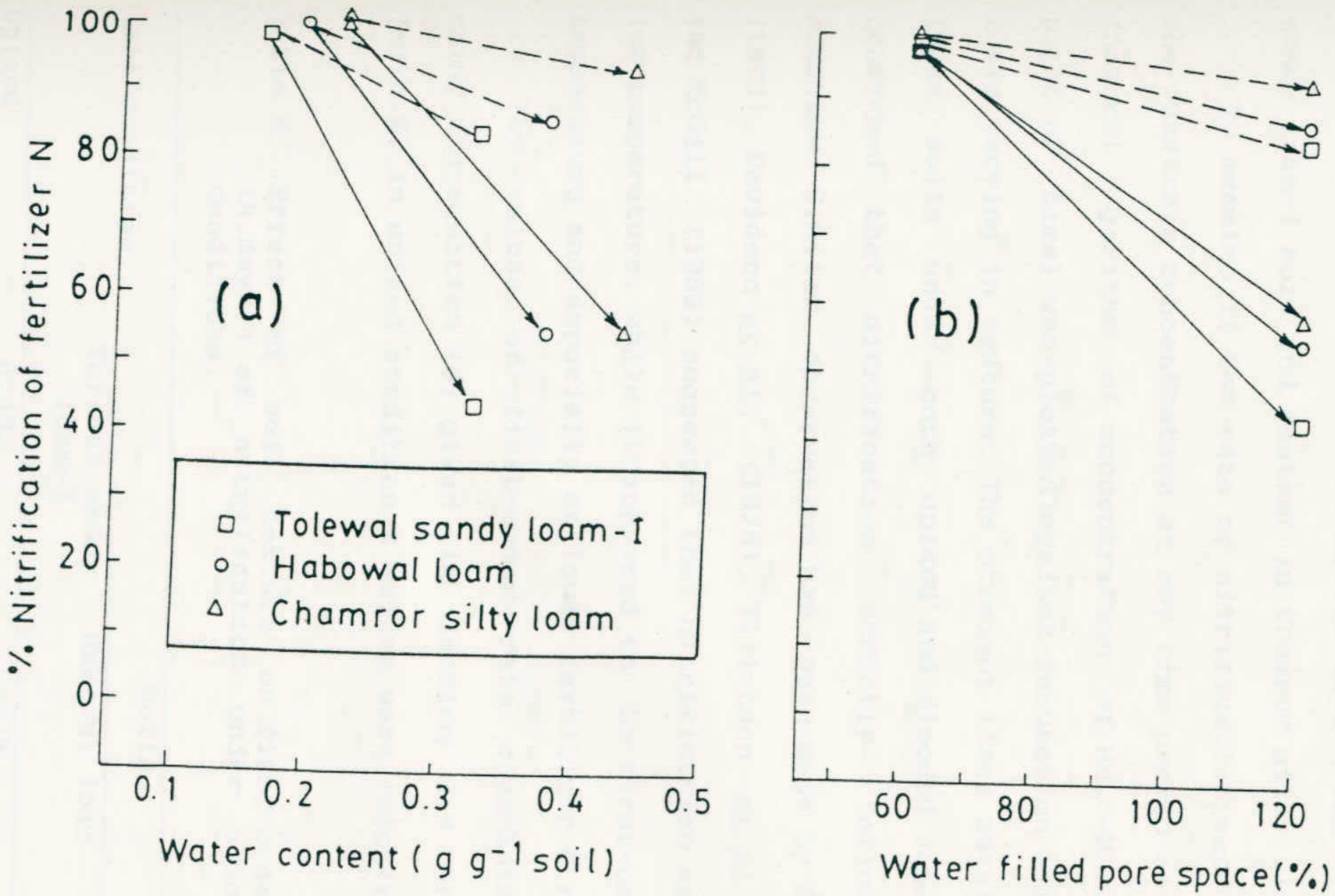


Fig.4 Relationship of nitrification with (a) soil water content and (b) water-filled pore space in three soils of varying soil texture incubated for 10 d (solid lines) or 30 d (broken lines)

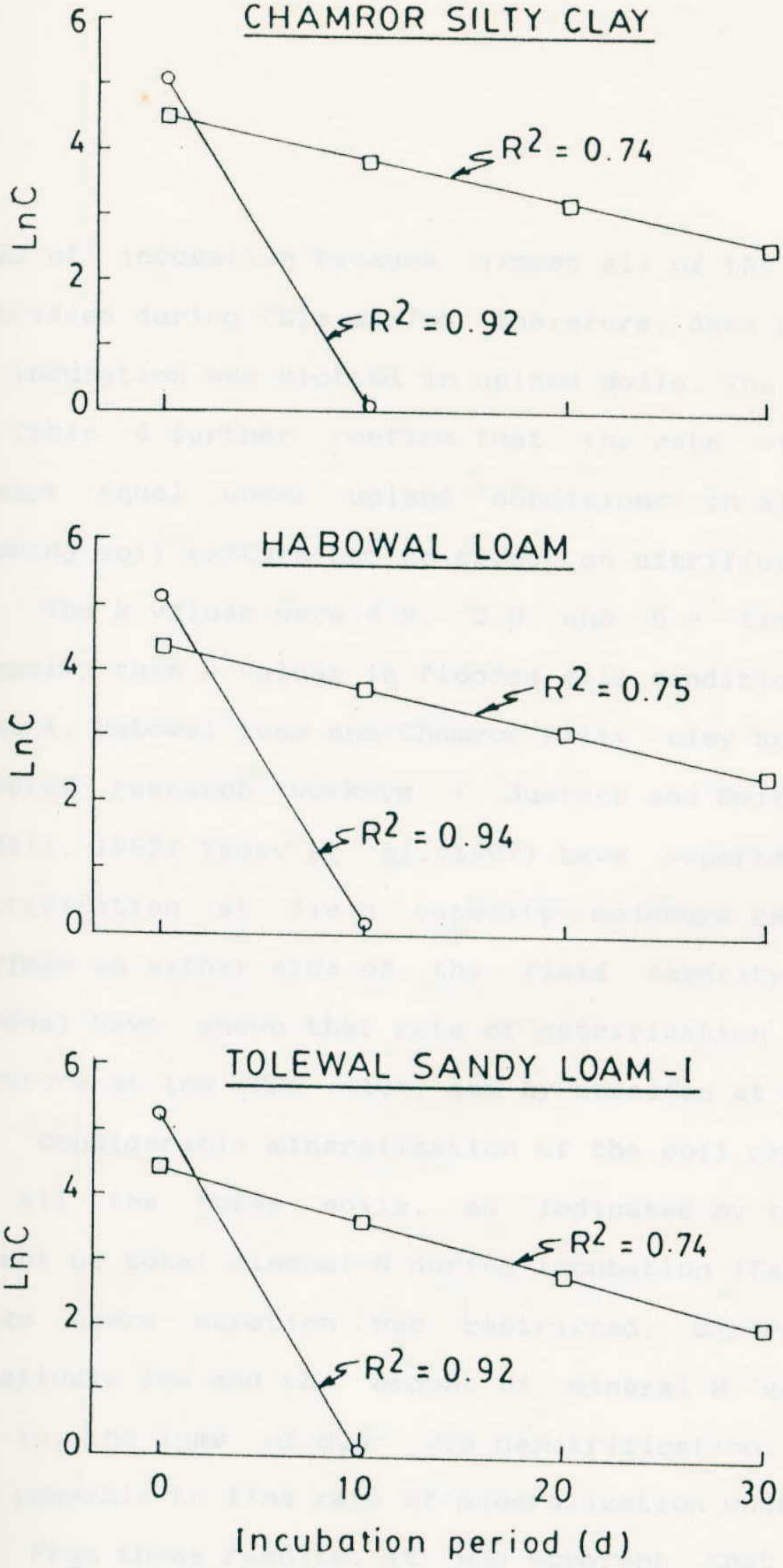
illustrate that the rate of nitrification was slowest in Tolewal sandy loam-I soil and fastest in Chamror silty clay soil.

To examine if the rate of nitrification was proportional to the substrate concentration at any time period of incubation, LnC (natural logarithm of concentration of NH_4^+-N unnitrified at a point of time) was plotted against incubation time for the three soils varying in texture. The straight lines obtained for all the three soils under both upland and flooded conditions (Fig. 5) confirmed that nitrification strictly followed first-order kinetics. Similar observation has been made by Beek and Frissel (1973), Davidson et al. (1978), Tillotson et al. (1980). Malhi and McGill (1982) suggested that nitrification was zero-order at low temperature, while it appeared to be first-order at optimum temperature and especially at lower fertilizer N rate.

The values of first-order rate constants (k) calculated using the equation (6) given in Section 3.9 are presented in Table 6. In upland condition k values were calculated upto 10

Table 6. Effect of soil texture on first-order rate constant (k, day^{-1}) of nitrification under upland and flooded conditions.

Soil condition	Soils		
	Tolewal sandy loam-I	Habowal loam	Chamror silty clay
Upland	0.402	0.375	0.358
Flooded	0.082	0.064	0.067



CHAMROR SILTY CLAY

HABOWAL LOAM

TOLEWAL SANDY LOAM-I

Fig.5 Plots showing first order kinetics of nitrification in upland (○) and flooded condition (□) for three soils varying in texture.

days of incubation because almost all of the applied NH_4^+-N was nitrified during this period. Therefore, data points upto 10 days of incubation was plotted in upland soils. The k values as listed in Table 6 further confirm that the rate of nitrification was almost equal under upland conditions in all the three soils, showing soil texture had no effect on nitrification.

The k values were 4.9, 5.8 and 5.8 times more at field capacity than k values in flooded soil condition in Tolewal sandy loam-I, Habowal loam and Chamror silty clay soils, respectively. Several research workers (Justice and Smith, 1962; Malhi and McGill, 1982; Yadav *et al*.(1987) have reported maximum rate of nitrification at field capacity moisture regime than moisture regimes on either side of the field capacity. Linn and Doran (1984a) have shown that rate of nitrification is limited by soil moisture at low WFPS (<10%) and by aeration at high WFPS (>90%).

Considerable mineralization of the soil organic N took place in all the three soils, as indicated by the increase in the amount of total mineral-N during incubation (Table 7). In flooded soils where aeration was restricted, mineralization of N was relatively low and the amount of mineral N decreased with time due to the loss of NO_3^- via denitrification. Therefore, it was not possible to find rate of mineralization under flooded soils.

From these results, it was apparent that (i) Nitrification of fertilizer N was very fast under ideal conditions and most of applied 100 mg NH_4^+-N kg^{-1} soil was nitrified within 10 days of

Table 7. Total mineral N (NH_4^+ + NO_3^- + NO_2^-) in three soils varying in texture incubated with or without 100mg N. kg^{-1} under upland and flooded conditions

Incubation period (d)	Upland		Flooded	
	-N	+N	-N	+N
		Chamror silty clay		
0	*39.2±0.5	123.9±0.8	37.1±0.4	125.5±1.4
3	39.6±0.6	130.1±0.8	35.4±0.4	107.9±1.0
6	40.8±1.0	123.3±2.7	26.0±0.3	83.4±0.9
10	51.3±3.0	103.5±1.3	19.0±1.0	53.0±0.4
20	57.7±0.6	130.8±6.3	23.6±0.7	48.0±1.2
30	61.8±0.3	162.8±1.4	19.9±0.3	35.0±1.7
		Habowal-loam		
0	22.8±0.0	111.7±0.0	24.6±0.0	115.5±0.0
3	26.9±0.6	100.8±2.6	30.4±0.5	92.0±1.3
6	27.6±0.3	110.0±2.3	36.1±0.1	82.2±0.0
10	44.4±0.2	92.4±0.3	21.1±0.0	51.8±0.0
20	50.8±0.8	122.4±0.3	14.5±0.0	30.0±0.1
30	53.8±0.2	137.1±0.3	13.8±0.3	18.0±0.5
		Tolewal sandy loam-I		
0	17.4±0.0	106.3±0.3	19.6±0.0	102.9±0.5
3	19.8±0.0	91.3±0.1	15.6±0.2	85.8±1.1
6	23.0±0.0	94.3±1.3	14.9±0.0	76.5±1.1
10	23.4±1.0	97.8±0.9	5.4±0.0	61.0±0.3
20	27.4±1.2	116.4±1.3	6.2±0.1	38.0±0.4
30	33.4±0.8	120.4±0.0	8.0±0.6	29.0±0.6

* Mean of 3 replicates ± Standard Deviation.

aerobic incubation. Whereas in flooded soil conditions, nitrification was slow and 8 to 16% of applied NH_4^+-N was still unnitrified even after 30 days. (ii) At similar water contents, rates of nitrification differed greatly in soils of varying texture, but when varying water holding capacity and bulk density were accounted for using WFPS, all soils behaved very similarly at 60% WFPS. Under impeded aeration (flooded conditions), however, substantial differences were observed in nitrification in soils of varying texture, and was highest in fine-textured Chamror silty clay followed by Habowal loam and was slowest in Tolewal sandy loam-I soil.

4.2 Effects of varying soil pH

Aerobic incubation (60% WFPS) of soils, varying in pH range from acidity through neutrality to alkalinity without or with 100 mg fertilizer NH_4^+-N kg^{-1} soil revealed distinct differences in the nitrifying characteristics (Figs. 6,7). Neutral Tolewal-II soil had the highest nitrifying rate, followed by alkaline Sodhi Nagar and acidic Andretta soil in that order. The similar trend was observed for control soils (without added NH_4^+-N).

Relatively slow nitrification in the acidic Andretta soil as compared with the neutral Tolewal-II soil was presumably because of the slow activity of nitrifying bacteria at pH 4.8. Nitrification was faster from 0 to 10 days than during the 10 to 30 days, period. The acid soil still contained 73 mg NH_4^+-N kg^{-1}

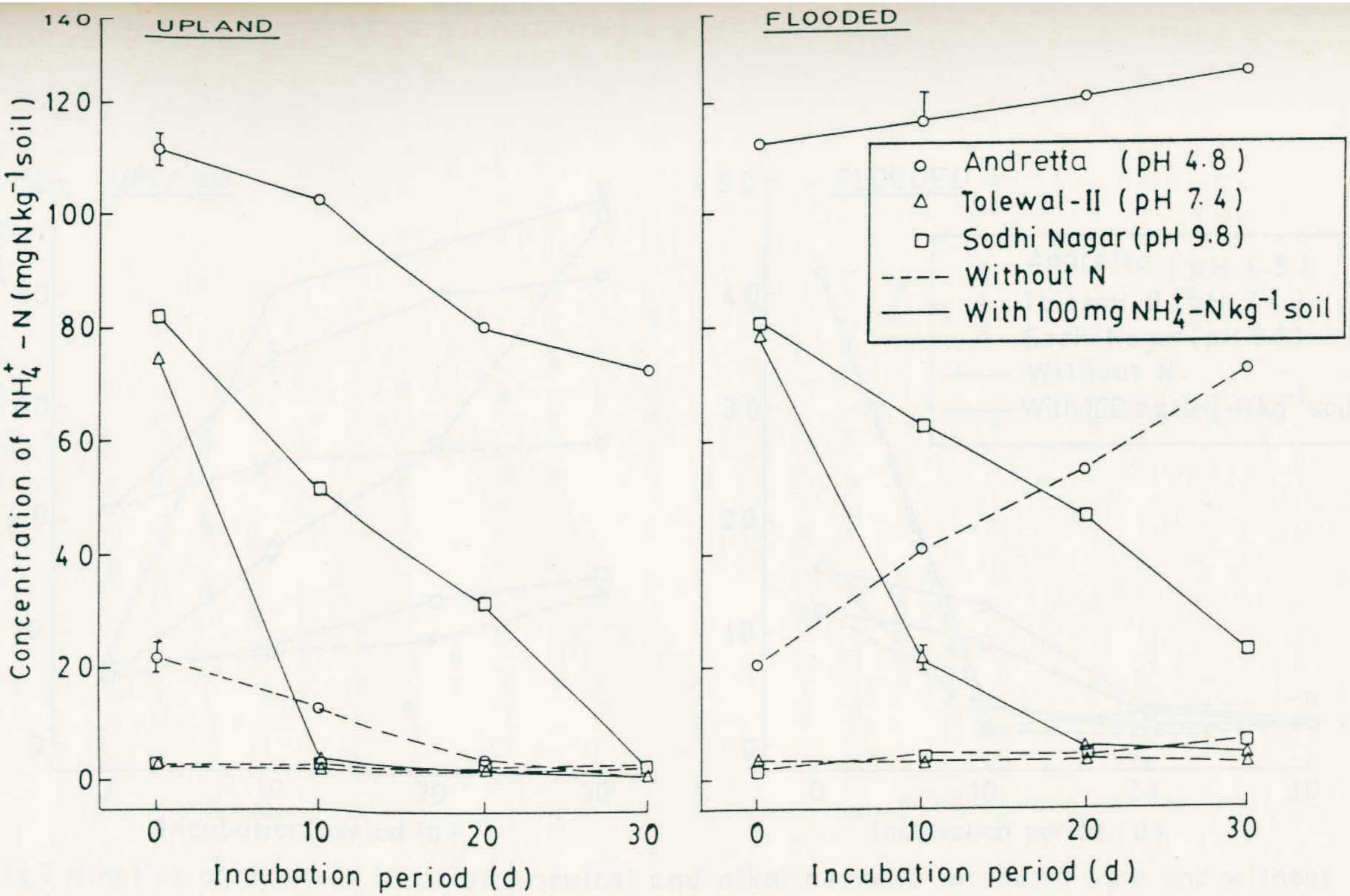


Fig. 6 Kinetics of ammonium-N in acidic, neutral and alkaline soils incubated with and without 100 mg NH$_4^+$−N kg^{-1} soil in upland and flooded conditions. Bars indicate the standard deviation.

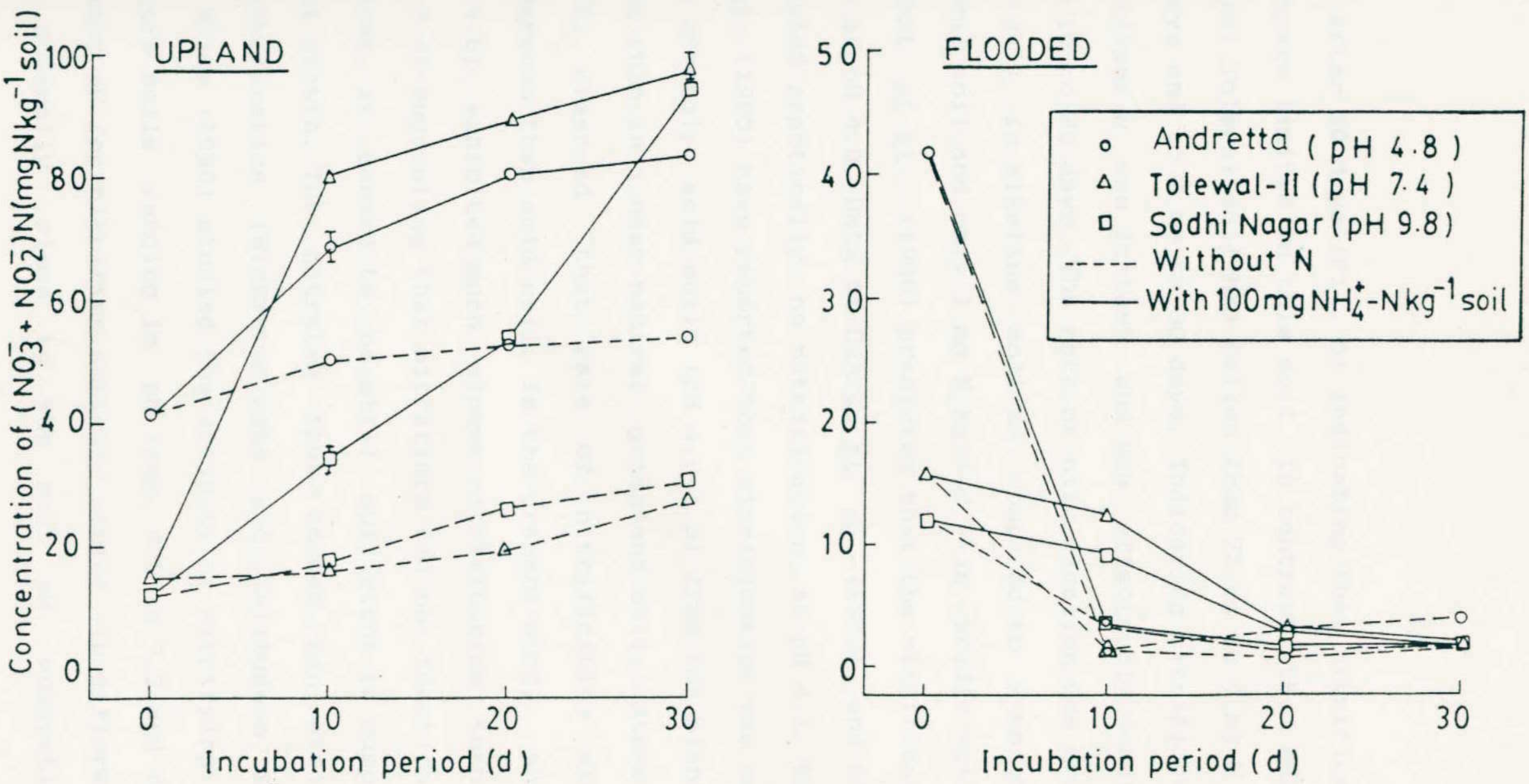


Fig. 7. Kinetics of nitrate-N in acidic, neutral and alkaline soils incubated with and without 100 mg NH$_4^+$-N kg^{-1} soil in upland and flooded conditions. (Note differences in the scale on y-axis). Bars indicate the standard deviation.

soil after 30 days (Fig. 6) indicating that nitrification was not substrate limited in this soil. In contrast, the NH_4^+-N level in neutral Tolewal soil had fallen from 75 mg to 4 mg N kg^{-1} soil by 10 days and to 2 mg by 30 days, indicating nitrification of added fertilizer N was fastest and was effectively substrate-limited from 10 to 30 days. The rate of nitrification was modest (3 mg N kg^{-1} d^{-1}) in alkaline soil as compared to 7 mg N kg^{-1} d^{-1} in neutral soil and only 1 mg N kg^{-1} d^{-1} in acidic soil. The model of Bhat et al. (1980) predicted that the nitrification rate was zero at pH 4.0. Data of Dancer et al. (1973) and Gilmour (1984) revealed practically no nitrification at pH 4.1. Wickramasinghe et al. (1985) have reported that nitrification was much slower in five strongly acid soils (pH 4.0→4.3) from tea-plantation in Sri Lanka than in a near neutral grassland soil. Stams and Marnette (1990) observed that rate of nitrification was higher in calcareous than acid soil. In the present study, the acidic soil (pH 4.8) exhibited much slower nitrification than neutral soil (pH 7.4) suggesting that nitrifiers did not function effectively. However, it seemed to be still sufficient to supply NO_3^--N for plant growth. The nitrates thus formed can also be lost by denitrification (Wickramasinghe and Talibudeen, 1987). Bramley and White (1990) studied the activity of nitrifying organisms in pasture soils ranging in pH from 4.9 to 7.3 and found that the optimum pH for nitrifier activity varied in different soils and was generally close to the soil pH, suggesting that the indigenous nitrifier population adjusted to the prevailing soil pH.

The plot of LnC vs t gave a straight line relationship (Fig. 8) which is a characteristics of first order reaction. The values of rate constant (k) were calculated using first-order reaction equation (6) (Section 3.9) for different pH soils upto 30 days in both upland and flooded condition except in neutral Tolewal-II soil, in which almost all the NH_4^+-N added was nitrified upto 10 days under upland soil condition and, therefore, data points upto 10 days of incubation were used. The k values (Table 8) further confirm that the rate of nitrification was fastest in Tolewal neutral soil (k=0.351 day^{-1}), modest in Sodhi Nagar alkaline soil (k=0.119 day^{-1}) and slowest in Andretta acidic soil (k = 0.009 day^{-1}). The k values obtained in Tolewal neutral soil were 1.13 and 15 times of k values for Sodhi Nagar alkaline and Andretta acidic soil, respectively. Dancer <u>et al</u>. (1973) found a 3 to 5-fold increase in the nitrification rate with soil pH increasing from 4.7 to 6.5.

In flooded soil conditions, where aeration was restricted resulting into anaerobic condition, rate of nitrification was relatively low. The k values in upland condition were 1.66, 1.13 and 2.33 times more than k values in flooded soil condition in Andretta acidic, Tolewal neutral-II and Sodhi Nagar alkaline soils, respectively. The rate constants computed for water-logged

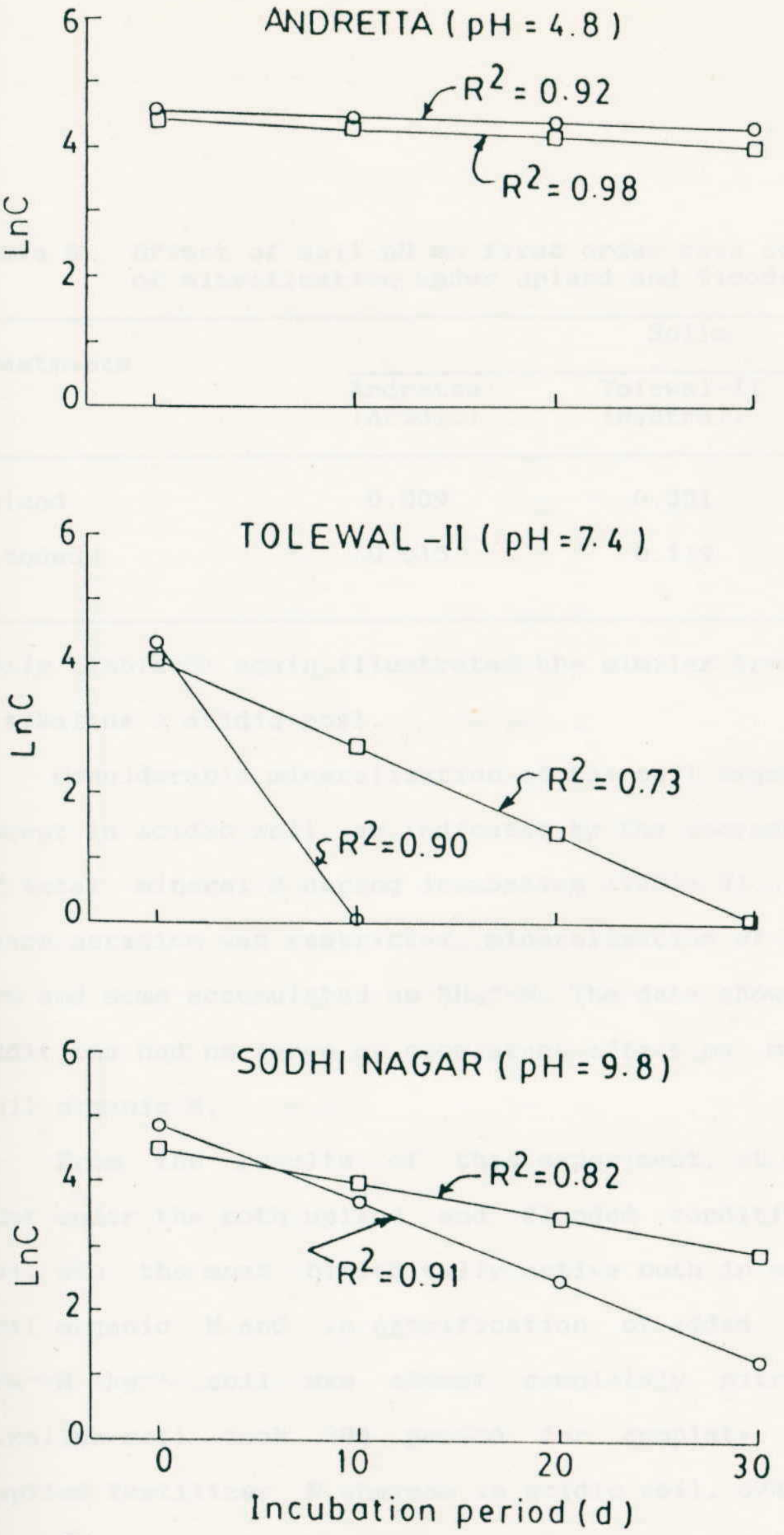


Fig. 8. Plots showing first order kinetics of nitrification in upland (○) and flooded condition (□) for three soils varying in pH

Table 8. Effect of soil pH on first order rate constant(k,day^{-1}) of nitrification under upland and flooded conditions.

Treatments	Soils		
	Andretta (Acidic)	Tolewal-II (Neutral)	Sodhi Nagar (Alkaline)
Upland	0.009	0.351	0.119
Flooded	0.015	0.119	0.051

soils (Table 8) again illustrated the similar trend viz. neutral > alkaline > acidic soil.

Considerable mineralization of the soil organic N took place except in acidic soil, as indicated by the increase in the amount of total mineral N during incubation (Table 9). In flooded soils where aeration was restricted, mineralization of N was relatively low and some accumulated as NH_4^+-N. The data showed that nitrogen additions had no large or consistent effect on mineralization of soil organic N.

From the results of this experiment, it may be concluded that under the both upland and flooded conditions the neutral soil was the most biologically active both in mineralization of soil organic N and in nitrification of added nitrogen (100 mg NH_4^+-N kg^{-1} soil was almost completely nitrified in 10d). Alkaline soil took 30d period for complete nitrification of applied fertilizer N whereas in acidic soil, 67% of it was still unnitrified at 30d. Furthermore, there was no difference in

Table 9. Total mineral-N (NH_4^+ + NO_3^- + NO_2^-) in three soils of different pH incubated with or without 100 mg N kg^{-1} under upland and flooded conditions.

Incubation period (d)	Upland		Flooded	
	-N	+N	-N	+N
		Andretta (Acidic)		
0	*61.9±1.9	112.9±1.5	63.1±1.2	156.5±1.2
10	63.4±1.1	171.8±0.9	42.2±0.4	119.7±3.1
20	56.9±0.4	161.5±1.0	56.3±0.3	121.9±0.4
30	54.9±0.7	156.9±1.2	69.4±0.8	128.1±0.9
		Tolewal-II (Neutral)		
0	17.8±0.4	89.7±0.5	19.1±0.4	93.9±1.2
10	17.2±0.4	84.8±0.5	4.3±0.3	34.0±1.5
20	21.8±0.8	92.5±0.5	7.0±0.4	9.2±0.7
30	30.5±0.7	98.7±1.2	6.8±0.1	7.1±0.3
		Sodhi Nagar (Alkaline)		
0	14.6±0.8	94.4±0.7	13.8±0.5	93.1±0.9
10	19.5±0.5	86.6±1.0	7.0±0.5	72.2±0.6
20	29.1±0.7	85.5±0.9	5.5±0.3	49.1±0.6
30	32.8±1.0	96.8±1.2	8.7±0.2	24.4±0.2

* Mean of 3 replicates ± Standard Deviation.

nitrification under upland and flooded condition in Andretta acidic soil.

4.3 Effects of crop residues varying in C/N ratio

As observed in previous experiments (Section 4.1 and 4.2), nitrification of applied NH_4^+-N in this neutral Tolewal sandy loam-III soil (incubated at 60% WFPS) was very fast and almost complete in initial 10 d in treatment without or with crop residues (Fig. 9). As a result of this NO_3^--N increased from 18.0 mg kg^{-1} soil at beginning of incubation to 92.0, 98.0 and 104.0 mg kg^{-1} in unamended soil at 10, 20 and 30 d, respectively (Fig. 10).

Wheat, soybean, moongbean and cowpea residue added to the soil at the rate of 2500 mg kg^{-1} contributed 11, 38, 54 and 79 mg of residue N kg^{-1} soil, respectively. Incorporation of soybean (C/N = 37) and wheat (C/N = 111) resulted in substantial N immobilization in soil incubated at 60% WFPS, especially during the initial 10 d incubation period followed by slow mineralization (Table 10). The apparent net immobilization (mineral N in "control" soil minus mineral N in "residue amended" soil) from incorporation of these wider C/N ratio residues with fertilizer N after 30 d was 18 and 37 mg N kg^{-1}, respectively (Table 10). On the other hand, significant accumulation of NO_3^--N occurred with the incorporated moongbean (C/N = 21) and cowpea (C/N = 14) residues with low C/N ratio. In the initial 10 d

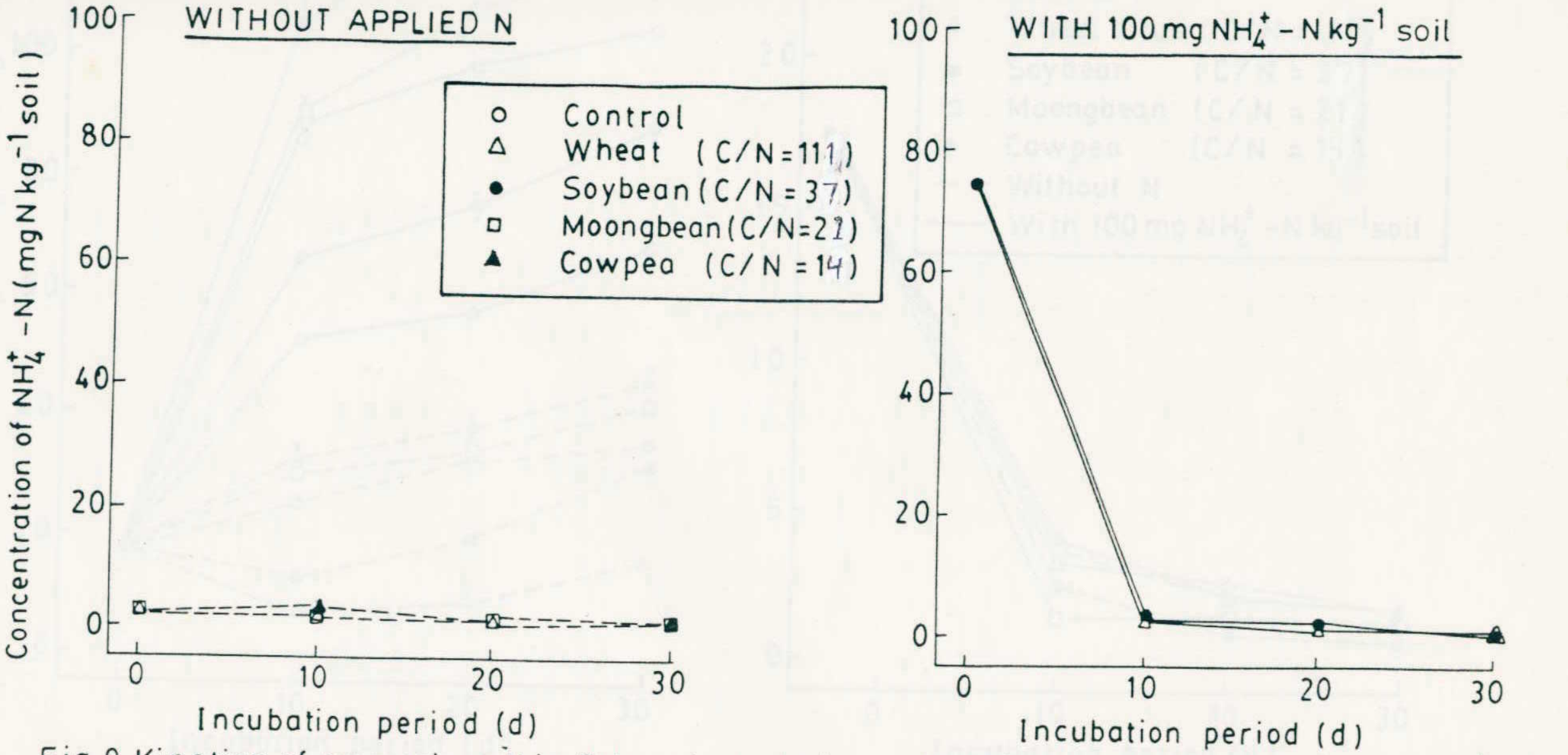


Fig. 9. Kinetics of ammonium-N in Tolewal sandy loam - III soil with and without 100 mg NH_4^+ -N kg^{-} soil in upland soil condition incorporated with wheat, soybean, moongbean and cowpea crop residues.

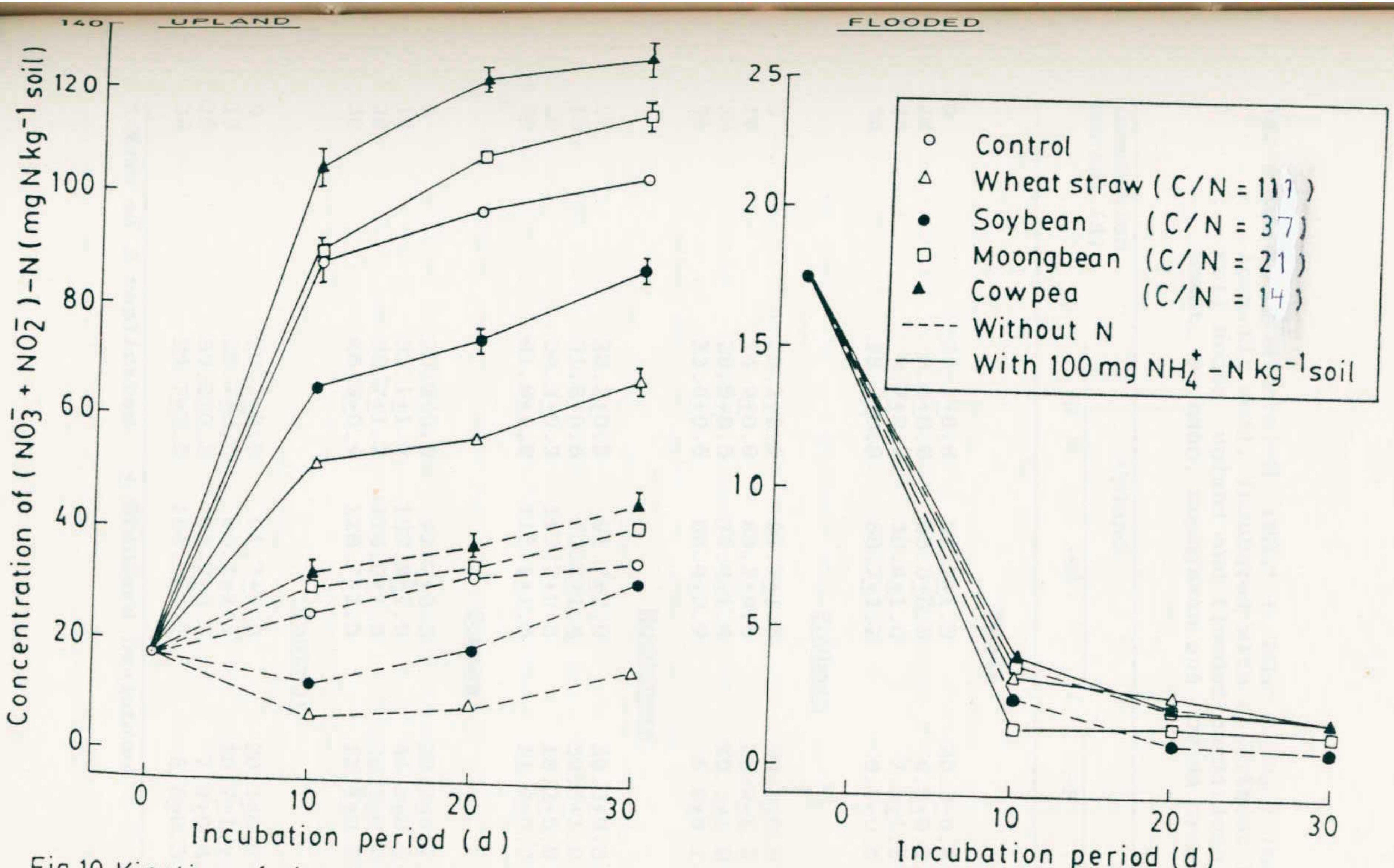


Fig.10 Kinetics of nitrate-N in Tolewal sandy loam - III soil with and without 100mg NH_4^+-N kg^{-1} soil in upland and flooded soil conditions incorporated with wheat, soybean, moongbean and cowpea crop residues. Bars indicate the standard deviation. (Note differences in the scale on y_axis)

Table 10. Total mineral-N (NH_4^+ + NO_3^- + NO_2^-) in Tolewal sandy loam-III soil, incubated with or without 100 mg N kg^{-1} soil under upland and flooded conditions, amended with wheat, soybean, moongbean and cowpea crop residues.

Incubation period (d)	Upland		Flooded	
	-N	+N	-N	+N
		Wheat		
0	*20.2±0.8	91.7±1.9	20.3±0.8	89.5±1.4
10	8.6±0.8	55.0±0.5	6.5±0.7	34.3±0.4
20	9.7±0.7	58.6±1.0	7.1±1.1	14.5±1.2
30	18.2±0.8	68.7±1.2	8.3±0.5	10.6±0.4
		Soybean		
0	20.2±0.7	91.7±1.5	20.3±0.6	89.5±1.3
10	14.9±0.0	68.1±0.6	22.9±1.2	41.0±0.9
20	20.5±0.5	76.4±1.4	10.1±1.0	25.2±1.6
30	32.4±0.6	88.4±0.9	6.9±0.1	16.0±0.4
		Moongbean		
0	20.2±0.8	91.7±2.0	20.3±0.8	89.5±1.4
10	31.8±0.6	92.7±1.4	34.5±1.0	54.1±2.5
20	34.3±0.3	112.7±0.5	18.2±0.8	33.3±0.9
30	41.8±0.8	115.1±1.5	11.9±0.3	25.4±0.9
		Cowpea		
0	20.2±0.8	91.7±3.3	20.3±0.7	89.5±1.4
10	35.1±1.0	107.9±1.9	46.8±0.9	70.7±0.2
20	38.7±1.2	124.9±1.5	20.3±0.4	41.3±0.7
30	46.3±0.9	128.7±1.3	12.7±0.8	29.3±0.6
		Control		
0	20.2±0.8	91.7±2.0	20.3±0.7	89.5±1.4
10	25.7±0.5	94.1±1.6	10.9±1.1	34.3±2.0
20	33.2±0.2	99.7±0.3	7.9±0.4	16.0±0.4
30	35.7±2.2	106.0±1.7	6.6±0.3	8.7±0.6

* Mean of 3 replicates ± Standard Deviation.

(without fertilizer N) there was a net accumulation of 5 and 7 mg NO_3^--N kg^{-1} soil with moongbean and cowpea residues, respectively. During the following 20 d, additional 1 and 3 mg NO_3^--N kg^{-1} was released resulting in a total of 6 and 10 mg N kg^{-1}. When fertilizer N was applied, the recovery of residue N enhanced and net release of NO_3^--N was 11 and 24 mg N kg^{-1} soil in moongbean and cowpea, respectively. The apparent recovery of added residue N [(mineral N in "amended soil" minus mineral N in "unamended" soil)/added crop residue N] through moongbean was 11 and 17% when applied without and with fertilizer N, respectively (Table 10). The corresponding values for cowpea were 13 and 29%, respectively. Similar fast mineralization of N incorporated through green manures such as sesbania (12 to 38%), alfalfa (12 to 28%), vetch (36%), moongbean (35%) and cowpea (37%) have been reported earlier (Yadvinder-Singh et al., 1988; Gale and Gilmour, 1988; Aulakh et al., 1991a; Buresh et al., 1991 and Tejinder Singh, 1993). Relatively low mineralization of crop residue N may also be due to addition of dry moongbean and cowpea instead of fresh green manure incorporation. Drying green manure before incorporation into soil is generally considered to reduce the rate and amount of N release. In upland crops, field drying reduced the mineralization of green manure by as much as 20% (Lohnis, 1926). According to Joachim (1931) drying green manure converts soluble hemicelluloses into less soluble forms. This retards decomposition. Easily decomposable organic forms of N are also reduced by drying. Ito and Watanabe (1985) found that fresh azolla released upto 2.5 times more NH_4^+-N than dried azolla. The NH_4^+-N released from fresh azolla reached a plateau after 16 days, whereas N mineralization in dry azolla was rapid only upto forth day of incubation.

The consistently substantial amount of release of NO_3^--N observed throughout the incubation in the cowpea and moongbean residue amended soils was essentially due to the mineralization in excess of immobilization since in cowpea and moongbean the C/N ratio is fairly low and N content was higher as compared to wheat and soybean residues. Patra <u>et al</u>. (1992) had shown that more nitrates were produced from low C/N ratio cowpea than those from wider C/N ratio wheat residues in a soil at 60% of maximum water holding capacity. Similarly, in a recent study Aulakh <u>et al</u>. (1991a) showed that the NO_3^--N content of Nicollet loam soil at 60% WFPS decreased from 104 mg N kg^{-1} to 70-72 mg N kg^{-1} with the incorporatioin of 2500 mg kg^{-1} of wider C/N ratio crop residues (wheat, corn, soybean) whereas the addition of narrow C/N ratio crop residue (vetch) resulted in an additional accumulation of 72 mg NO_3^--N kg^{-1} soil in 35 d. The present study reconfirms that incorporation of wider C/N ratio crop residues (wheat and soybean) immobilizes mineral-N and narrow C/N ratio crop residues (cowpea and moongbean) result in the accumulation of nitrates in aerobic incubation.

Under flooded condition, the native NO_3^--N in soil (17.5 mg kg^{-1}) in all the treatments (with and without crop residue incorporation) disappeared quickly and traces of NO_3^--N were observed at 10 d or thereafter till the termination of incubation study (Fig. 10), indicating that the fate of NO_3^--N under flooded condition was short lived. In residue-amended soils, at 120% WFPS soil NO_3^--N decreases rapidly through denitrification and immobilization (Aulakh et al., 1991a).

It is interesting to note that in all the experiments discussed above, as well as in this experiment, NH_4^+-N did not accumulate substantially in Tolewal sandy loam soil even at 120% WFPS (Fig. 11). This may be partly due to incomplete inhibition of nitrification in flooded soils because NH_4^+ could be oxidized to NO_3^- in the thin O_2-containing surface soil layer and in the overlying water phase of flooded soils (Engler and Patrick, 1974). The so formed nitrates in this upper oxidized zone move into the lower anaerobic zone where they may be lost via denitrification (Tusneem and Patrick, 1971).

In this experiment incorporation of crop residues resulted in accumulation of NH_4^+-N at 10 d period when fertilizer N was not applied (Fig. 11). In poorly aerated soils, O_2 transport cannot keep up with O_2 demand, and degree of anaerobiosis, often expressed by redox potential (Khind et al., 1987) or by content of reduced species such as Mn, Fe and Cu (Walters et al., 1992) is increased. The rate of increase of reduction intensity would

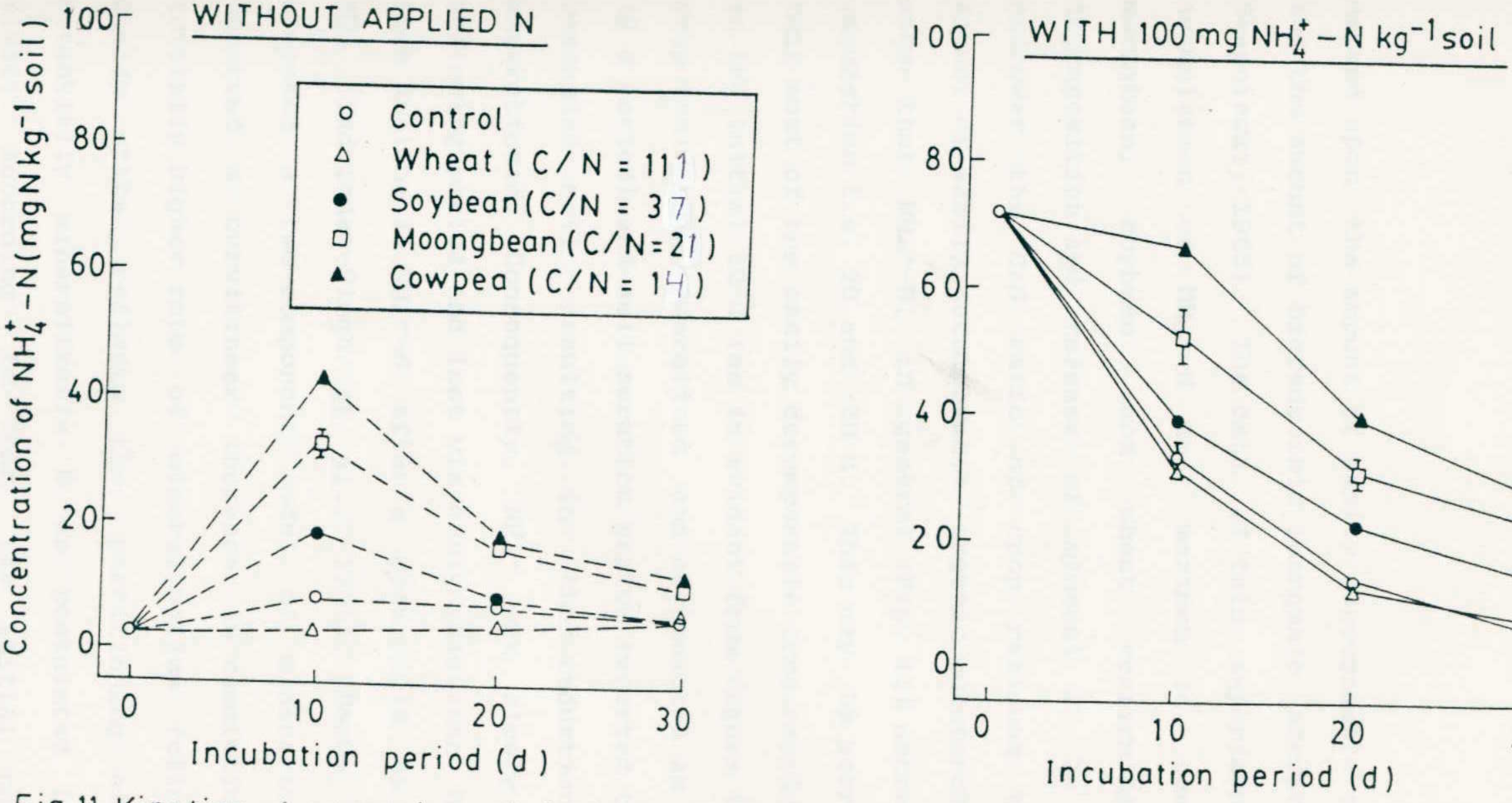


Fig. 11. Kinetics of ammonium-N in Tolewal sandy loam - III soil with and without 100 mg NH_4^+ – N kg^{-1} soil in flooded condition incorporated with wheat, soybean, moongbean and cowpea crop residues. Bars indicate the standard deviation.

depend upon the amount of easily decomposable organic substrates and the amount of bioreducible inorganic acceptors (Gilinski and Stepniewki, 1985). The data of this experiment illustrate that acumulation of NH_4^+-N was maximum in cowpea followed by moongbean, soybean, and wheat confirming their ease of decomposition and release of mineral N. In other words the narrower the C/N ratio of crop residues, the highest is the amount of easily decomposable organic substance. However, it is seen that NH_4^+-N, in general (Fig. 11) decreased with further incubation i.e. 20 and 30 d. This may be ascribed to the fact that most of the easily decomposable crop residues were exhausted in the initial 20 d (as is evident from figure 10) (43 and 45% of crop residue N mineralized and accumulated as NH_4^+-N in initial 10 d period) and soil aeration status reverted to that existed in unamended soil resulting in the reduction of degree of anaerobiosis. Consequently, NH_4^+ was slowly nitrified during following period and lost via denitrification. Another reason for this decline in NH_4^+-N after a peak could be volatilization as NH_3 (Yadvinder-Singh _et_ _al_., 1991). Bonde _et_ _al_. (1988) who proposed a two-component model of mineralization, similarly, observed a curvilinear increase in cumulative inorganic-N. An initially higher rate of mineralization followed by a fairly steady state reflects the partitioning of two pools of potentially mineralizable N as postulated by Molina _et_ _al_. (1980). According to them the initial phase corresponded presumably to more labile pool. Similarly two components : more available and more recalcitrant soil organic-N were proposed by Bonde and Rosswall (1987).

From these results it was apparent that under upland conditions incorporation of wider C/N ratio crop residues (wheat and soybean) resulted in substancial N immobilization especially during the initial 10 d followed by slow mineralization. On the other hand, the narrow C/N ratio crop residues (moongbean and cowpea) resulted in accumulation in NO_3^--N. The apparent recovery of added residue N was 17 and 29% with moongbean and cowpea, respectively. Under flooded conditions, NO_3^--N content disappeared quickly in all the treatments. Incorporation of crop residues resulted in accumulation of NH_4^+-N at 10 d period when fertilizer was not applied. Accumulation of NH_4^+-N was maximum with incorporated cowpea followed by moongbean, soybean and wheat crop residues.

4.4 Effects of different nitrification inhibitors

To evaluate and compare the relative efficiency of different nitrification inhibitors (NI) viz. ATC (4-amino 1,2,4 triazole), DCD (Dicyandiamide) and ECC (encapsulated calcium carbide) in soil, following parameters were obtained:

(i) Concentration of NH_4^+-N and $(NO_3^-+NO_2^-)$-N,

(ii) Percent nitrification inhibition,

(iii) Ratio of NH_4^+-N/$(NO_3^-+NO^{2-}$,)-N,

(iv) Total mineral N.

4.4.1 Concentration of NH_4^+-N and $(NO_3^- + NO_2^-)$-N

The concentration of NH_4^+ and NO_3^--N found in the soil, under upland and flooded conditions is presented in Figures 12 and 13. Again in this experiment, in control soil where no NI was added, nitrification of the applied 100 mg NH_4^+-N kg^{-1} soil was very rapid and only traces of NH_4^+-N were found after 10d period. Nitrification of applied NH_4^+-N was retarded with the addition of different NIs, and after 10d incubation only 6.7, 7.6 and 32.4% of fertilizer NH_4^+-N was nitrified with ECC, ATC and DCD, respectively (Table 11). However, thereafter the inhibitory effect of ECC was reduced and, therefore, 80 and 96.9% of added N nitrified after 15 and 20 d of incubation. Corresponding values of nitrification in case of ATC were 10.9 and 37.3%, and with DCD 15.8 and 40.2% at 15 and 20 d, respectively.

Table 11. Effects of different nitrification inhibitors (NIs) on nitrification of applied NH_4^+-N under upland condition (60% WFPS) in Tolewal sandy loam-III soil.

Treatments	Incubation period (d)				
	3	6	10	15	20
			% nitrification		
Without NI	26.5	51.3	96.7	98.4	98.4
ATC	1.5	3.9	7.6	10.9	15.8
DCD	8.0	18.0	32.4	37.3	40.2
ECC	1.2	2.8	6.7	80.0	96.8

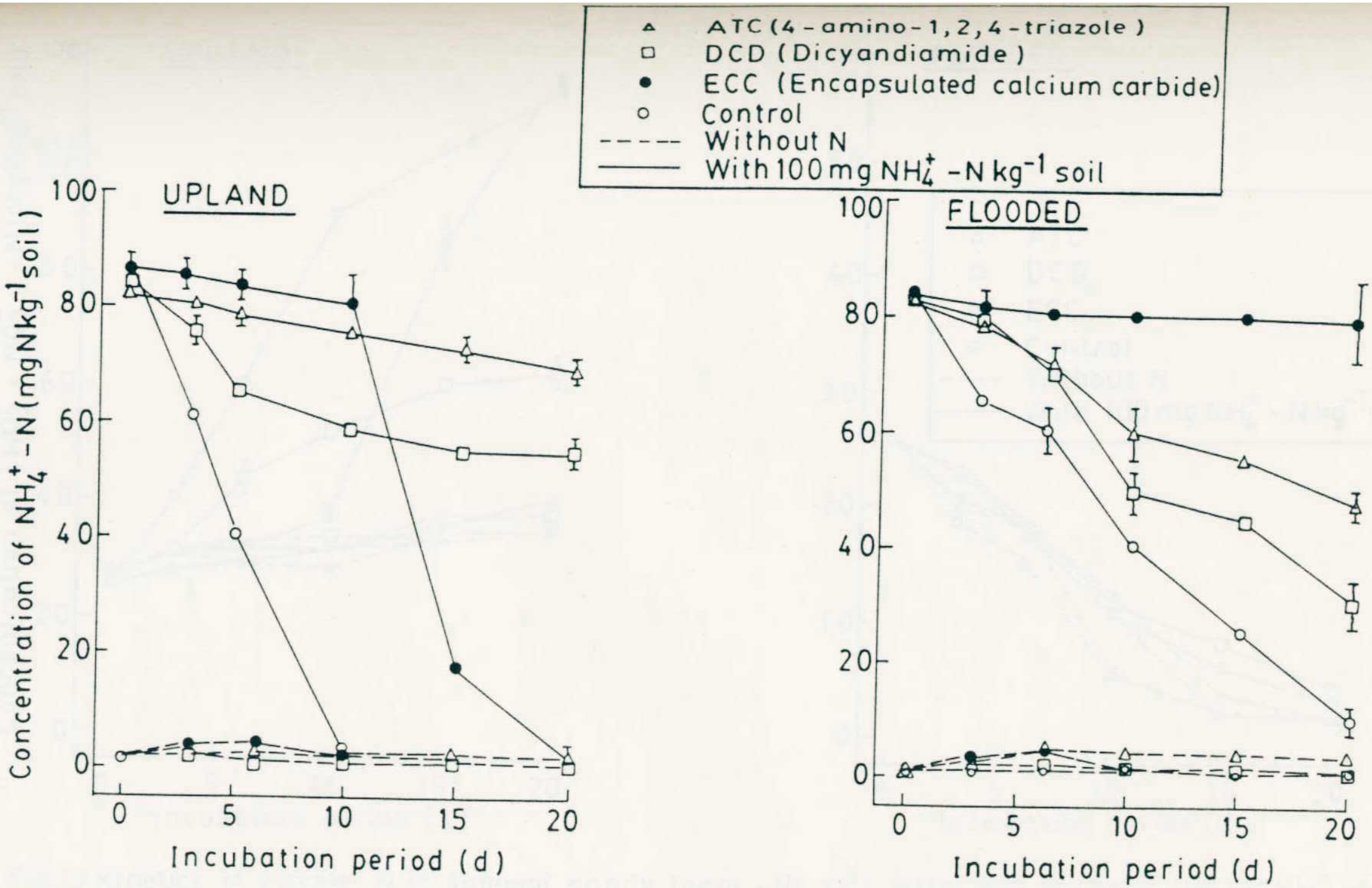


Fig. 12 Kinetics of ammonium-N in Tolewal sandy loam - III soil with and without 100 mg NH_4^+ - N kg^{-1} soil in upland and flooded conditions as influenced by ATC, DCD and ECC nitrification inhibitors. Bars indicate the standard deviation.

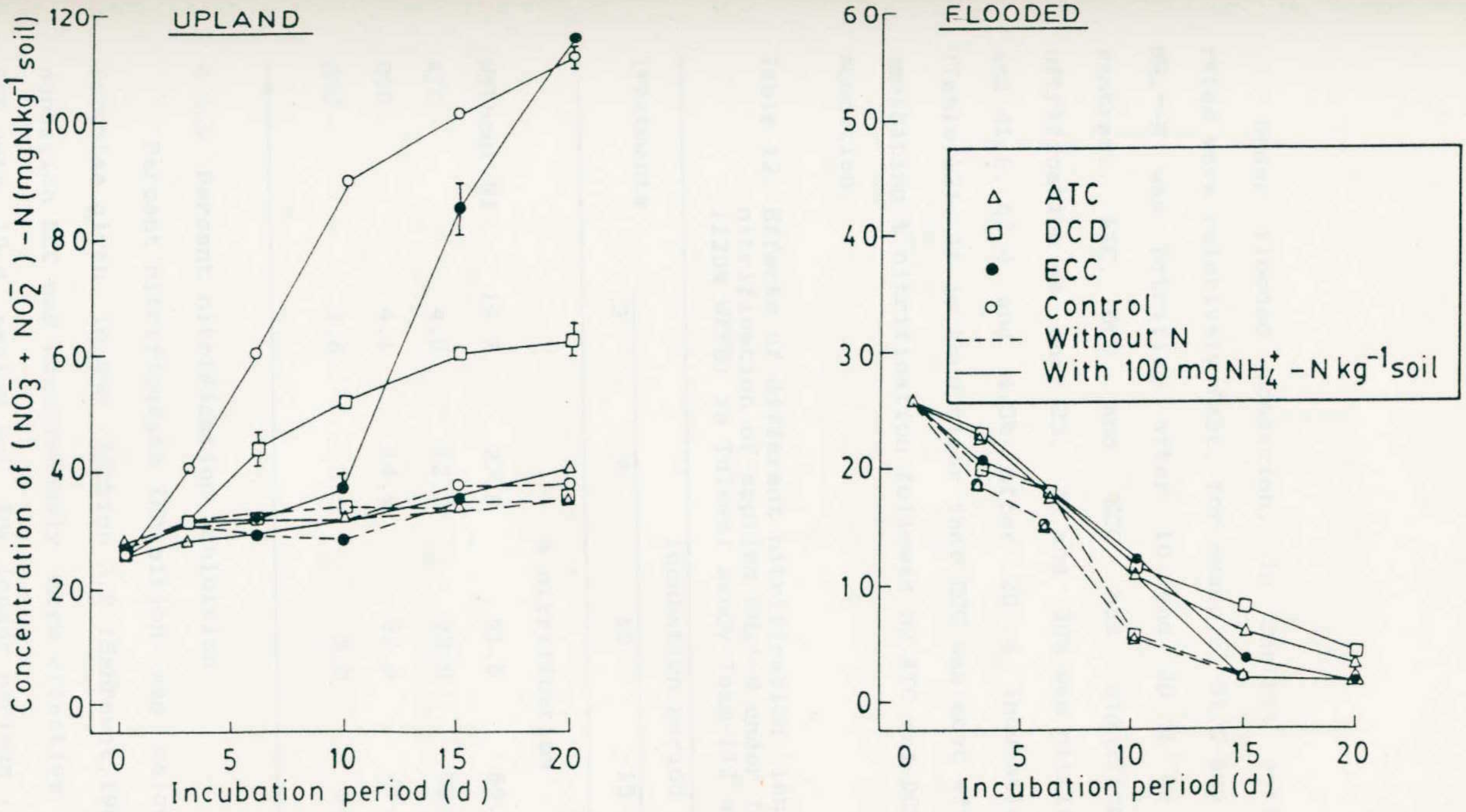


Fig.13 Kinetics of nitrate-N in Tolewal sandy loam - III soil with and without 100 mg NH_4^+ -N kg^{-1} soil in upland and flooded soil conditions as influenced by ATC, DCD and ECC nitrification inhibitors. (Note differences in the scale on Y-axis) Bars indicate the standard deviation

Under flooded condition, in control soil, nitrification rates were relatively fast, for example, 51.5 and 87% of applied NH_4^+-N was nitrified after 10 and 20 d of incubation. In contrast, ATC, DCD and ECC had significantly inhibited nitrification as only 23, 32 and 38% was nitrified, after 10 d and 41.6, 62.4 and 4.5% after 20 d incubation, respectively (Table 12). It is thus clear that ECC was most effective NI in inhibiting % nitrification followed by ATC and DCD in the flooded condition.

Table 12. Effects of different nitrification inhibitors (NIs) on nitrification of applied NH_4^+-N under flooded condition (120% WFPS) in Tolewal sandy loam-III soil.

Treatments	Incubation period (d)				
	3	6	10	15	20
			% nitrification		
Without NI	19.7	27.9	51.5	69.5	87.7
ATC	4.0	12.2	23.0	31.9	41.6
DCD	4.1	14.9	32.0	45.0	62.4
ECC	2.6	3.5	3.8	3.8	4.5

4.4.2 Percent nitrification inhibition

Percent nitrification inhibition was calculated using the formulae given in the Section 3.9 (Sahrawat,1980). Under upland condition ECC was conspicuously more effective NI than ATC and DCD upto 10 d period but for longer periods (20 and 30 d) ATC appeared to be more effective followed by DCD and ECC (Table 13). Under flooded conditions ECC was most effective NI throughout the incubation period (Table 14) and after 20 d incubation, % nitrification inhibition was 95, 52 and 28 with ECC, ATC and DCD, respectively.

Table 13. Percent nitrification inhibition as influenced by nitrification inhibitors (NIs) of applied NH_4^+-N under upland condition (60% WFPS) in Tolewal sandy loam-III soil.

Treatments (NI)	Incubation period (d)				
	3	6	10	15	20
ATC	94.4	92.4	92.1	88.9	83.9
DCD	69.8	66.8	66.5	62.1	59.1
ECC	95.5	94.5	93.1	18.7	1.6

Table 14. Percent nitrification inhibition as influenced by nitrification inhibitors (NIs) of applied NH_4^+-N under flooded condition (120% WFPS) in Tolewal sandy loam-III soil.

Treatments (NI)	Incubation period (d)				
	3	6	10	15	20
ATC	79.7	56.3	55.3	54.1	52.6
DCD	79.2	46.6	37.9	35.3	28.8
ECC	86.8	87.4	92.6	94.5	94.8

4.4.3 Ratio of NH_4^+-N/(NO_3^-+NO_2^-)-N

The NH_4^+-N/(NO_3^-+NO_2^-)-N ratio is considered a better and more sensitive measure of inhibitor effectiveness as it is independent of the rate of N, method of application, or spatial variability (Hauck, 1982). Data on ratio of NH_4^+-N/(NO_3^-+NO_2^-)-N in upland condition (Table 15) further corroborate that ECC was most effective NI upto 10 d period and thereafter ATC was more effective. The results also revealed that some inhibition of nitrification persisted throughout the study period with ATC and DCD. Under flooded conditions the ratio of NH_4^+-N/(NO_3^-+NO_2^-)-N indicates that ECC was most effective NI throughout the incubation period as it was highest with ECC, followed by ATC and DCD (Table 16).

Table 15. Ratio of NH_4^+-N/(NO_3^-+NO_2^-)-N in Tolewal sandy loam-III soil as influenced by nitrification inhibitors (NIs) under upland condition.

Treatments (NI)	Incubation period (d)					
	0	3	6	10	15	20
Without NI	3.0	1.5	0.7	0.0	0.0	0.0
ATC	3.2	2.9	2.7	2.3	2.0	1.7
DCD	3.2	2.5	1.5	1.1	0.9	0.8
ECC	3.3	3.1	2.9	2.2	0.0	0.0

Table 16. Ratio of NH_4^+-N/(NO_3^-+NO_2^-)-N in Tolewal sandy loam-III soil as influenced by nitrification inhibitors (NIs) under flooded condition.

Treatments (NI)	Incubation period (d)					
	0	3	6	10	15	20
Without NI	3.15	1.5	0.1	0.0	0.0	0.0
ATC	3.2	3.4	4.1	5.6	8.6	13.6
DCD	3.2	3.4	3.9	4.3	5.2	7.1
ECC	3.2	3.9	4.5	6.6	22.2	27.4

4.4.4 Total mineral-N

Table 17 presents the data pertaining to the total mineral-N as influenced by ATC, DCD and ECC under upland and flooded soil conditions. Under upland condition the increase in total mineral-N was small. In flooded condition the loss of mineral N in NIs treated soils was very small and 51.4, 35.2, 82.5 mg N kg^{-1} soil were still present after 20 d indicating that accumulation of mineral N is possible even in flooded condition. The data also revealed that accumulation of mineral N was more in ECC treatment as compared to other NI.

Relatively the short period (10 d) effectiveness of ECC under upland condition could be due to its rapid hydrolysis, and volatilization of so produced C_2H_2. On the other hand, slow and consistent degradation of ATC and DCD was responsible for their

Table 17. Total mineral-N (NH_4^+ + NO_3^- + NO_2^-) in Tolewal sandy loam-III soil incubated with or without 100 mg N kg^{-1} soil under upland and flooded conditions as influenced by nitrification inhibitors.

Incubation period (d)	Upland		Flooded	
	-N	+N	-N	+N
		ATC		
0	*29.3±0.8	108.2±0.9	32.8±0.5	107.9±2.3
3	34.2±0.7	109.0±1.4	21.8±0.7	100.8±1.5
6	33.8±0.8	108.5±1.2	20.3±0.1	89.7±2.3
10	34.2±0.3	108.4±0.8	10.2±1.5	70.8±1.6
15	36.6±0.9	109.9±0.6	7.3±0.3	62.3±0.6
20	37.5±0.7	110.1±0.8	6.7±0.2	51.4±0.6
		DCD		
0	29.4±0.7	110.1±1.3	32.8±0.9	108.2±2.3
3	34.2±0.0	107.0±2.3	23.2±1.2	101.1±0.9
6	34.9±0.5	110.3±1.1	20.9±1.0	88.0±1.4
10	35.2±0.9	111.5±1.0	8.1±0.3	62.0±0.5
15	34.4±0.3	116.2±0.3	5.8±0.9	53.9±0.3
20	37.1±0.6	113.0±0.9	5.8±0.3	35.2±0.9
		ECC		
0	29.4±0.8	110.1±1.3	32.8±0.2	109.3±0.8
3	31.8±0.3	101.3±1.3	34.8±0.5	102.4±1.5
6	33.6±0.5	101.3±1.2	21.5±0.6	98.5±2.4
10	33.6±0.8	97.7±1.5	8.2±0.8	92.4±1.6
15	38.7±0.8	103.4±0.6	7.8±0.8	83.8±1.1
20	38.7±0.9	113.7±0.9	7.2±0.7	82.5±1.0
		Control		
0	29.4±0.6	110.1±0.9	32.8±0.3	109.0±1.3
3	31.8±0.2	101.3±0.5	22.6±0.5	87.5±1.7
6	33.6±0.0	101.3±0.5	17.9±0.5	81.5±0.6
10	33.6±1.2	97.7±0.8	14.8±0.9	51.2±1.1
15	38.7±0.5	103.4±1.4	7.3±0.7	27.5±1.2
20	38.7±1.0	113.7±2.1	2.7±0.3	12.6±0.6

* Mean of 3 replicates   ± Standard Deviation.

prolonged effectiveness. Earlier studies of Bundy and Bremner (1973) and Bhupinderpal-Singh (1990) revealed that effectiveness of ATC in inhibiting nitrification was greater than DCD. In several other studies (Bundy and Bremner, 1974; Rodgers, 1983; Rodgers et al., 1984; Yadvinder-Singh and Beauchamp, 1987) both DCD and ATC have been reported to markedly retard the nitrification of applied-N in soils.

Encapsulated calcium carbide was more effective in slowing NH_4^+-oxidation under flooded condition than in the aerobic soil. It is expected that the ECC reaction rate was similar under both moisture conditions, but solubility of C_2H_2 in water and slower NH_4^+ oxidation contribute to the maintenance of high NH_4^+ concentration till 20 d in soil amended with ECC. These results agree with the finding of Sahrawat et al. (1986) that ECC is an effective NI when conditions permit C_2H_2 to remain in the soil system.

From these results, it was apparent that nitrification of added fertilizer NH_4^+-N could be retarded with the use of NIs. Under upland condition, ECC was most effective upto 10 d of incubation period and for longer periods ATC was more effective. Whereas in flooded soil conditions ECC was more effective in retarding nitrification throughout 20 d incubation period followed by ATC and DCD.

4.5 Effects of green manuring and fertilizer N in wetland rice

4.5.1 Nitrate dynamics in soil profile

The data on the content of $(NO_3^-+NO_2^-)$-N, NH_4^+-N and total mineral N in soil profile measured periodically during the growing period of rice (5 May, 1992 to 22 October, 1992) are presented in Tables 18, 19 and 20. These results indicate small temporal changes in the content of NO_3^-, NH_4^+ and mineral N, irrespective of applied N and incorporated green manure treatments.

The soil used in this field experiment was sandy loam and it was difficult to maintain a layer of water continuously on the surface of this coarse textured soil. After each irrigation (flooding), water percolated very quickly due to its high percolation rate (Katyal _et_ _al_.. 1985, 1987; Bijay-Singh _et_ _al_.. 1991b). Hence, alternate drying and flooding cycles during the growing period resulted in aerobic-anaerobic conditions leading to nitrification-denitrification processes. A fairly well distribution of applied fertilizer N in the soil profile to a depth of about 100 cm may be expected in such coarse textured soils. Hence, application of even 40 kg N ha^{-1} (highest rate of 120 kg N ha^{-1} was applied in 3 splits) would increase mineral N by about 2 to 3 mg N kg^{-1} soil only. Similarly, release of green manure N may not substantially increase soil mineral N content. Therefore, such a minor change often remained undifferentiated keeping in view the errors due to sampling and sub-sampling,

Table 18. Content of nitrate-N (mg kg^{-1} soil) during growing period of rice as influenced by rate of fertilizer N and green manuring.

Soil depth (cm)	Days after transplanting								
	0 26Jun	7 3Jul	14 10Jul	21 17Jul	28 24Jul	35 31Jul	42 7Aug	63 28Aug	125 22Oct
					N_0GM_0				
0-15	3.46	1.08	1.99	2.22	1.66	3.00	2.86	2.88	1.75
15-30	2.28	1.25	1.70	2.15	1.87	3.13	2.10	1.34	1.75
30-60	3.60	0.70	1.58	1.63	1.34	2.64	1.60	1.34	0.87
					$N_{60}GM_0$				
0-15	3.46	1.08	2.50	3.19	3.04	2.26	2.38	2.79	5.25
15-30	2.28	1.76	1.77	2.10	1.07	2.61	1.84	2.31	3.50
30-60	3.60	1.0	1.78	1.27	1.38	2.59	2.38	2.10	3.50
					$N_{120}GM_{25}$				
0-15	3.46	2.15	3.77	1.86	1.76	3.53	0.85	3.45	5.75
15-30	2.28	1.42	2.54	1.85	0.54	3.68	3.16	0.65	1.75
30-60	3.60	1.60	2.54	2.30	1.49	3.15	2.39	0.65	1.75
					N_0GM_{25}				
0-15	3.84	1.61	2.74	2.23	1.40	3.37	2.26	2.78	4.25
15-30	4.01	1.12	2.99	2.86	1.62	2.51	2.90	1.51	3.50
30-60	4.13	1.16	2.14	2.20	1.34	2.36	1.32	2.27	3.50
					$N_{60}GM_{25}$				
0-15	3.84	1.42	5.77	2.47	5.98	2.80	2.23	2.10	4.37
15-30	4.01	1.06	1.06	3.22	7.80	2.38	2.37	4.03	1.75
30-60	4.13	0.88	2.16	2.13	1.60	2.10	2.39	1.16	1.75
					$N_{120}GM_{25}$				
0-15	3.84	1.44	5.80	2.96	4.20	3.35	3.12	4.25	3.50
15-30	4.01	1.24	1.23	2.51	0.00	3.14	2.38	0.66	3.50
30-60	4.13	1.05	1.42	3.53	0.00	2.90	2.42	0.66	1.75
					N_0GM_{50}				
0-15	3.84	1.61	5.09	2.09	2.24	1.92	3.65	3.14	6.00
15-30	4.01	2.10	3.16	2.49	2.78	1.05	1.60	2.00	6.00
30-60	4.13	1.59	3.02	2.48	1.63	1.05	1.87	5.63	2.62

Fertilizer N (urea) applied on 26 June, 24 July and 6 August, 1992, just after soil sampling.

Table 19. Content of ammonium-N (mg N kg^{-1} soil) during growing period of rice as influenced by rate of fertilizer N and green manuring.

Soil depth (cm)	Days after transplanting 0 26Jun	 7 3Jul	 14 10Jul	 21 17Jul	 28 24Jul	 35 31Jul	 42 7Aug	 63 28Aug	 125 22Oct
					N_0GM_0				
0-15	2.73	2.70	2.16	3.56	2.00	3.27	1.27	2.52	3.25
15-30	2.81	0.72	0.89	2.48	1.30	2.84	0.75	1.33	1.25
30-60	2.07	0.00	0.88	1.24	1.64	2.89	1.07	1.34	1.25
					$N_{60}GM_0$				
0-15	2.73	1.09	0.52	2.43	1.36	3.00	2.66	1.09	2.73
15-30	2.81	0.00	1.42	1.58	0.53	2.35	1.31	1.65	2.79
30-60	2.07	0.00	1.06	0.53	1.36	1.03	1.05	1.64	3.50
					$N_{120}GM_0$				
0-15	2.73	1.41	1.13	2.24	2.52	4.35	3.48	2.20	2.37
15-30	2.81	0.53	0.71	2.18	1.34	2.08	1.84	1.16	2.37
30-60	2.07	0.70	0.89	2.43	1.60	1.83	1.33	1.00	3.50
					N_0GM_{25}				
0-15	2.43	5.50	3.03	4.10	2.53	5.05	3.10	2.93	5.25
15-30	2.07	1.18	0.87	1.41	1.30	2.09	1.84	1.33	3.50
30-60	2.81	0.00	1.07	2.14	1.56	3.13	1.86	2.01	4.37
					$N_{60}GM_{25}$				
0-15	2.43	4.25	3.86	5.20	2.80	2.80	2.52	1.93	4.37
15-30	2.07	1.05	2.15	1.97	1.60	1.58	0.53	2.02	2.25
30-60	2.81	0.00	1.08	2.25	1.07	1.57	1.33	1.05	3.37
					$N_{120}GM_{25}$				
0-15	2.43	6.52	7.48	5.18	2.21	2.83	1.40	2.64	4.25
15-30	2.07	2.63	1.42	3.76	1.07	1.82	1.08	1.33	4.00
30-60	2.81	0.35	0.70	1.97	1.8	2.63	0.80	1.66	3.27
					N_0GM_{50}				
0-15	2.43	8.13	6.53	5.64	4.71	3.35	3.60	1.52	5.20
15-30	2.07	3.20	2.12	2.95	1.63	1.86	1.06	3.01	4.00
30-60	2.81	0.71	1.61	2.08	1.63	2.91	1.30	1.35	3.25

Fertilizer N (urea) applied on 26 June, 24 July and 6 August, 1992, just after soil sampling.

Table 20. Content of total mineral-N (mg N^{-1} kg soil) during growing period of rice as influenced by rate of fertilizer N and green manuring.

Soil depth (cm)	Days after transplanting								
	0 26Jul	7 3Jul	14 10Jul	21 17Jul	28 24Jul	35 31Jul	42 7Aug	63 28Jul	125 22Oct
				N_0GM_0					
0-15	6.19	3.78	4.15	5.78	3.66	6.27	4.13	5.40	5.00
15-30	5.09	1.97	2.59	4.63	3.17	5.97	2.85	2.67	3.00
30-60	5.67	0.70	2.46	2.87	2.98	5.53	2.67	2.68	2.12
				$N_{60}GM_0$					
0-15	6.19	2.17	3.02	5.62	4.40	5.26	5.04	3.88	7.98
15-30	5.09	1.76	3.19	3.68	1.60	4.96	3.15	3.96	8.04
30-60	5.67	1.06	2.84	1.80	1.74	3.62	3.43	3.74	7.00
				$N_{120}GM_0$					
0-15	6.19	3.55	4.90	4.10	4.28	7.88	4.33	5.65	8.12
15-30	5.09	1.95	3.25	4.03	1.88	5.76	5.00	1.81	4.12
30-60	5.67	2.30	3.43	4.73	3.09	4.98	3.72	1.65	5.25
				N_0GM_{25}					
0-15	5.27	7.11	5.77	6.33	3.93	8.42	5.36	5.71	9.50
15-30	6.08	2.30	3.86	4.27	2.92	4.60	4.74	2.84	7.00
30-60	6.94	1.16	3.21	4.34	2.90	5.49	3.18	4.28	7.87
				$N_{60}GM_{25}$					
0-15	5.27	5.67	10.97	7.77	8.78	5.60	4.75	4.03	8.74
15-30	6.08	1.11	3.03	5.19	9.40	3.96	2.90	6.05	4.00
30-60	6.94	0.88	4.41	4.38	2.67	3.67	3.72	1.21	5.12
				$N_{120}GM_{25}$					
0-15	5.27	7.96	13.28	8.14	6.41	6.18	4.52	6.89	7.75
15-30	6.08	3.87	2.65	6.27	1.07	4.96	3.46	1.99	7.50
30-60	6.94	1.40	2.12	5.50	1.86	5.53	3.22	2.32	5.00
				N_0GM_{50}					
0-15	5.27	9.74	11.62	7.73	6.95	5.27	7.25	4.66	7.20
15-30	6.08	5.30	5.28	5.44	4.41	2.91	2.66	5.01	6.00
30-60	6.94	2.30	4.63	4.56	3.26	3.96	3.17	6.98	5.87

Fertilizer N (urea) applied on 26 June. 24 July and 6 August. 1992, just after soil sampling.

extraction and distillation involved in the determination of soil NO_3^-, NH_4^+ and total mineral-N.

Ammonium-N either added through fertilizer or released during mineralization of soil organic N and of added green manure N did not accumulate substantially, may be partly due to its nitrification during "dry spells" or even during flooded period as NH_4^+ could be oxidized to NO_3^- in the thin O_2-containing surface soil layer and in the overlying water phase of flooded soils (Engler and Patrick, 1974). The so formed NO_3^- in this upper oxidized zone moves into the lower anaerobic zone where it may be lost via denitrification (Tusneem and Patrick, 1971). In the presence of rice crop, NO_3^--N and NH_4^+-N would also decrease due to their uptake by growing plants.

Some workers (Aspiras, 1966; Nagarajah, et al., 1989) who observed rapid release of NH_4^+-N from different green manures up to 2 to 4 weeks, and peak of NH_4^+-N after 7 to 15 days of transplanting of wetland rice, have reported that accumulated NH_4^+-N decreases quickly due to N loss via denitrification and NH_3 volatilization. Results of several other studies (Singh et al., 1981; Bhardwaj and Dev, 1985; Yadvinder-Singh et al., 1988; Beri et al., 1989; Aulakh et al., 1991b) revealed large losses of N from green manure during incubation.

4.5.2 Crop response to fertilizer N and green manuring

Application of successive rates of fertilizer N upto 120 kg ha^{-1} increased the grain yield of rice significantly (Table 21).

Table 21. Effect of green manure applied in conjuncton with different rates of fertilizer N on grain and straw yield of rice.

Rate of fertilizer N (kg N ha^{-1})	*Green manure incorporated (t ha^{-1})		
	0	25	50
	Grain yield (q ha^{-1})		
0	36.2	53.2	60.4
60	49.0	59.2	-
120	55.3	46.6	-
LSD (0.05) : N = 0.96; GM = 0.78 and N x GM = 1.35			
	Straw yield (q ha^{-1})		
0	47.7	74.0	81.1
60	66.6	80.5	-
120	73.5	84.7	-
LSD(0.05) : N = 1.6; GM = 1.3 and N x GM = 2.2			

*25 and 50 t GM contained 128 and 256 kg N.

An increase of 12.8 and 19.1 q ha^{-1} was observed with the application of 60 and 120 kg N ha^{-1}, respectively. Individual application of 25 and 50 t GM biomass ha^{-1} resulted in a significant increase in grain yield and showed its effectiveness equal to fertilizer N. For instance, grain yield obtained with 25 t GM ha^{-1} (containing 128 kg N ha^{-1}) was comparable with that obtained with 120 kg N ha^{-1}. When N and GM were applied together, grain yield increased further and the highest yields of 59.2 and 60.4 q ha^{-1} were obtained with the combined application of 60 kg

N ha^{-1} and 25 t GM ha^{-1} or with lone application of 50 t GM ha^{-1}, respectively. However, the response to GM decreased when applied with the highest N rate (120 kg N ha^{-1}) probably due to excessive increase in the vegetative growth (as is evident from the highest straw yield of 84.7 q ha^{-1} obtained with the combined application of 120 kg N ha^{-1} and 25 t GM ha^{-1}) (Table 21) which caused lodging of crop and more infestation by insect pests.

Like grain yield, fertilizer N and GM increased the straw yield when they were applied individually or in combination (Table 21). An increase of 18.9 and 6.9 q ha^{-1} was observed with the application of first and second dose of 60 kg N ha^{-1} and, 26.3 and 7.1 q ha^{-1} with first and second dose of 25 t GM ha^{-1}, respectively, revealing that increase in straw yield of rice was less with successive levels of applied N, irrespective of source of N.

Nitrogen contribution of green manure was measured by comparing rice yield response to N fertilizer with or without GM. The nitrogen fertilizer equivalence (NFE) of GM was calculated as the quantity of fertilizer N (X, kg ha^{-1}) that must be applied to wetland rice in a fallow (no-GM) treatment to attain grain yield (Y, kg ha^{-1}) equal to that obtained with GM and no fertilizer and following relationship was obtained:

$$Y = 36.17 + 0.2441 X - 0.00051 X^2$$

The relative efficiency of green manure N varied from negligible to 66% (Table 22), indicating that green manure N was more

Table 22. Nitrogen Fertilizer Equivalence (NFE) and relative efficiency (RE) of Green Manure (GM).

Treatment	GM-nitrogen (kg N ha^{-1})	NFE (kg N ha^{-1})	RE of GM-nitrogen (%)
N_0GM_{25}	128	84.6	66.1
N_0GM_{50}	256	139.5	54.5
$N_{60}GM_{25}$	128	68.5	53.5
$N_{120}GM_{25}$	128	–	–

effective when added alone or with low rate of fertilizer N (60 kg N ha^{-1}). Like fertilizer N, application of green manure N in excess of that needed for the highest rice yields, resulted in its poor efficiency.

4.5.3 Plant N content and total N removal

With N fertilization, nitrogen supplying capacity of the soil increased, and this reflected its effect on N concentration in rice grain and straw (Fig.14). For instance, N content of rice grain increased from 0.97 in control to 1.38% with the combined application of 60 kg N ha^{-1} and 25 t GM ha^{-1}, and further to 1.59% with 120 kg N ha^{-1} and 25 t GM ha^{-1}. Nitrogen content of rice grain which is an index of protein (% Nx6.25) revealed that grain protein content increased from 6.1% in control to 7.4 and 7.9% with application of 60 and 120 kg N ha^{-1}, respectively. Application of 25 and 50 t ha^{-1} green manure

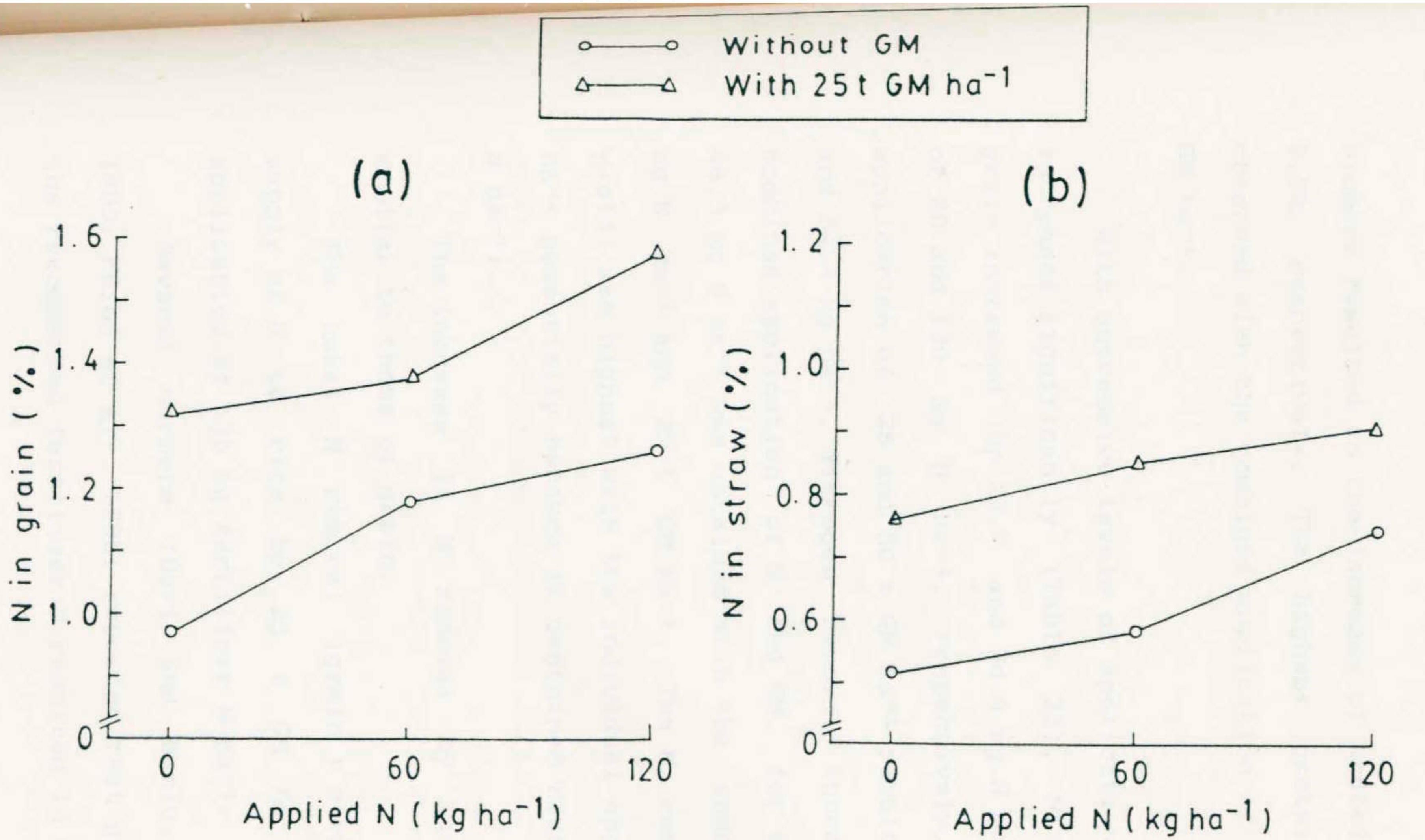


Fig.14 Effect of various levels of applied N and green manure (GM) on the N content of (a) grain and (b) straw of rice.

biomass resulted in the increase of protein content to 8.3 and 9.3%, respectively. The highest protein content of 9.9% was observed with the combined application of 120 kg N ha^{-1} and 25 t GM ha^{-1}.

With successive levels of application, N removal per hectare increased significantly (Table 23). Nitrogen removal by rice grain increased by 22.7 and 34.4 kg N ha^{-1} with the application of 60 and 120 kg N ha^{-1}, respectively. Similarly, individual application of 25 and 50 t GM ha^{-1} resulted in an increase of 35 and 54.4 kg ha^{-1}. Nitrogen removal increased further with the combined application of N and GM, for example, an increase of 46.3 kg N ha^{-1} was obtained with the combined application of 60 kg N ha^{-1} and 25 t GM ha^{-1}. The N removal (as well as grain yield) was highest with the individual application of GM @ 50 t ha^{-1} essentially because it contained highest amount of N (256 kg N ha^{-1}).

The increase in N removal by rice straw showed trends similar to those of grain.

The total N removal (grain + straw) again confirmed that supply of N to rice by 25 t GM ha^{-1} was as effective as application of 120 kg fertilizer N ha^{-1}.

Several workers (Beri and Meelu, 1981; Rekhi and Meelu, 1983; Khind <u>et</u> <u>al</u>., 1985) reported that green manure plus 50% of the recommended fertilizer N resulted in higher rice yields than

Table 23. Effect of green manure application in conjunction with different rates of fertilizer N on removal of N by rice and straw and total N removal.

Rate of fertilizer (kg N ha^{-1})	Green manure incorporated (q ha^{-1})		
	0	25	50
	N removal in rice grain (kg N ha^{-1})		
0	35.0	70.0	82.4
60	57.7	81.3	-
120	69.4	74.4	-
LSD (0.05) : N = 3·9	GM = 3·2	and N x GM = 5·5	
	N removal in rice straw (kg N ha^{-1})		
0	24.4	53.8	75.0
60	38.8	68.8	-
120	54.4	76.9	-
LSD (0.05) : N = 2·7	GM = 2·3	and N x GM = 3·9	
	Total N removal (grain plus straw) (kg N ha^{-1})		
0	59.4	123.8	164.4
60	96.2	150.1	-
120	123.8	151.3	-
LSD (0.05) : N = 5·6	GM = 4·5	and N x GM = 7·9	

when recommended N rates were applied. Tiwari et al. (1980) reported that green manure plus 40 kg fertilizer N ha^{-1} produced rice yield comparable with 120 kg fertilizer N ha^{-1} alone. Ishikawa (1988) reported that combining green manure and fertilizer N resulted in greater rice yields than from fertilizer alone. Rabindra et al. (1989) showed that application of part of N (30%) through green manure produced significantly more rice yield and N uptake than from 100 kg urea N ha^{-1} alone. In most of the studies, rice yield potential was high when green manure and an optimum quantity of fertilizer N were applied together. The present study is also in line with the above results that the yield, removal of N and protein content of rice grain were substantially higher with the combined application of 60 kg N ha^{-1} and 25 t GM biomass ha^{-1} than with 120 kg N ha^{-1} alone. Possible explanation for the improved yield potential may include more favourable physical, chemical and biological conditions of the soil amended with green manure (MacRae and Mehyus, 1985; Walters et al.,1992; Yadvinder-Singh et al., 1992). The results of this field study further demonstrate that excessive application of fertilizer N must be avoided when green manure is incorporated as N in excess of that needed for highest rice yields not only results in its poor efficiency but also causes lodging of crop and infestation by insect-pests and diseases.

It is apparent from above discussed results that although application of fertilizer N and incorporation of green manures in the soil reflected small changes in the NO_3^-. NH_4^+ and total mineral N content of the soil, yet the grain yield, removal of N and protein content of rice grain were substantially higher with the combined application of 60 kg N ha^{-1} and 25 t GM biomass ha^{-1} than with individual application of fertilizer N and green manures. Comparable rice yields obtained with 120 kg fertilizer N ha^{-1} and 25 t GM ha^{-1} (which contained 128 kg N ha^{-1}) illustrated equal efficiency of N added through green manure. The grain yield and N removal decreased when highest rate of 120 kg N ha^{-1} was applied in conjunction with 25 t GM biomass ha^{-1} because of lodging of crops due to excessive vegetative growth.

Chapter-V

SUMMARY

Investigations were carried out in laboratory and field to study the effects of different factors and management practices on extent of nitrification and nitrate dynamics in six soils. Effects of varying soil texture and pH; crop residues varying in C/N ratio, and different nitrification inhibitors, with or without applied fertilizer N in upland and flooded soils were studied under laboratory condition. The field study included effects of green manuring and fertilizer N on nitrate dynamics in the soil profile under wetland rice.

5.1 Effects of varying soil texture

Three soil samples varying in soil texture sandy loam, loam, silty clay were incubated at 35°C for 30 days when 100 mg NH_4^+-N kg^{-1} soil was applied. The nitrification of fertilizer N was very fast under ideal upland conditions and most of applied NH_4^+-N was nitrified within 10 days of incubation in all the three soils, irrespective of the difference in texture. Whereas in flooded soil conditions, nitrification was slow and only 84 to 92% of applied NH_4^+-N was nitrified even after 30 days.

Nitrification could be described by first-order kinetics at both the upland and flooded moisture regimes. In upland condition, the rate constant (k) calculated upto 10 d of incubation (because most of NH_4^+-N nitrified upto this period) were almost equal in all the three soils.

At similar gravimetric water contents, rates of nitrification differed greatly in soils of varying texture, but when varying water holding capacity and bulk density were accounted for using WFPS (water filled-pore space), all the soils behaved similarly at 60% WFPS. Under impeded aeration (flooded conditions), however, substantial differences were observed in nitrification in soils of varying texture; the largest in fine-textured Chamror silty clay followed by Habowal loam and the smallest in Tolewal sandy loam-I soil.

5.2 Effects of varying soil pH

Effects of soil pH (ranging from acidity through neutrality to alkalinity) was studied by incubating the three soils having acid, neutral and alkaline pH at 35°C for 30 days. Under upland conditions the neutral soil was biologically most active in nitrifying the added NH_4^+-N. The rate of nitrification was highest in neutral Tolewal soil (7 mg N kg^{-1} d^{-1}), modest in alkaline soil (3 mg N kg^{-1} d^{-1}) and was lowest in acidic soil (1 mg N kg^{-1} d^{-1}). Applied NH_4^+-N was completely nitrified in 10 d in neutral soil. Alkaline soil took 30 d. In acidic soil, 67% of it was still not nitrified at 30 d. Under flooded condition rate of nitrification was relatively low, but followed the same trend i.e. neutral > alkaline > acidic.

Highest first order rate constant (k) obtained in neutral soil as compared to other two soils in both the upland and flooded conditions further reconfirmed that neutral Tolewal sandy loam-II soil was biologically most active and possessed high nitrification potential.

5.3 Effects of crop residues varying in C/N ratio

Effects of different crop residues i.e. wheat, soybean, moongbean and cowpea having C/N ratio of 111, 37, 21 and 14, respectively, was studied on neutral Tolewal sandy loam-III soil. Nitrification of applied 100 mg NH_4^+-N kg^{-1} soil under upland condition was very fast and almost complete in initial 10 d both in the presence and absence of crop residues. Incorporation of wider C/N ratio crop residues (wheat and soybean) resulted in substantial N immobilization especially during initial 10 d period followed by slow re-mineralization. The apparent net immobilization from incorporation of wheat and soybean residues with fertilizer N after 30 d was 18 and 37 mg N kg^{-1}, respectively. On the other hand, significant accumulation of NO_3^--N occurred with the incorporated moongbean and cowpea residues (having low C/N ratio). The apparent recovery of added residue N through moongbean was 11 and 17% when applied without and with fertilizer N, respectively. The corresponding recoveries of cowpea N were 13 and 29%, respectively.

Under flooded conditions, NO_3^--N content disappeared quickly in all the treatments and traces of NO_3^--N were observed throughout the incubation period. Incorporation of crop residues resulted in accumulation of NH_4^+-N at 10 d period when fertilizer N was not applied and accumulation of NH_4^+-N was maximum with incorporated cowpea followed by moongbean, soybean and wheat. However, in general, NH_4^+-N in flooded condition decreased with further incubation.

5.4 Effects of different nitrification inhibitors

Effects of relative efficiency of different nitrification inhibitors (NIs) ATC (4-amino 1,2 4 triazole), DCD dicyandiamide), and ECC (encapsulated calcium carbide) on nitrification and nitrate accumulation in upland and flooded soil condition, was studied in a Tolewal sandy loam-III soil for 20 d. Under upland conditions nitrification of the applied NH_4^+-N was retarded more effectively by ECC upto 10 d of incubation whereas for longer periods, ATC was more effective. After 20 d, only 37% of applied NH_4^+-N was nitrified with ATC as compared to 43% with DCD and 96% with ECC.

Under flooded soil conditions, ECC was conspicuously effective in retarding nitrification throughout the incubation period followed by ATC and DCD. After 20 d, 96, 58 and 38% of NH_4^+-N was still present in soil where ECC, ATC and DCD were used, respectively.

5.5 Effects of green manuring and fertilizer N in wetland rice

A field study was conducted during 1992 to study the effects of green manure (GM) and fertilizer N application in wetland rice on Tolewal sandy loam-III soil at the research farm of Department of Soils, P.A.U., Ludhiana. Treatments consisted of three rates of fertilizer N (0, 60 and 120 kg N ha^{-1}) without and with green manure (25 or 50 t fresh biomass ha^{-1}).

Application of fertilizer N and incorporation of GM resulted in small temporal changes in the content of NO_3^-, NH_4^+ and mineral N. Rice grain yield and N uptake significantly increased with successive rates of fertilizer N upto 120 kg ha^{-1} and GM upto 50 t ha^{-1}. Maximum grain yield and N removal were obtained with the combined application of 60 kg N ha^{-1} and 25 t GM ha^{-1}. Grain yield decreased with the combined application of 120 kg N ha^{-1} and 25 t GM ha^{-1} due to increased vegetative growth which caused lodging of crop. However, protein content of rice grain was the maximum with this treatment.

Comparable rice yields obtained with 120 kg fertilizer N ha^{-1} and 25 t GM ha^{-1} (which contained 128 kg N ha^{-1}) illustrated equal efficiency of N added through green manure. The relative efficiency of green manure N varied from negligible to 66%, indicating that green manure N was more effective when added alone or with low rate of fertilizer N (60 kg N ha^{-1}).

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