NUTRIENT DYNAMICS AND TRANSFORMATION IN AEROBIC AND FLOODED SYSTEMS OF RICE IN LATERITIC SOILS OF KERALA

By

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(2010-21-113)

THESIS

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DECLARATION

I, hereby declare that this thesis entitled **"Nutrient dynamics and transformation in aerobic and flooded systems of rice in lateritic soils of Kerala"** is a bona-fide record of research work done by me during the course of research and that the thesis has not previously formed the basis for the award to me of any degree, diploma, fellowship or other similar title, of any other university or society.

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Certified that this thesis, entitled **"Nutrient dynamics and transformation in aerobic and flooded systems of rice in lateritic soils of Kerala"** is a record of research work done independently by **Mrs. Geetha, P.** under my guidance and supervision and that it has not previously formed the basis for the award of any degree, diploma, fellowship or associate ship to him.

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We, the undersigned members of the Advisory Committee of **Mrs. Geetha P. (2010-21-113)**, a candidate for the degree of **Doctor of Philosophy in Agriculture** with major in **Soil Science and Agricultural Chemistry,** agree that the thesis entitled **"Nutrient dynamics and transformation in aerobic and flooded systems of rice in lateritic soils of Kerala"** may be submitted by Mrs. Geetha P. in partial fulfilment of the requirements for the degree.

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Geetha, P.

DEDICATED TO MY FAMILY

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Introduction

1. Introduction

Rice (*Oryza sativa*) the 'Global Grain' is the most important staple food crop worldwide for nearly half of the world population. Rice production and food security largely depend on the irrigated lowland rice system, whose sustainability is threatened by fresh water scarcity, water pollution and competition for water use (Gleick, 1993; Postel, 1997). The situation is further aggravated by drought, global warming, methane emission, adverse climatic changes, over-pumping of ground water causing aquifer resources to decline and the high 'cost' of water.

The introduction of high-yielding varieties, fertilizers, pesticides and irrigation with expansion of the area under rice has improved rice yields significantly. However, globally, in the last 20 years, yield and the area under rice have declined considerably.

The area under rice cultivation has been declining in Kerala in recent years. Urbanization, non-availability and high cost of labour, higher input prices, and severe water constraints (because of failure of monsoon and untimely rains) are the factors responsible for this decline.

International Rice Research Institute (IRRI) has coined the concept of "aerobic rice". It is a water-saving rice production system in which potentially high yielding, fertilizer responsive adapted rice varieties are grown in fertile aerobic soils with supplementary irrigation. The soil is therefore "aerobic" or with oxygen throughout the growing season, as compared to the traditional "anaerobic" flooded fields.

Rice under aerobic soil environment can definitely cut short the water requirement. Transformations and availability of nutrients will also be quite different from that in flooded rice as there is definite change in redox environment. This will directly control the forms of ions like iron, manganese etc., which have more than one redox state depending on the redox potential. Further there will be change in pH under both systems which indirectly influence the transformation and availability of nutrients.

Ponnamperuma (1972) has studied in detail the changes in pH, redox potential, and sequential reduction of different nutrient forms starting from the oxidized aerobic stage, where O_2 is available (814 mV) to the highly reduced level where methane is emitted due to reduction of organic carbon(-244 mV). In case of upland crops, under aerobic environment such reductions and changes in pH and redox potential seldom happen. These redox transformation under flooded environment and the absence of such transformations under aerobic environment influence the forms of ions existing in soil solution as well as their availability, eg., pH tends to neutrality under submergence and under this neutral pH most of the nutrients exist in plant available forms. On the other hand, the availability of iron and manganese may attain a level of toxic concentration due to reduction to soluble ferrous (Fe^{2+}) and Mn^{2+} forms under anaerobic environment which may antagonistically affect the availability of other cations like K^+, Zn^{2+}, etc., leading to induced deficiencies.

Rice when grown as a semi aquatic plant develops aerenchymatous tissues on roots, enabling transport of oxygen to roots for respiration. This anatomical modification may not be conspicuous under aerobic environment. Such anatomical differences in roots may influence the absorption of nutrient ions by changing the root CEC, apparent free space etc., and ultimately the root absorbing power.

Thus the flooded (anaerobic) soil environment will be different from the aerobic environment with respect to physical/chemical environment of the rhizosphere which ultimately influences the availability and absorption of nutrient ions, nutrient use efficiency as well as the growth and yield.

It is under the above rationale, the present study was undertaken to study critically the two environments with respect to nutrient dynamics and ultimately the growth and yield of rice. Thus the study was undertaken with the following objectives:

- To study the nutrient dynamics under the aerobic and flooded (anaerobic) systems of rice in lateritic soils of Kerala.
- To compare the nutrient transformations, availability and absorption under the aerobic and flooded soil environment.
- To elucidate the changes in availability pattern if any and the dynamics of nutrients under both aerobic and flooded rice systems.

Review of literature

2. Review of literature

Rice (*Oryza sativa*) the 'Global Grain' is the most important staple food crop in the diet worldwide for nearly half of the world population (Maclean *et al.*, 2002; Mahabub and Narciso 2004). As per Grassi *et al.* (2009), Asia has the largest area dedicated to rice cultivation with an estimated 140 Mha, out of 156 Mha worldwide. According to FAO (2008), Asia contributes 90 % to the world's total rice production of 674 MT. Out of India's total food grain production of 255.36 MT, rice contributes 41 % with an average yield of 2.37 t ha^{-1} from an area of 42.72 Mha (GOI, 2014).

Rice cultivation is a water intensive activity. Rice production consumes about 30 per cent of all fresh water used worldwide (Barker *et al.*, 2009). Rice production and food security largely depend on the irrigated lowland rice systems, whose sustainability is threatened by fresh water scarcity, water pollution and competition for water use (Postel, 1997).

2.1. Different types of rice cultivation systems

The factors considered in classifying the rice growing environments are water regime (deficit, excess, or optimum), drainage (poor or good), temperature (optimum or low), soils (normal or problem) and topography (flat or undulating) (Bouman *et al.*, 2002).

Based on soil water conditions rice production ecosystems are classified as conventional irrigated/rainfed lowland, irrigated/rainfed upland or aerobic, and deepwater/floating ecosystems. Irrigated lowland rice is grown in bunded fields with assured water supply for one or more crops per year. In South Asia, Southeast Asia, and East Asia, irrigated lowland rice is dominant in the vast, flat and low-lying flood plains and deltas of many of the world's major rivers, which are flooded annually during the rainy season. The average yields of irrigated lowland rice vary from about 3 to 10 t ha^{-1}. Aerobic rice production is recently practiced as a response to water shortage. Here the soils are freely drained. Rainfed lowland rice ecosystems are found in tropical climate areas; in river deltas, flood plain and inland swamps. Bunds and dykes are built around rainfed lowland fields to capture and conserve rainfall for growth and development of rice plants. Rice fields are covered with a layer of standing water up to 5 cm during half of the growing season. Rainfed upland rice fields are found in tropical climate areas; on flat land or on slopes of hills and mountains. Deepwater/floating rice ecosystems are found in low lying areas in deltas, estuaries, swamps, and rivers' valleys in tropical Asia and Africa, where the water is stagnant during rice growing season (FAO, 2008).

2.2.1. Conventional irrigated/ rainfed lowland rice cultivation

Lowland rice in Asia is mostly transplanted or direct (wet) seeded into puddled, paddy-fields. Land preparation of a paddy consists of flooding, ploughing and puddling. Puddling is an important management practice in lowland rice culture wherein the soil structure is deliberately destroyed and dispersed by ploughing and harrowing the soil in a flooded or saturated state. Ghildyal (1978) defined puddling as mixing soil and water to render it impervious. It essentially increases micro pore volume (Moorman and van Breemen 1978), water retention, reduces soil permeability and eases field leveling and transplanting (De Datta, 1981).

Lowland rice has very low water-use efficiency since it consumes 3000 to 5000 liters of water to produce one kg of rice (Barker *et al.*, 1999; 2001; Joshi *et al.*, 2009). The increasing water crisis threatens the sustainability of irrigated rice production in the world. The situation is further aggravated by drought, global warming, methane emission, adverse climatic changes, over-pumping of ground water causing aquifer resources to decline and the high 'cost' of water. It is estimated that, by 2025, 2 million ha of Asia's irrigated dry-season rice and 13 million ha of its irrigated wet-season rice may experience ''physical water scarcity'', and most of the approximately 22 million ha of irrigated dry-season rice in South and Southeast Asia may suffer ''economic water scarcity" (Tuong and Bouman, 2001; 2003).

Improved rice growing technologies help to reduce water loss and increase the water productivity of the rice crop. Those are saturated soil culture (Borell *et al.*, 1997), alternate wetting and drying (Li, 2001; Tabbal *et al.*, 2002), ground cover systems (Lin *et al.*, 2002) and system of rice intensification (Stoop *et al.*, 2002).

Decreasing water resources for rice cultivation has prompted research on the development of water efficient 'aerobic rice' varieties by combining the drought resistant characteristics of upland varieties with the high yielding traits of lowland varieties (Belder *et al.*, 2005; Lafitte *et al.* 2002).

2.2.2. Irrigated/rainfed upland or aerobic rice cultivation systems

Flooded rice uses two to three times more water than other cereal crops. In Asia, flooded irrigated rice consumes more than 45 per cent of total fresh water used (Barker *et al.*, 1999). The increasing water crisis threatens the sustainability of irrigated rice production. It is estimated that about 15 out of 75 Mha of Asia's flooded rice will suffer from severe water scarcity by 2025 (Bouman, *et al.*, 2005).

Hence to tackle this problem, International Rice Research Institute (IRRI) has coined new term "aerobic rice". It is a water saving rice production system in which potentially high yielding, fertilizer responsive adapted rice varieties are grown in fertile aerobic soils that are non puddled and have no standing water with supplementary irrigation (Maclean *et al.*, 2002; Bouman *et al.*, 2005).

The soil is therefore "aerobic" or with oxygen throughout the growing season, as compared to traditional "anaerobic" flooded fields. The aerobic rice cultivation involves direct seeding with surface irrigations when required and is characterized by aerated soil environment during the entire period of crop growth.

Aerobic rice system inquire lesser water inputs (50 %), labour (55 %) and higher water productivities (66 to 88 %), than that of flooded rice cultivation (Sandhu *et al.*, 2012).

Aerobic rice is a new way of cultivating rice that requires less water than lowland rice. It entails the growing of rice in aerobic soil, with the use of external inputs such as supplementary irrigation and fertilizers, and aiming at high yields. The increased water savings and fertilizer responsiveness combine with the inherent yield potential of aerobic rice could realize an estimated yield potential of 6- 7 t ha^{-1} (Peng *et al.*, 2006). Aerobic rice was reported to be cultivated with 600 to 700 mm of total water in summer and as rainfed in wet season without much yield gap (Hittalmani, 2008).

Generally, rice grown on fertile uplands using high yielding cultivars with adequate water supply can be regarded as aerobic rice and non-irrigated or rain-fed rice with lower productivity expectations is regarded as upland rice (Kato *et al.*, 2009; Wang *et al.*, 2002).

2.2.2.1 Changes due to submergence under flooded systems

Within a few hours of submergence, a soil's dissolved and gaseous oxygen is consumed by aerobic microorganisms, then the facultative anaerobes, followed by the obligate anaerobes, use soil components and dissimilation products of organic matter as electron acceptors in their respiration, reducing the sequence predicted by thermodynamics and lowering its Eh or pE (Ponnamperuma, 1972). These chemical changes are associated with physical reactions between the soil and water and also because of biological processes set in motion as a result of excess water or oxygen deficiency. The most important change in the soil as a result of flooding is the conversion of the root zone of the soil from an aerobic environment to an anaerobic or near-anaerobic environment where oxygen is absent or limiting (Patrick and Mahapatra 1968). The oxygen movement through the flooding water is four times slower than the rate of oxygen depletion in the soil result in the formation of two distinctly different layers in a waterlogged soil (Gao *et al.*, 2002; Tanji *et al.*, 2003). On the top is an oxidized or aerobic surface layer, with a reduced or anaerobic layer underneath.

The pH, Eh or pE, specific conductance, ionic strength, ion exchange, sorption and desorption, chemical kinetics and mineral equilibria profoundly influence the fertility of submerged soils by controlling the availability of plant nutrients and regulating their uptake by rice roots. A pH of about 6.6, an Eh from

0.01 to 0.12 V or a pE from 0.2 to 2.0 at pH 7.0, a specific conductance of about 2 mmhos/cm at 25°C, and a temperature from 30 to 35 °C (all in soil solution) appear to favour nutrient uptake by rice. Under these conditions, the availability of N, P, K, Ca, Mg, Fe, Mn and Si is high, the supply of Cu, Zn and Mo is adequate and injurious concentrations of Al, Mn, Fe, CO_2 and organic acids are absent. Under normal tropical soils, the nutrient uptake will be improved by incorporating organic matter and keeping the soil submerged for 2 to 4 weeks before planting (Ponnamperuma, 1977).

The single electrochemical property that serves to distinguish a submerged soil from a well-drained soil is its redox potential (Eh). The low potentials (0.2 to -0.4 V) of submerged soils and sediments reflect this reduced state, the high potentials (0.8 to 0.3 V) of aerobic media, their oxidized condition. Redox reactions in soils are mainly controlled by microbial activity (Munch *et al.*, 1978). Organisms use organic substances such as carbon sources as electron donors during respiration. Molecular oxygen acts as the preferred electron acceptor. Flooding a field for subsequent rice cultivation cuts off the oxygen supply from the atmosphere, the microbial activities switch from aerobic (i.e. oxic condition) to facultative (i.e. hypoxic condition) and to anaerobic decomposition of organic matter, where alternative electron acceptors are used. The redox sequence is determined by thermodynamics and includes, in terms of Eh, from high to low: aerobic respiration, nitrification, de nitrification, Mn^{4+} reduction, Fe^{3+} reduction, SO_4^{2-} reduction and methanogenesis (Ponnamperuma, 1972; Patrick and Reddy, 1978; Patrick and Jugsujinda, 1992).

When the rice fields are drained one to two weeks before harvest, the redox potential increases, i.e. reduced compounds such as Fe^{2+} are oxidised (Jackel *et al.*, 2001; Kruger *et al.*, 2001). Besides oxygen, other inorganic soil constituents contribute sequentially to the oxidation of organic matter (Ponnamperuma, 1972).

The magnitude of redox changes in paddy soils can vary from one soil to another, and depends strongly on the ratio of oxidizing capacity to reducing capacity

(Bouman, 1991), which is the result of the cultivation system and the length of cultivation (Xue *et al.*, 2008).

When an aerobic soil is submerged, its pH decreases during the first few days (Motomura, 1962, and Ponnamperuma, 1965), reaches a minimum, and then increases asymptotically to a fairly stable value of 6.7 to 7.2 a few weeks later. The overall effect of submergence is to increase the pH of acid soils except those low in iron to 7.

Ponnamperuma *et al., (*1966) studied the influence of redox potential and partial pressure of carbon dioxide on the pH values of rice soils (pH between 3.6 and 9.4) in a pot culture study for 16 weeks. The results showed that the pH values of alkali and calcareous soils decreased and those of acid soils increased to a fairly stable range of 6.7 to 7.2, 12 weeks after flooding. Further, it was established that the increase in soil solution pH of the acid soils was related to the potential of the Fe $(OH)_3$–Fe (II) system.

Thenabadu, (1967) observed that the rise in pH acid soil on submergence depends on initial pH, the content of organic matter and duration of submergence as well as the increased concentrations of ammonia, manganese and ferrous- ferric equilibrium.

Sahrawat (2005) reported that the pH of acidic soils increases under flooded condition by using, ferric iron as an electron-acceptor for oxidizing organic matter and during this process acidity is neutralized.

$$Fe_2O_3 + \frac{1}{2} CH_2O + 4H^+ \longleftrightarrow 2Fe^{2+} + 5/2\ H_2O + \frac{1}{2} CO_2$$

In this redox reaction, ferric iron (from amorphous ferric hydroxides) serves as an electron-acceptor and organic matter (CH_2O) as the electron donor. This reaction results in the neutralization of acidity and increase in pH.

Patra and Neue (2010) reported that soil drying and re flooding significantly influenced soil solution pH of soils. The rates of pH increase on flooding and subsequent drop due to soil drying were more in the ultisol soils due to their higher active Fe and higher organic matter content.

According to Karan *et al.* (2014), the pH of the laterite soil at West Bengal was increased from 4.8 (at initial) to 6.9. The pH of this soil was increased gradually up to 45 days of submergence and then remained stable. The rate of increase was more under limed soil.

Aerobic rice does not benefit from the electrochemical and chemical changes that occur in soils when the rice crop is grown under flooded conditions (Narteh and Sahrawat 1999). The first and the foremost disadvantage to aerobic rice is the lack of amelioration and convergence of soil pH in the neutral range (Ponnamperuma 1984), as opposed to that in the flooded rice soils where the soil pH is adjusted in the neutral range (Ponnamperuma 1972). Hence application of lime in case of acid soils and of that of gypsum in case of alkaline soils is necessary to neutralize the pH (Sahrawat, 2012).

Since aerobic rice is grown in diverse soils under ambient soil pH conditions the availability of plant nutrients in this soil also varies (Yoshida 1981; Sahrawat 1983). The availability of the most plant nutrients is optimum under neutral soil pH.

The specific conductance of the soil solution increases after submergence, attains a maximum, and declines to a fairly stable value. The increase in conductance during the first few weeks of flooding is due to the release of Fe^{2+} and Mn^{2+} from the insoluble from the insoluble Fe (III) and Mn (IV) oxide hydrates (Ponnamperuma, 1972).

2.3. Dynamics of organic matter under flooded and aerobic systems of rice cultivation

Soil organic matter (SOM) or organic carbon (SOC) is considered to be a key attribute of soil fertility and productivity because of its importance to soil physical, chemical as well as biological properties (Stevenson, 1986).

The decomposition of organic matter in a submerged soil differs from that in a well drained soil in two respects: it is slower; and the end products are different. In a well drained soil, decomposition of plant residues is accomplished by a large group of microorganisms assisted by the soil fauna. Owing to the high energy release associated with the aerobic respiration of these organisms, decomposition of substrate and synthesis of cell substance proceed rapidly. The bulk of freshly added organic matter disappears as CO_2, leaving a residue of resistant material, chiefly altered lignin. Also, there is a heavy demand on nutritional elements, especially nitrogen. In submerged soils, the decomposition of organic matter is almost entirely the work of facultative and obligate anaerobes. Since anaerobic bacteria operate at a much lower energy level than aerobic organisms, both decomposition and assimilation are much slower in submerged soils than in aerobic soils. The accumulation of plant residues in marshes and in underwater sediments illustrates this point (Ponnamperuma, 1972). In a normal well drained soil the main end products are: CO_2, nitrate, sulfate, and resistant residues (humus). In submerged soils they are CO_2, hydrogen, methane, ammonia, amines, mercaptans, hydrogen sulfide, and partially humified residues.

According to Saharawat (2012), lowland rice cultivation maintains or improves the OM status of paddy soils. Organic matter status of soils under continuous rice (two or three crops per year) is either maintained or even increased compared with soils under upland rice or in wetland rice-upland crop sequence where a general decline in soil organic matter has been reported (Witt *et al.* 2000; Sahrawat 2004, Pampolino *et al.*, 2008 and Cheng *et al.*, 2009). This is due to lack of supply of free oxygen which is the major electron acceptor in organic matter decomposition and hence, the decomposition of organic matter under flooding is slow, inefficient, and incomplete and this leads to net accumulation of organic matter under flooding. Moreover, flooded rice systems sequester C within short period of time.

Witt *et al.* (2000) showed that the sequestration of organic C and total N in wetland soils was significant during two years of cropping under flooded condition.

An experiment was conducted on a clay soil at the International Rice Research Institute, Philippines where five successive cropping involving rice-rice or maize-rice was grown. There was a net gain in soil organic C and total N under the rice-rice system and a net decline under the maize-rice system. Replacement of dry season flooded rice crop by maize caused a reduction in C and N sequestration in the soil. The results demonstrated the capacity of continuous irrigated lowland rice system to sequester C and N (Zhang and He 2004; Pampolino *et al.*, 2008; Cheng *et al.*, 2009; Nayak *et al.*, 2009).

Results reported from long-term experiments suggest that soil organic matter (SOM) levels under rice-wheat system in the Indo-Gangetic Plains have declined (Bhandari *et al.*, 2002). On the other hand, prolonged submerged soil conditions stimulate SOM accumulation and C sequestration in wetland soils and sediments (Pampolino *et al.*, 2008; Nayak *et al.*, 2009). Nishimura *et al.*, (2008) studied the effects of land use change from paddy cultivation to upland crop cultivation on soil C budget and found that the drainage of paddy fields for upland cultivation caused significant C loss from crop land soil. The drainage of paddy fields for upland crop cultivation causes loss of SOM due to enhanced decomposition of OM under aerobic condition (Mitsuchi, 1974). The benefits of OM accumulation under long-term paddy rice cultivation were reversed by bringing the land under upland crop culture (Sahrawat 2004; Olk *et al.*, 1996).

Slow decomposition of OM and higher net primary productivity of submerged rice soils lead to net accumulation of organic matter and N in submerged soils and sediments (Saharawat, 2012).

Li *et al.*, (2005) and Zhang and He (2004) reported that long-term rice cropping significantly increased OC up to 2 % after 100 years of cropping and N contents in the plough layer.

Yang *et al.* (2005) reported that continuous water logging increased SOC contents in paddy soils, especially under combined application of fertilizers and farmyard manure or wheat straw. Cheng *et al.*, (2009) found higher C contents in a paddy soil chronosequence established for several hundred years under a rice/non-rice cropping system compared to upland soils in the same region.

2.4. Dynamics of nutrients under aerobic and flooded systems of rice cultivation

Nitrogen

The mineralization or ammonification (ammonium production) of organic nitrogen (N) is a key process that regulates the bioavailability of N, wetland productivity and environmental quality (Reddy and De Laune 2008). Thus, N mineralization in lowland ecosystems assumes much importance for both agricultural productivity and ecological health. Nitrogen mineralization in soils is the biological transformation of organic forms of N to ammonium and this process can occur in either aerobic or anaerobic conditions. In aerobic soils, the end product of mineralization of organic nitrogen is NO_3^-. The loss of NO_3^- is more under aerobic soil environment due to leaching compared to that of flooded soils. However, the N mineralization process in submerged soil stops at ammonium production because of lack of oxygen. Ammonium in flooded soil and sediments is produced by reductive de amination (the conversion of amino acid-N to ammonia via saturated acids) of amino acids and degradation of purines, with the release of ammonia, carbon dioxide and volatile fatty acids as the end products (Ponnamperuma, 1972). Ammonium is stable under reduced conditions of lowland soils and thus accumulates in flooded soils. The mineralization of organic N in lowland soils and sediments is influenced by soil, environmental and agronomic factors. The most important among these are temperature, soil water regime, microbial activity and microbial biomass, pH, redox potential, C:N ratio, the loadings of alternate acceptors, amount and nature of soil clay, cation exchange capacity of soil, nature and amounts of salts, inputs and quality of organic materials, amount and quality of soil organic matter and the supply of nutrients such as phosphorus among others involved in the decomposition of organic matter and release of ammonium (Sahrawat, 2005). Moreover, the redox status of a lowland soil system impacts organic N mineralization (Savant and Ellis, 1964) and the redox potential in flooded system is controlled by the quantity and quality of organic matter and the loading of electron acceptors. A range of redox potentials are encountered in lowland soils and sediments viz., +700 to +500 mV in aerated, +400 to +200 mV in moderately reduced, +100 to -100 mV in reduced and -100 to -300 mV in highly reduced condition. The availability and amount of inorganic electron acceptors including oxygen, nitrate, manganic manganese, ferric-iron, sulfate and carbon dioxide regulates redox potential. The reduction process in a submerged soil system follows the sequence- oxygen, nitrate, manganese, iron, sulphate and carbon dioxide.

2.5. Phosphorus

Phosphate availability limits primary crop production in aquatic ecosystems (Schindler, 1977). Inorganic P in wetland soils predominantly present in the form of precipitates with Ca, or adsorbed onto Al and Fe oxides and hydroxides (Goldberg and Sposito, 1984).

Phosphorus availability for rice in paddy soil varies depending on soil water regimes (Kirk *et al.*, 1990). Changes in pH and Eh caused by wet-dry soil conditions influence the availability of P because they control the P sorption characteristics of soils (Krairapanond *et al.*, 1993). The increased solubility of P by reduction under submergence was noted by Mortimer (1941); Valencia (1962).

The concentration of P in soil solution increases initially after submergence and then decreases (Ponnamperuma 1965, Ponnamperuma, 1972; Narteh and Sahrawat, 1999). The initial increase in soil solution P in submerged soils is linked to the transformations of Fe and changes in pH. The main processes related with P solubility under flooding are the reduction of Fe^{3+} compounds holding P on their surfaces and within their crystal lattices and dissolution of Ca-P compounds in acid soils as the pH increases (Ponnamperuma, 1965).

Ponnamperuma (1976) noted that the increased pH of acid soils to 6.7 to 7.2, twelve weeks after flooding would favour the formation of insoluble calcium phosphate.

Phosphorus availability is increased in the flooded soils because of the reduction of ferric phosphate to the more soluble ferrous form and the hydrolysis of phosphate compounds. This may be more pronounced in acidic soils where P is immobilized by Fe and Al oxides. Similarly, P uptake in flooded alkaline soils also improves because of the liberation of P from Ca resulting from the decrease in pH. The formation of insoluble tri calcium phosphate is favored at a high pH (Fageria, 2012).

Shahanadeh *et al.*, (2003) observed that P availability is strongly tied to Fe in rice paddies where extractable Fe and Mn are high. Quintero *et al.*, (2007) suggested that changes in P fractions as a result of anaerobic conditions were related to soil carbon, pH and soluble and weakly adsorbed Fe.

According to Zhang *et al.*, 2004 the release of P to the soil solution is due to the initial reduction of free Fe oxidized during flooding. The subsequent decline in soluble P is caused by re-sorption or precipitation on clays and oxides as soil conditions continue to change, and decomposition of organic anions chelating P or chelating Al and Fe with which it would otherwise react (Kirk, 2004). Following submergence, soils often release more native P to solution low in P but adsorb more P from solutions high in P (Najafi, 2013).

The available P is low in aerobic rice soils due to precipitation of P in the forms of Fe^{3+}-P and Al-P in acidic soils and Ca-P in alkaline soils. Maximum availability of P is under neutral soil reaction.

2.6. Potassium, Calcium and Magnesium

Deficiency of potassium, calcium and magnesium typically occurs in highly weathered tropical soils (Oxisols, Ultisols) and coarse-textured soils (Dobermann *et al.*, 1996)

The influence of flooding is lesser on the chemistry of K than on the chemistry of N and P. According to Fageria *et al.* (2011), the reducing conditions result in displacement of exchangeable K into the soil solution. Under acidic condition, the exchangeable K, Ca and Mg present in the solid phase are released to the soil solution. This leads to the increase in the concentration of bio-available K, Ca and Mg under flooding. The dominant cations in the acidic soil environment are Fe and Mn. The competition of K, Ca and Mg with Fe^{2+} and Mn^{2+} results in low plant uptake of K, Ca and Mg (Fageria *et al.*, 2008).

Under aerobic system, potassium, calcium and magnesium present in the soil solution are available to plants due to less competition for uptake under acidic situation and due to less leaching under alkaline condition (Fageria *et al.*, 2002).

According to Fageria and Baligar (1999), calcium and magnesium deficiencies are rare in low land rice. In highly acidic soils, dolomitic lime can be added to supply Ca and Mg. Only a small amount of these elements are removed in the grain, and unless the straw is removed from the field, the total removal is small.

2.7. Sulphur

Plants uptake sulphur in the form of SO_4^{2-} from the soil. Under flooded systems, the main changes are the reduction of SO_4^{2-} to form S_2^{2-} and the dissimilation of the amino acids, cysteine, cystine and methionine to H_2S, thiols, ammonia and fatty acids (Ponnamperuma, 1972).

In flooded soils, SO_4^{2-} ion is reduced to hydrogen sulfide (H_2S) by anaerobic microbial activities. Furthermore, in flooded soils, Fe^{3+} reduction to Fe^{2+} precedes SO_4^{2-} reduction. Ferrous ions will always be present in the soil solution by the time H_2S is produced to form insoluble iron sulfide (FeS).

The reaction is as follows: $H_2S + Fe^{2+} \longleftrightarrow FeS + 2H^+$

This reaction protects microorganisms and higher plants from the toxic effects of H_2S. Overall, availability of S is reduced in flooded soils due to formation of insoluble FeS (Patrick and Reddy 1978).

The deficiency of S is not observed in acidic soil environment. H_2S reacts with Zn, Cu and other metals and causes precipitation leading to unavailability of these metal cations. The free H_2S present in alkaline soils show toxicity due to sulphide. This may damage the plant as well as soil microbes due to sulphide toxicity (Fageria and Baligar, 2005; Fageria *et al.*, 2002).

According to Bell and Dell (2008), the availability of native sulphur to rice in submerged soils decreases because of the slower mineralization of organically bound sulphur.

Under aerobic soil environment, there is no reduction to sulphide form. The native SO_4^{2-} is available for plant uptake. Deficiency of sulphur is so far not reported in aerobic rice soils (Sahrawat, 2012).

In acid laterite soil, alternate flooding and drying is more beneficial to rice than continuous flooding, as it significantly increases the bio availability of sulphur (Karan *et al.*, 2014).

2.8. Iron

In oxidized soils iron is generally in the ferric form (Fe^{3+}) tied up with oxides and hydroxyoxides. The solubility of Fe^{3+} iron is very low. In addition, the major form of Fe uptake by plants is ferrous (Fe^{2+}) ion (Lindsay and Schwab, 1982). Hence, Fe has to be reduced to Fe^{2+} form for uptake by crop plants. The principal Fe toxicity inducing factors are, release of Fe from parent material to soil solution, reduction in oxidation reduction potential, increase in ionic strength, low soil fertility, low soil pH, soil organic matter content, microbial activities, interaction with other nutrients and plant genetic variability. Oxidation-reduction affects the valence of Fe and thereby its uptake by plants. The Fe^{3+} ion reduced to Fe^{2+} due to oxidation-reduction processes and increases its uptake. The critical redox potentials for Fe reduction and consequent dissolution are between +300 mV and +100 mV at pH 6 and 7, and –100 mV at pH 8, while at pH 5 appreciable reductions occur at +300 mV (Gotoh and Patrick, 1976).

Iron toxicity in lowland rice has been reported in South America, Asia, and Africa (Sahu, 1968; Fageria 1984; Fageria *et al.*, 1984; Fageria and Rabelo, 1987; Fageria *et al.*, 2003; Sahrawat, 2004).

Metal toxicity in crop plants can be expressed in two ways. One is when metal is absorbed in higher amounts, and becomes lethal to the plant's cells. This is known as direct toxicity of metals. Another metal toxicity is associated with inhibition of uptake and utilization of essential nutrients by plants. This is known as indirect metal toxicity. Indirect toxicity creates nutrient imbalance in plants. This type of iron toxicity is more common in lowland rice compared to direct toxicity (Fageria *et al.*, 1990; Fageria *et al.*, 2006). The concentration of Fe increases to about 500 mg kg^{-1} under flooding and causes Fe toxicity. This will further leads to root injury and bronzing in rice plants. Ultimately, the rice yield will get reduced by 12 to 100 % (Sahrawat, 2004). Most of the Fe present in the soil is in the insoluble form under aerobic rice soils. The bio-available form of Fe is very low under this system of rice cultivation. Deficiency of Fe is common in alkaline soils which are low in soil Fe. But, deficiency is not reported in acidic soils (Sahrawat, 2012).

2.8.1. Nutrient imbalance due to iron toxicity under flooded condition

The most important nutrient deficiencies observed in irrigated or flooded rice are phosphorus (P), potassium (K), and zinc (Zn) (Filho *et al.*, 1983). Fageria *et al.* (1981) reported that uptake of P, K, Ca, and Mg decreased in the nutrient solution with the increasing Fe concentration in the range of 0 to 160 mg Fe L^{-1}. The nutrient imbalances and decreased absorption of other plant nutrients by rice plant, especially P and K is also reported by Yoshida (1981) and Olaleye *et al.* (2001).

It has been reported that the increased availability of Fe causes reduction in Zn uptake in the rice plant. This antagonistic effect on Zn is generally more pronounced during the initial phase of flooding of the soil (Tadano, and Yoshida, 1978). In strongly acid soils, an excess Fe and Al may lead to induced deficiency of P, K, Ca, and Mg in the plant. The deficiency of nutrients curtail rice plant's ability to decrease Fe uptake to the tops through physiological functions carried out by roots such as Fe oxidation, Fe-exclusion, and Fe-retention (Randhawa *et al.*, 1978; Yoshida, 1981).

Ikehashi and Ponnamperuma (1978) reported that reduction of the yield on Fe toxic soil ranged from 29 % for moderately tolerant lines to 74 % for susceptible lines.

2.9. Manganese

Manganese is the 12th most abundant element in earth's crust. Of the different ionic forms of Mn, Mn^{2+} is the primary form absorbed by the plants. Under aerobic conditions, Mn oxides by themselves are insoluble and thus unavailable for plant uptake (Sparrow and Uren, 2014). Under submergence the dominant Mn^{4+} reduces to Mn^{2+} leading to increased solubility of Mn. Thus the concentration of soluble Mn increases up to 90 ppm within two weeks of submergence and declines to 10 ppm due to precipitation of $MnCO_3$. Ultimately, flooding improves the availability of Mn (Ponnamperuma, 1972).

Manganese is reduced and is rendered available when a soil is reduced due to microbial activity (Thenabadu, 1967). Soluble Mn is susceptible to leaching from the soil (Schulte and Kelling, 1999; Hong *et al.*, 2010).

Available Mn content is low in alkaline soils due to the insolubility of Mn compounds in soil. Mn deficiency does not prevail under acidic soils under aerobic condition (Sahrawat, 2012). Clark *et al.* (1957) indicated that the absorption of Mn by rice is very high under flooded condition.

2.10. Zinc

Zinc deficiency is recognized as one of the most widespread constraints in wetland rice affecting up to 50 % of the rice growing area (White and Zasoki, 1999). Hazra *et al.*, (1987) reported that submergence caused an increase in concentration of amorphous sesquioxides bound Zn and a decrease in each of other three forms such as water soluble, exchangeable and crystalline sesquioxide bound forms respectively. Zinc relations in rice have therefore been studied extensively. The deficiency is often associated with poor drainage and perennial soil wetness. The soils typically have weak profile development, reflecting the poor drainage, and much of the Zn is in primary minerals or in other highly insoluble forms.

According to Neue and Lantin (1994), Zn deficiency has been associated with soil conditions of high pH, low available Zn content, prolonged submergence and low redox potential, high organic matter and bicarbonate content, high Mg/Ca ratio, and high available P. Greater concentrations of Fe^{2+} and Mn^{2+} in the soil solution antagonize Zn absorption (Mandal *et al.*, 2000; Sajwan and Lindsay 1986). The uptake, translocation, metabolism, and plant use of Zn is inhibited by high P availability or greater rates of P fertilizer applications (Lindsay 1979).

Zinc concentration in the soil solution initially decreases after flooding; it may temporarily increase immediately (Mikkelsen and Kuo 1976), and equilibrates around 0.3–0.5 μM (Forno *et al.*, 1975). This decrease is associated with increase in soil pH after flooding (Ponnamperuma, 1975), high P availability, precipitation of $Zn(OH)_2$ with an increase in pH, formation of insoluble franklinite ($ZnFe_2O_4$) (Sajwan and Lindsay 1986), ZnS (Kittrick, 1976) in acidic soils and $ZnCO_3$ in calcareous soils (Bostick *et al.*, 2001). There is increased Zn adsorption by oxide minerals such as sesquioxides, carbonates, soil organic matter and clay minerals, subsequently lowering uptake by rice roots.

The availability of Zn under aerobic system of rice cultivation is favoured by the reduced contents of soluble phosphates and sulphides. Further, the high rate of decomposition of organic matter due to ambient temperature and optimum moisture condition under aerobic rice cultivation systems leads to increase in zinc bioavailability (Gao *et al.*, 2002).

Rhizosphere processes due to root induced changes under aerobic conditions such as increased root acquisition area, role of mycorrhiza, the changes in pH and root released exudates play important role in Zn uptake by rice roots under aerobic conditions (Gao *et al.*, 2012). Hajiboland *et al.* (2005) established the role of root-exuded low molecular weight organic compounds in the rhizosphere on Zn mobilization in rice. Organic acid anions can increase Zn availability due to chelation and frequently exudation with protons (to balance charges), thereby reducing rhizosphere pH (Jones and Darrah 1994).

2.11. Copper

The solubility of Cu increases immediately due to desorption of sesquioxide occluded Cu during submergence. But this solubilised Cu immediately get precipitated as CuS (in acid sulphate soils) and as Cu $(OH)_2$ (with increase in pH).

Formation of carbonates and bicarbonates of Cu decreases the solubility of Cu. Ultimately leading to decrease in availability of Cu under both acidic as well as alkaline conditions (Das, 1996).

2.12. Boron

The availability of B is influenced by dynamic soil properties like organic matter, texture, cultivation, drought, and microbial activity (Mengel and Kirkby, 2001). Boron availability decreased with increasing pH and most of the total soil B is unavailable to plants.

Application of lime increases B fixation by soils due to rise in the soil solution pH (Elseewi, 1974, Elseewi and Elmalky 1979; Mondal *et al.,* 1993). In addition, $CaCO_3$ also acts as an important B adsorbing surface in calcareous soils (Elseewi, 1974; Elseewi and Elmalky, 1979; Goldberg and Forster, 1991).

2.13. Yield and yield attributes of aerobic rice

Rice is characterized by a shallow root system compared with other cereal crops, having limited water extraction below 60 cm (Fukai and Inthapan, 1988). The form of the rice root system also varies with the cultivation method (Yoshida and Hasegawa 1982). In upland conditions with direct sowing, the root system generally develops deeper than in transplanted plantings in lowland conditions (Gowda *et al.*, 2011).

A study by Sandhu *et al.* (2012) on aerobic rice genotypes, reported that aerobic rice genotypes had 54–73.8 % greater root length and 18 to 60 % higher fresh root biomass compared to lowland *indica* rice varieties. The grain yield was positively correlated with the root length and biomass. They suggested that root length and biomass might be the key factor for improving grain yield under water-saving conditions.

The yield difference under flooded and aerobic rice primarily depends on the varietal characteristics (Patel *et al.*, 2010). Aerobic rice varieties with minimum yield gap compared to flooded rice is the key for success of aerobic rice cultivation. Patel *et al.* (2010) observed that sink size i.e. spikelets per panicle contributed more to the yield and is considered to be the most important factor responsible for yield gap between aerobic and flooded rice among the yield components evaluated. Growth parameters like plant height, root length and root biomass/hill and tillers/m^2 varied under aerobic and flooded conditions. They also reported a non-significant correlation in the number of panicles under flooded rice and aerobic rice.

Correlation studies between yield and yield components of aerobic rice varieties by Malath and Gomathinayagam, (2013) showed that productive tillers, grains per panicle and spikelet fertility were positively correlated with seed yield and the traits viz., plant height, panicle length, grains per panicle, 100 grain weight and root dry weight were inter correlated among themselves. Therefore, these traits are to be given priority during selection of new aerobic rice to improve the grain yield.

Rice is derived from a semi-aquatic ancestor, and thus has unique characteristics in root morphology and anatomy suitable for wetland conditions, including the development of aerenchyma and a more compact root system than in dry land crops. But these characteristics need to be modified for aerobic culture. By comparing root growth in aerobic culture with that in flooded culture, it is revealed that, rice plants develop roots poorly in the surface soil in aerobic culture. Vigorous growth of 'superficial' roots leads to the continuous absorption of nutrients well after anthesis (Ida *et al.*, 2009, Zhang *et al.*, 2009). Speedy aerenchyma formation is seen in anaerobic environment as an integral part of ordinary root development (Jackson *et.al.*, 1985) which is reduced in drained soils for at least some variation.

2.13. Root cation exchange capacity and apparent free space.

The adsorption of ions by dead or damaged plant roots is called cation-exchange capacity of roots (Drake *et al.*, 1951; Crooke, 1958). Drake *et al.*, (1951) suggested that the "differences in the ability of plants to take up cations from the soil are largely controlled by the cation exchange capacity of the plant root and the valence of the cation."

Crooke and Knight (1962) showed that "the cation exchange capacity of roots is positively correlated with the content in the tops of the total cations, the ash, the excess base, and the total trace elements." Cation exchange capacity also showed a positive correlation with protein content and dry matter in the ether extract and negative correlation with crude fiber. Ram (1980), suggested that cation exchange capacity of the roots was maximum at tillering stage, the uptake of P, K, Fe and Mn by shoot was significantly and positively correlated with CEC of the root throughout their plant life.

As stated by Briggs *et al.* (1961) "the concept of free space was introduced to describe the phase in the cell or tissue into which solutes move relatively freely." "Free space (F.S.) is defined as that part into and through which the solute and solvent from the external solution move readily; clearly there may be subdivisions of the free space based on different degrees of accessibility to solute."

"Since free space cannot be measured directly, the apparent free space (A.F.S.) is estimated and was precisely defined by Briggs and Robertson, (1957) as follows: the apparent volume of the free space equals the amount of solute in the F.S. divided by the amount of solute per unit volume of external solution when free space and external solution are in equilibrium."

Materials and Methods

3. Materials and methods

The present investigation entitled "Nutrient dynamics and transformation in aerobic and flooded systems of rice in lateritic soils of Kerala" was carried out at Department of Soil Science and Agricultural Chemistry, Radiotracer laboratory, College of Horticulture, Kerala Agricultural University during 2010-2013. This project included field experiments and lab analysis of soil and plant samples. The materials used and the methods adopted to achieve the objectives mentioned in the introduction are summarized below.

Three simultaneous field experiments were conducted in farmer's field at Nellikkattiri, Thirumittakkode panchayat in Palakkad district to investigate the dynamics and transformation of nutrients under flooded and aerobic rice cultivation systems. The details of the experiments are furnished below.

3.1. Experiment on flooded rice

Under flooded system of rice cultivation, two separate experiments were done *ie.* one, application of fertilizers and lime based on analysis of wet samples as such (wet analysis) and the other based on analysis after air drying (dry analysis). The initial soil samples from the experiment site was collected and characterized with respect to pH, EC, available nutrient status (organic carbon, P, K, Ca, Mg, S, Fe, Cu, Mn, Zn and boron as well as the fractions of P, Zn, Fe and B. The methodology adapted for analysis of soil samples on wet basis is detailed hereunder.

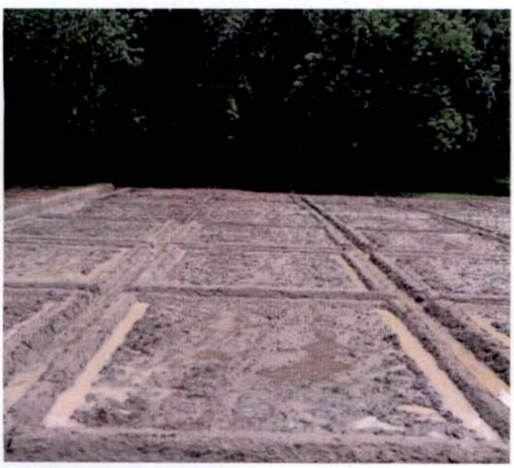
3.1.1. Analysis of soil samples on wet basis

The core soil samples were collected (0-15 cm depth) from the field to a plastic cover and kept air tight. The moisture content of the soil samples were analysed immediately and expressed on wet basis. For that purpose, an initially weighed wet soil of weight W_1 was oven dried at 105 °C and weight W_2 was recorded. The moisture content of the soil sample was calculated using the formula $[(W_1 - W_2)/W_1] \times 100$. The moisture content was deducted from the weight of the wet soil and calculations were done to express the results on dry weight basis.

Plate 1. Location of experiment on flooded rice

Plate 2. Location of experiment on aerobic rice

Plate 3. Field lay out under aerobic and flooded systems



3.1.2. Analysis of air dried soil samples

A part of the collected soil samples was air dried under shade, ground and sieved through 2 mm sieve and used for analysis. The initial physico-chemical properties of the soil samples are furnished in table 2.

3.2. Experiment on aerobic rice

The initial soil samples from the experiment site were collected and characterized with respect to pH, EC, CEC and exchangeable cations, available nutrient status (organic carbon, P, K, Ca, Mg, S, Fe, Cu, Mn, Zn and boron as well as the fractions of P, Zn, Fe and B. The soil samples were analysed after shade drying.

3.3 Details of the experiments

Under both the systems, field experiments (two experiments under flooded system and one experiment on aerobic rice) were conducted to unravel the objectives of the study in the field mentioned above. The details of the experiments are as follows.

Design: RBD (Randomized block design)

Treatments:

I. Doses of fertilizer: 2

i. As per package of practices recommendations, KAU (KAU, 2011) (F_1)

ii. As per soil test based fertilizer application (F_2)

II. Doses of lime

i. As per package of practices recommendations, KAU(KAU, 2011) (L_1)

ii. Based on ΔpH (L_2) (DOA, 2013)

iii. Lime requirement based on SMP buffer method (Shoemaker *et al.*, 1961) (L_3)

No of treatments: 2 x 3

Replications: 4

Plot size: 20 m^2

Variety: Jyothi

Plate 4. Transplanting under aerobic and flooded systems

Plate 5. Aerobic rice- Active tillering

The details of the treatment combinations for the experiment on flooded rice are presented in table 1.

Table.1. **Treatment combinations of the experiments**

Treatment No.	Treatment combinations	Treatment details
T1	F_1L_1	Fertilizers and lime as per POP
T2	F_1L_2	Fertilizers as per POP, lime as per ΔpH
T3	F_1L_3	Fertilizers as per POP, lime as per SMP buffer method
T4	F_2L_1	Fertilizers as per soil test, lime as per POP
T5	F_2L_2	Fertilizers as per soil test, lime as per ΔpH
T6	F_2L_3	Fertilizers as per soil test, lime as per SMP buffer method

3.3.1. Land preparation

The experimental area was ploughed well and plots of 5m x 4m were prepared by constructing bunds of 30 cm width and height. Irrigation and drainage channels were provided between each plot.

3.3.2. Crop culture

The rice cv. Jyothi, a short duration cultivar of 110-120 days duration was used for the study. The seeds were soaked in carbendazim @ 2 g kg^{-1} for 12 hours before nursery sowing. Seedlings of 18 days were transplanted at a spacing of 15 cm x 10 cm.

The experimental area was ploughed well and plots of 5 m x 4 m were prepared by constructing bunds of 30 cm width and height. Irrigation and drainage channels were provided between each plot.

A water level of 5 cm was maintained in the field till the harvest of the crop in case of the experiment on flooded rice.

The field condition for experiment on aerobic rice was maintained by reducing the water level in the field after transplanting within one week for occurrence of hairline cracks in the field and thereafter by providing irrigations for the crop just to remove the hairline cracks formed in the field at two to three days interval during evening hours.

Plate 6. Flooded rice - active tillering

Plate 7. Field visit by advisory committee members

3.3.3. Application of organic manure, lime and fertilizers in experiment fields

Organic manure was applied in the field @ 5 tonnes ha^{-1} as per package of practices recommendations (KAU, 2011) at the time of land preparation. Lime and fertilizers were applied to the field as per the treatments detailed in table 3 in two equal splits. Half of the lime was applied as basal dose four days before transplanting and half as top dressing one week before panicle initiation. Half of the required dose of fertilizers were supplied as basal dose, was added to the field four days after transplanting. The topdressing of fertilizers was done during panicle initiation stage of the crop.

3.4. Insitu measurement of pH and electrical conductivity from experiment fields

The pH of the soil of different treatments were measured in situ daily immediately after transplanting till the harvest of the crop using pH meter (Eutech - model pHtestr 30) and conductivity meter (Eutech - model ECtestr 11^{+} multi range)

3.5. Measurement of redox potential

The redox potential of the experiment site was measured immediately after transplanting till the harvest of the crop from three different depths viz. 15 cm, 30 cm and 45 cm. This was done by installing the redox electrode in the field in the above mentioned depths. The measurements from these depths were taken daily till the harvest of the crop using redox meter (model RM 1K TOA).

3.6. Collection and analysis of soil samples

The soil samples from both the experiments were collected at three different stages of the crop viz. at active tillering, at panicle initiation and at harvest of the crop. The procedures adopted for the analysis of soil samples from both the experiments viz. 1. flooded rice 2. aerobic rice are detailed below.

3.6.1. Soil pH

The pH of the soil samples was determined in a 1:2.5 soil water suspension, potentiometrically using a pH meter (Jackson, 1958).

Plate 8. Flooded rice – Field ready to harvest

Plate 9. Aerobic rice – Field ready to harvest

3.6.2. Electrical conductivity

Electrical conductivity was estimated in the soil water suspension (1:2.5) using a conductivity meter (Jackson, 1958).

3.6.3. Organic carbon

Organic carbon of the soil was estimated by wet digestion method (Walkley and Black, 1934).

3.6.4. Available phosphorus

Available phosphorus in the soil samples were extracted using Bray No.1 reagent (Bray and Kurtz, 1945) and estimated colourimetrically by reduced molybdate ascorbic acid blue colour method (Watanabe and Olsen, 1965) using a spectrophotometer (Model: Spectroaquant Pharo M)

3.6.5. Available potassium

Available potassium in the soil samples were extracted using neutral normal ammonium acetate and its content in the extract was estimated by flame photometry (model: Elico CL 365) (Jackson, 1958).

3.6.6. Available calcium and magnesium

Available calcium and magnesium in the soil samples were extracted using neutral normal ammonium acetate and its content in the extract was estimated using Atomic Absorption Spectrophotometer (Model: PerkinElmer AAnalyst 400).

3.6.7. Available sulphur

Available S was extracted by using 0.15% $CaCl_2$ (Tabatabai, 1982) and estimated by turbidimetry (Massoumi and Cornfield, 1963) using a spectrophotometer (Model: Spectroaquant Pharo M)

3.6.8. Available Micronutrients (Fe, Cu, Mn and Zn) in soil

Available micronutrients in soil samples were extracted using 0.1M HCl (Sims and Johnson, 1991). Four gram soil with 40 ml of 0.1M HCl was shaken for 5 minutes. It was filtered through Whatmann No.42 filter paper and the filtrate was

Plate 10. Aerobic rice –harvest

Plate 11. Flooded rice –harvest

collected and analysed for Fe, Cu, Mn and Zn using Atomic Absorption Spectrophotometer (Model: PerkinElmer AAnalyst 400).

3.6.9. Available boron

Available boron in soil samples were extracted with hot water (Berger and Truog, 1939, Gupta, 1972) and estimated colourimetrically by Azomethine – H using spectrophotometer (Model: Spectroaquant Pharo M)

3.6.10. Fractionation of soil Phosphorus

Fractions of soil P was extracted by the method proposed by (Peterson and Corey, 1966). The extraction procedure involves sequential extraction with

i) 1 M NH_4Cl to get soluble P

ii) 0.5 M NH_4F and saturated NaCl to remove Al-P

iii) 0.1 M NaOH and saturated NaCl to remove Fe–P

iv) Sodium citrate–dithionate–bicarbonate to remove sesquioxide occluded P

v) 0.25 M H_2SO_4 to remove the Ca-P

3.4.10.1. Extractions of P fractions

Flow chart for the P fractionation is depicted in Fig.1. One gram soil was taken in a 100 mL centrifuge tube. To this 50 mL of 1 M NH_4Cl solution was added and shaken for 30 minutes. The tubes with the extract were then centrifuged. The solution was decanted into another tube (Soluble P, Extract A).

The soil residue in the centrifuge was added with 0.5 M NH_4F and shaken for 1 hour. Then the tube was centrifuged and the solution was decanted. The soil residue was washed twice with 25 mL saturated NaCl and these two extracts were combined together and made up the volume (Al - P, Extract B).

To the soil residue, 50 mL 0.1 M NaOH was added and shaken for 17 hours. The solution was centrifuged and decanted. The residue was again washed twice with 25 mL saturated NaCl solution and centrifuged and decanted; they were mixed together and made up the volume to 100 mL (Fe bound-P, Extract-C).

Table 2. Physicochemical properties of the soil of the experiment sites

	Flooded rice Wet analysis	Ratings	Flooded rice Dry analysis	Ratings	Aerobic rice	Ratings
pH	4.9	Very strongly acidic	4.45	Extremely acidic	4.2	Extremely acidic
EC dSm^{-1}	0.01	Normal	0.053	Normal	0.05	Normal
OC %	0.95	Medium	1.47	Medium	0.94	Medium
Available Nutrient status						
P $kg\ ha^{-1}$	11.35	Medium	10.06	Medium	13.33	Medium
K $kg\ ha^{-1}$	51.07	Low	81.70	Low	113.3	Low
Ca $mg\ kg^{-1}$	68.02	Deficient	137.2	Deficient	95.6	Deficient
Mg $mg\ kg^{-1}$	8.18	Deficient	6.3	Deficient	6.2	Deficient
S $mg\ kg^{-1}$	14.39	Sufficient	22.22	Sufficient	11.3	Sufficient
Fe $mg\ kg^{-1}$	113.74	Sufficient	51.73	Sufficient	56.8	Sufficient
Cu $mg\ kg^{-1}$	6.10	Sufficient	8.72	Sufficient	9.6	Sufficient
Mn $mg\ kg^{-1}$	18.24	Sufficient	15.40	Sufficient	29.5	Sufficient
Zn $mg\ kg^{-1}$	2.80	Sufficient	2.52	Sufficient	1.7	Sufficient
B $mg\ kg^{-1}$	0.110	Deficient	0.07	Deficient	0.07	Deficient

Table 3. Rate of application of lime and fertilizer to the crop for flooded and aerobic rice

Treatment No.	Lime t ha^{-1}	Fertilizers (kg ha^{-1})				
		Urea	Factomphos	Muriate of potash	$MgSO_4$	borax
Aerobic rice						
T1	0.60	97.80	225.00	75.00	Not applied	Not applied
T2	0.776	97.80	225.00	75.00		
T3	8.50	97.80	225.00	75.00		
T4	0.60	86.08	211.50	79.50	80.00	10.00
T5	0.776	86.08	211.50	79.50		
T6	8.50	86.08	211.50	79.50		
Flooded rice -Wet analysis						
T1	0.60	97.80	225.00	75.00	Not applied	Not applied
T2	0.689	97.80	225.00	75.00		
T3	2.40	97.80	225.00	75.00		
T4	0.60	86.08	211.50	79.50	80.00	10.00
T5	0.689	86.08	211.50	79.50		
T6	2.40	86.08	211.50	79.50		
Flooded rice dry analysis						
T1	0.60	97.80	225.00	75.00	Not applied	Not applied
T2	0.692	97.80	225.00	75.00		
T3	5.55	97.80	225.00	75.00		
T4	0.60	48.91	238.50	79.50	80	10
T5	0.692	48.91	238.50	79.50		
T6	5.55	48.91	238.50	79.50		

To the soil residue, 40 mL of 0.3 M citrate solution and 5 mL of 1 M $NaHCO_3$ solution were added and heated in a water bath to 85 °C. To this, 1 g of $Na_2S_2O_4.2H_2O$ was added with rapid stirring and the heating was continued at 85 °C for 15 minutes. The solution was decanted into another flask after centrifugation. The soil residue was washed with 25 mL of saturated NaCl. This was centrifuged and decanted the supernatant solution to the above flask (occluded P, Extract-D).

To the soil residue, 50 mL 0.25 M H_2SO_4 was added and shaken for 1 hour on a shaker. The solution was centrifuged and decanted into another flask. The soil residue was washed twice with 25 mL saturated NaCl, centrifuged and decanted. This was decanted to the above flask and volume made up to 100 mL (Ca - P, Extract E).

3.4.10.2. Estimation of P fractions

3.4.10.2.1. Concentration P in soluble and Ca-P fractions

Five milli Liters of each of the extracts were pipetted out into a 50 mL volumetric flask. To this, distilled water was added to increase the volume to 20 mL. 4 mL of reagent B (ascorbic acid in ammonium molybdate and potassium antimony tartarate with 5 N H_2SO_4) was added. The volume was made up and the absorbance was read at 660 nm.

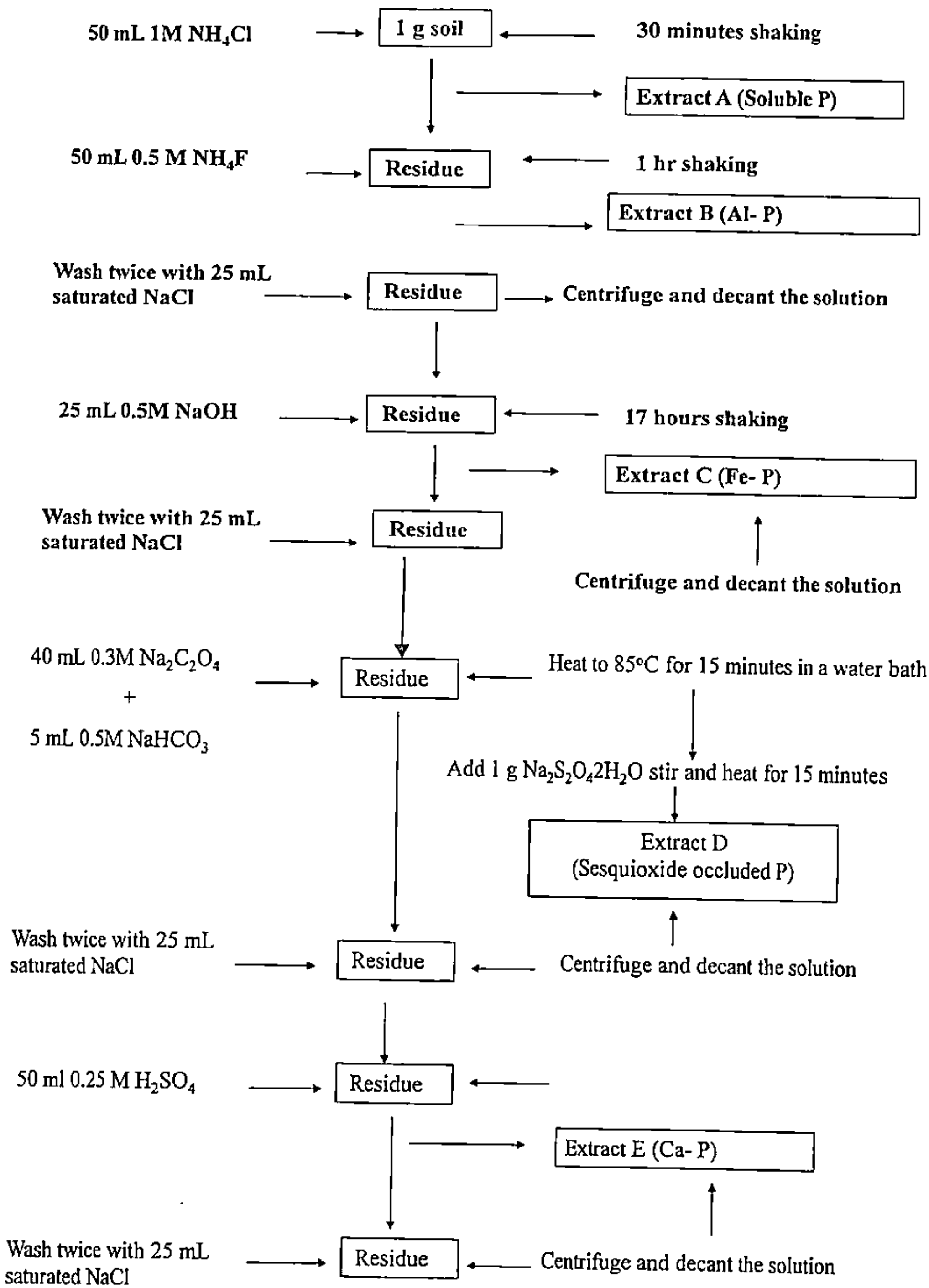
3.4.10.2.2. Concentration of P in Al-bound P (Extract-B)

Five milli liters of the extracts were pipetted out into 50 mL volumetric flask. To this 7.5 mL 0.8 M Boric acid was added. Then blue colour was developed using reagent B. The intensity was read in spectrophotometer at 660 nm.

3.4.10.2.3. Concentration of P in Fe-bound P and sesquioxide occluded P

Five milli liters of the extracts were pipetted out. The solution pH was adjusted using 2 M HCl in the presence of 0.25 % p- nitrophenol. For this a separate 5 mL aliquot was pipetted out to which 2 drops 0.25 % p-nitrophenol was added and 2 M HCl was added drop wise from a burette till the colour changed from yellow to colourless. This estimated amount of 2 M HCl was added to the aliquot (5 mL) pipetted for estimation.

Figure 1. Flow chart of fractionation of soil phosphorus (Soil 1 g < 2 mm) in to100 mL centrifuge tube



3.6.11. Fractionation of zinc and iron

To study the distribution of Zn and Fe in the soil sequential fractionation method outlined by Iwasaki and Yoshikawa (1990) which is the modified form of the fractionation scheme of Miller *et al.* (1986) was used. The reagents used and chemical forms solubilized from 1.5 g of soil samples are listed below.

3.6.11.1. Water soluble + Exchangeable (neutral salt) fraction

Soil samples of 1.5 g were weighed into centrifuge tube, was added with 25 ml (0.5 M $CaNO_3)_2$ and shaken for 16 hours. The filtrate was collected after centrifugation for 2 minutes at 3000 rpm

3.6.11.2. Specifically adsorbed Pb displaceable fraction:

The soil residue was added with 25 ml of 0.05 M $Pb(NO_3)_2$ and 0.5 M $CH_3COO\ NH_4$ at pH 6, shaken for 2 hours and the filtrate was collected after centrifuging at 3000 rpm for 2 minutes.

3.6.11.3. Acid soluble fraction:

The soil residue was added with 25 ml CH_3COOH (2.5 per cent), shaken for 2 hours. The filtrate was collected as described above.

3.6.11.4. Manganese oxide occluded fraction:

The soil residue was added with 50 ml of 0.1 M $NH_2OH\ HCl$ at pH 2, shaken for 0.5 hours and the filtrate was collected and analysed for Zn, Mn, Fe and Cu.

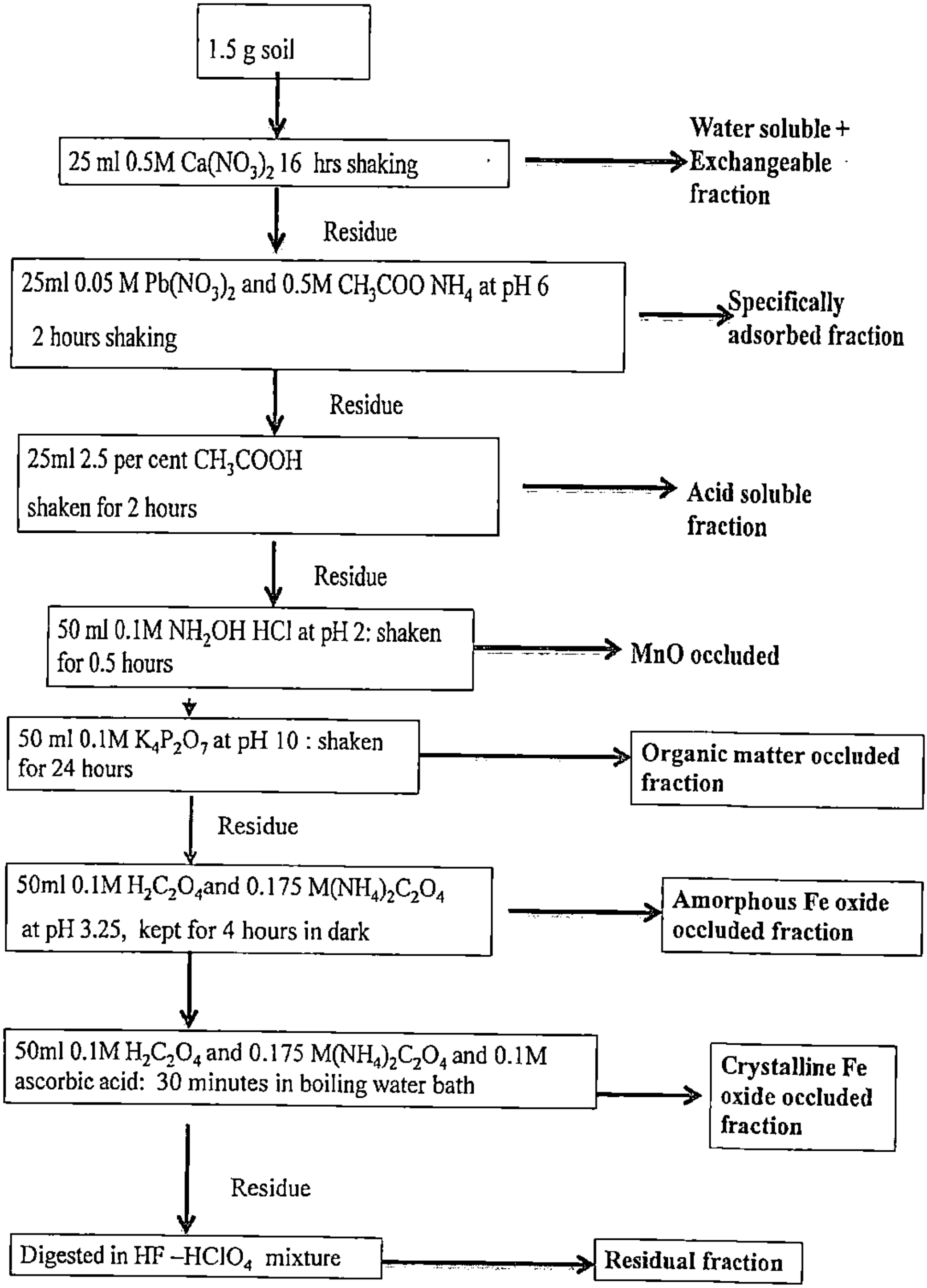
3.4.11.5. Organic matter occluded fraction:

Organic matter occluded fraction was extracted using 50 ml of 0.1 M $K_4P_2O_7$ at pH 10, shaken for 24 hours. The filtrate was collected after centrifuging at 3000 rpm for 2 minutes.

3.4.11.6. Amorphous iron oxide occluded fraction:

The soil residue was added with 50 ml of 0.1 M $H_2C_2O_4$ and 0.175 M $(NH_4)_2C_2O_4$ at pH 3.25, kept for 4 hours in dark. The filtrate was centrifuged and decanted and analyzed for amorphous iron occluded fraction.

Fig 2: **Flow sheet showing extraction mode to be followed for distribution of zinc among various soil fractions**



3.4.11.7. Crystalline iron oxide occluded fraction:

The residue was added with 50 ml of 0.1 M $H_2C_2O_4$ and 0.175 M $(NH_4)_2C_2O_4$ and 0.1 M ascorbic acid, kept for 30 minutes in boiling water bath for extracting crystalline iron oxide occluded fraction. The filtrate, after centrifuging was analyzed to determine Fe, Cu, Zn and Mn.

3.4.11.8. Residual fraction

The final soil residue was then digested in HF –$HClO_4$ mixture and the digest was analyzed for Fe, Cu, Zn and Mn. The filtrates collected to determine all the above described fractions were analyzed by atomic absorption spectrophotometer (PerkinElmer - model AAnalyst 400).

3.6.12. Extraction and estimation of fractions of boron

The summary of the sequential extraction of and determination of soil B fractions as given by Datta *et al.* (2002) is presented below

3.6.12.1. Readily soluble B (RS B)

Five grams of soil in duplicate were weighed into 50 ml polythene centrifuge tubes to which 10 ml of 0.01 M $CaCl_2$ were added and shaken for 16 hours (Hou *et al.*, 1994, 1996). After Centrifuging at 10000 rpm for 30 minutes the supernatant solution was filered through whatman No.42 filter paper. Boron was determined in clear extracts using azomethine-H (Bingham, 1982)

3.6.12.2. Specifically adsorbed B (SA B)

The residue from the step was then extracted with 10 ml of 0.05 M KH_2PO_4 by shaking for one hour (Hou *et al.*, 1994, 1996). After Centrifuging at 10000 rpm for 30 minutes the supernatant solution was filered through whatman No.42 filter paper. Boron was determined in clear extracts using azomethine-H (Bingham, 1982).

3.6.12.3. Oxide bound B (OX B)

The residue from the previous step was extracted with 20 ml of 0.175 M ammonium oxalate, pH 3.25 (Hou *et al.*, 1994, 1996; Jin *et al.*, 1987; McLaren and Crawford, 1973) by shaking for 4 hours (Hou *et al.*, 1994, 1996). The yellow to reddish colour of the extracts due to the dissolution of Fe and organic matter was eliminated by treating with NaOH and $HClO_4$

3.6.12.3.1. Elimination of colour of the extracts

To remove the colour, a 14 ml aliquot of the extracts was taken into a 50 ml Teflon beaker and 2 ml of 5 N NaOH solution was added and weighed and then warmed on a hot plate to completely precipitate the dissolved Fe as $Fe(OH)_3$ (Jackson, 1973). The beaker with the aliquot was weighed again and the loss in weight was made up with distilled water. The suspension was filtered through Whatman no.42 to separate the Fe. A 9 ml aliquot of the filtrate was taken into a 50 ml Teflon beaker and 4 ml concentrated H_2SO_4 and 1 ml $HClO_4$ (60 %) were added and heated on a hot plate at 135 °C to destroy the organic matter. When the volume was reduced to about 6 ml, $HClO_4$ was added in an increment of 0.5 ml until the solution became colourless and the volume reduced to 4 or 5 ml. the content was transferred to a 15 ml graduated polyethylene and the final volume was made up to 6 ml. After centrifuging at 10,000 rpm for 15 min., B in the clear extracts was determined by the carmine method (Bingham, 1982).

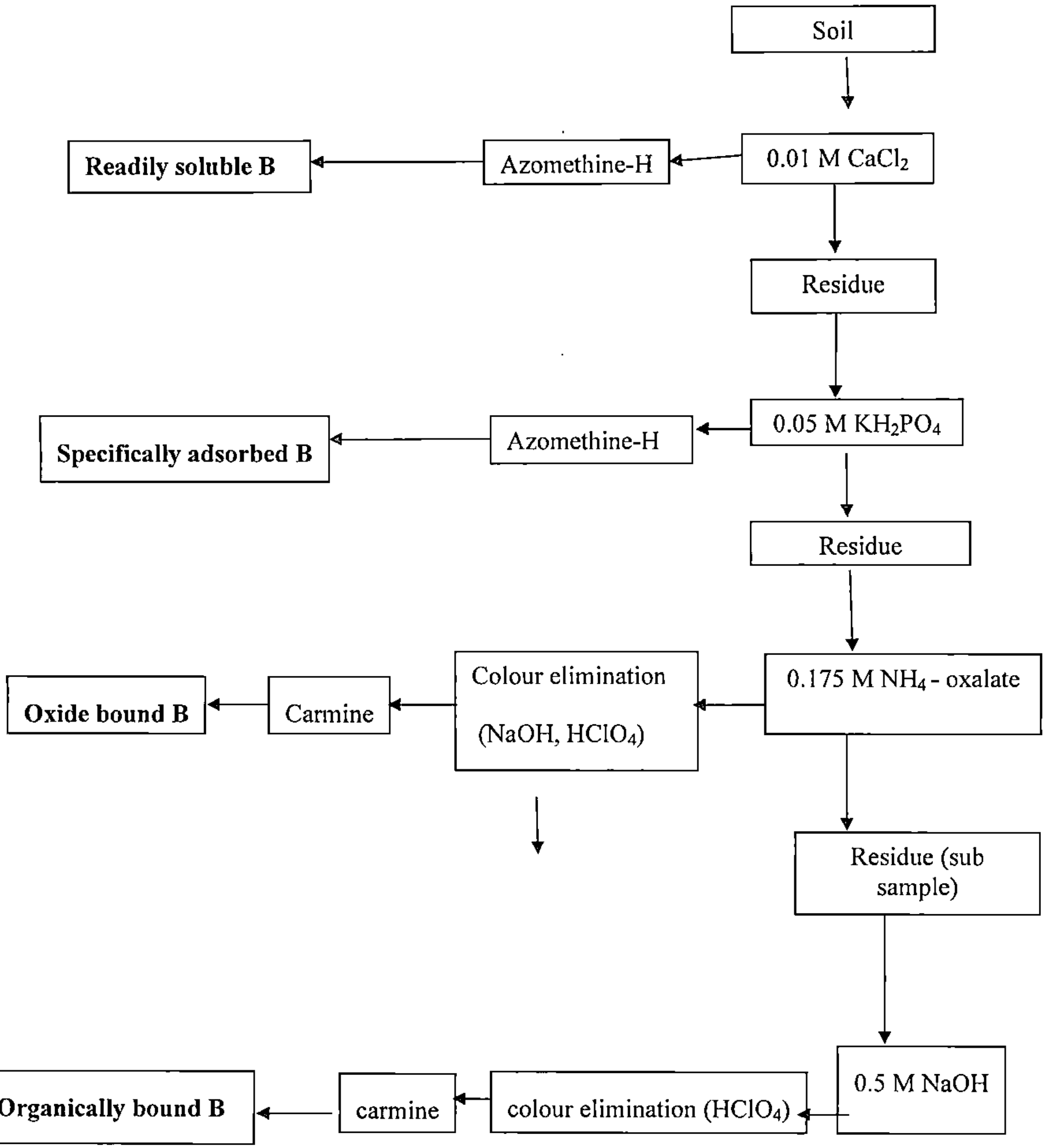
3.4.12.4. Organically bound B (ORG B)

A sub sample of two grams of the residue from the ammonium oxalate extraction was treated with 20 ml of 0.5 M NaOH (Choudhari and Stevenson, 1957) by shaking for 24 h followed by filtration through Whatman no. 42. All the extracts were dark red in colour due to the dissolution of organic matter which was eliminated by the same procedure detailed in 3.6. 12.3.1. The final volume was made up to 7 ml. After centrifuging the samples at 10,000 rpm for 15 minutes B in the supernatant was determined with carmine.

3.4.12.5. Total B (TB)

Soil sample of 0.2 gram of was taken in 50 ml Teflon beaker and 3 ml aqua regia was added and kept overnight for wet digestion. Later digested at 135 ^{0}C for 2 hr

Fig 3.The flow diagram of for the fractionation of B in soil



and filtered through Whatman no. 42 and diluted with distilled water and B was estimated with carmine.

3.4.12.6. Residual B (RB)

The residual B was estimated by subtracting the sum of RS B, SA B, OX B, ORG B from total boron.

3.7. Collection of plant samples

Plant sampling (shoot) was done at three different stages of the crop viz. at active tillering, at panicle initiation and at harvest of the crop. The methods followed to estimate N, P, K, Ca, Mg, S, Fe, Cu, Mn and Zn are mentioned in table.

Table 4. Methods of analysis of shoot and grain

Sl. No.	Element	Method
1	Nitrogen	Modified Kjeldhal's digestion method (Jackson, 1973)
2	Phosphorous	Vanabdomolybdate phosphoric yellow colour in nitric acid system (Piper, 1966)
3	Potassium	Flame photometry determination (Jackson, 1973)
4	Calcium and magnesium	Diacid digestion of leaf sample followed by filtration. The filtrate was collected, analysed for Ca and Mg using Perkin elmer AAS (Piper, 1966)
	Sulphur	Diacid digestion of leaf sample followed by filtration and estimation by turbidimetry (Massoumi and cornfield, 1963).
5	Iron, manganese, zinc and copper	Diacid digestion of leaf sample followed by filtration. The filtrate was collected, analysed for Fe, Mn,Zn and Cu using Perkin elmer AAS (Piper, 1966)
	Boron	Determined by dry ashing (Gaines and Mitchell, 1979) and then colorimetrically by Azomethine-H (Bingham, 1982).

3.7.1. Estimation of wet root cation exchange capacity (Root CEC)

About 3 g of the fresh roots collected from the two different experimental plots were washed thoroughly and wrapped in muslin cloth. The roots in the cloth wraps were dipped in 0.01 N HCl taken in a beaker kept in the ice bath. The wraps were intermittently raised and lowered for 5 minutes. The excess acid was removed by a series of washings in distilled water taken in at least three beakers, all kept cooled in ice bath. The cloth wrap was then unwrapped and the roots were transferred to about 150 ml of 1N neutral KCl (pH exactly 7). The KCl solution was titrated potentiometrically using 0.01 N KOH to pH 7.0.

3.7.2. Estimation of apparent free space

The fresh roots collected from the two different experimental plots were washed thoroughly and dried between folds of filter paper. 2 g of the root samples each were weighed and transferred to beaker and 200 ml of 0.01 N KCl was added and allowed to equilibrate for 30 minutes. The roots were taken out after the stipulated time, washed gently with distilled water and adhering KCl was removed. The roots were then immersed in 50 ml of distilled water to remove the KCl in the free pore space. The KCl brought in the solution was titrated with 0.01 N $AgNO_3$ using K_2CrO_4 indicator.

3.7.3. Chlorophyll content of flag leaf- Biochemical observation

The chlorophyll a, chlorophyll b, and total chlorophyll were estimated by method suggested by Hiscox and Israelstam (1979). 100 mg leaf sample was added to 10 ml DMSO (dimethyl sulphoxide) and kept in dark for overnight. The final volume was made up to 25 ml after filtration during next day. The chlorophyll content was estimated in spectrophotometer ((Model: Spectroaquant Pharo M) at two wave lengths viz. 645 nm and 663 nm and expressed as mg g^{-1} fresh weight of plant tissue. The calculation was done using the formulae

Chlorophyll a $= [(12.7 \text{ x } A_{663}) - 2.69\text{x}A_{645})] \text{ x } (V/1000) \text{ x } W$

Chlorophyll b $= [(22.9 \text{ x } A_{645}) - 4.68\text{x}A_{663})] \text{ x } (V/1000) \text{ x } W$

Total chlorophyll = $[(8.02 \times A_{663}) + 20.2 \times A_{645})] \times (V/1000) \times W$

Where A = Absorption at given wavelength

V = Total volume of sample

W = Weight of sample

3.8. Measurement of total water requirement by the crop

Measurement of total water requirement by the crop under both systems was done, by quantifying the irrigation water.

3.9. Biometric observations

3.9.1. Tiller production

The number of tillers per hill at weekly interval was recorded up to harvest.

3.9.1 **Productive tillers**

The number of productive tillers per hill was recorded at panicle initiation.

3.9.2. **Thousand grain weight**

One thousand grains were counted from the produce of each plot and their weight was recorded in each plot and expressed in grams.

3.9.3. Number of grain per panicle

The number of filled grains per panicle was counted and recorded.

3.9.2. Grain and straw weight

The crop was harvested from each plot threshed, winnowed and weight of straw and grain was recorded separately and expressed as Mg ha^{-1}.

3.9.3. Dry matter yield per plant

The dry matter yield per plant was recorded at harvest stage.

3.9.4. Cost of cultivation

Cost of cultivation was worked out by adding cost of labour, inputs and cost of plant protection measures.

3.9.5. Statistical analysis

Pooled analysis of data was carried out by the method suggested by Panse and Sukatme (1978). Correlation analysis of data generated was carried out based on the method suggested by Cox (1987) using SPSS package. Path coefficient analysis was carried out in SPAR1 package. Analysis of variance in RBD was made in MSTATC package.

Result

4. Results

The data generated from the field experiments conducted to achieve the objectives of the study are given in this chapter.

The physicochemical properties of the initial samples collected from the experiment sites of both aerobic and flooded soils were presented in table 1.

The pH of the soil of the experimental field on aerobic rice was 4.2 (extremely acidic), and that of flooded rice was 4.9 (very strongly acidic). The organic carbon and available phosphorus status of the soil in both the fields were medium. The available potassium status was low. Both the soils were severely deficient in available Ca and Mg. The level of available sulphur was sufficient. The soils were sufficient in all the plant available micronutrients except boron (0.07 mg kg^{-1}).

Under flooded system of rice cultivation, two separate experiments were done *ie.* one, application of fertilizers and lime based on analysis of wet samples as such (wet analysis) and the other based on analysis after air drying (dry analysis). The soil samples collected from both the experiment fields at different stages were analysed as such on wet basis and after air drying. The available nutrient status, obtained by wet analysis as well as dry analysis was correlated with the plant content at corresponding stages. Significant better correlations were obtained for data from wet analysis with corresponding plant content at all the stages. Hence the result of the experiment where, application of fertilizers and lime was done based on wet analysis is only discussed here.

4.1. In situ measurement of soil pH, electrical conductivity and redox potential

4.1.1. Soil pH

In situ measurement of soil pH was done immediately after transplanting till the harvest of the crop under both systems of rice cultivation. The data are presented in table 5.

Table 5 a. In situ measurement of soil pH (days after transplanting)

Days after transplanting	Aerobic rice			Flooded rice		
	L_1	L_2	L_3	L_1	L_2	L_3
1	6.5	6.8	7.5	5.9	6.4	7.0
2	6.3	6.7	7.7	5.8	6.3	7.0
3	6.2	6.7	7.5	5.8	6.4	6.9
4	6.0	6.6	7.5	5.8	6.4	6.9
5	6.2	6.5	7.8	5.8	6.4	6.8
6	5.8	6.2	7.5	5.8	6.3	6.8
7	5.9	6.2	7.4	5.8	6.4	6.8
8	5.8	6.2	7.4	5.8	6.3	6.7
9	5.8	6.1	7.4	5.7	6.3	6.7
10	5.9	6.1	7.5	5.7	6.3	6.6
11	5.8	6.1	7.4	5.7	6.2	6.6
12	5.7	6.2	7.5	5.7	6.2	6.5
13	5.5	6.1	7.5	5.8	6.2	6.5
14	5.3	6.0	7.5	5.8	6.3	6.5

Table 5 b. In situ measurement of soil pH (weeks after transplanting)

Weeks after transplanting	Aerobic rice			Flooded rice		
	L_1	L_2	L_3	L_1	L_2	L_3
1	5.9	6.2	7.4	5.8	6.4	6.8
2	5.3	6.0	7.5	5.8	6.3	6.5
3	5.5	5.9	6.9	5.7	6.1	6.3
4	4.9	5.2	6.2	5.6	5.9	6.2
5	4.9	5.1	6.2	6.0	6.6	6.9
6	6.7	6.8	8.0	6.6	6.6	6.8
7	6.8	6.8	7.9	6.2	6.2	6.8
8	6.5	6.6	7.4	6.1	6.4	6.7
9	5.9	6.2	7.2	6.0	6.3	6.6
10	5.4	5.8	6.9	5.8	6.2	6.5
11	5.3	5.5	6.9	5.6	6.3	6.4
12	5.0	5.2	6.6	5.9	6.1	6.3
13	4.9	5.0	6.5	5.6	6.1	6.2
14	4.8	5.0	6.4	5.7	6.0	6.2

The data show that the pH increased immediately after application of lime, which was applied just before transplanting under both systems of rice cultivation. The rate of increase was in proportion to the quantity of lime applied under both systems. However, the rate was observed to be less under flooded system of rice. Soil pH was found to decrease to the initial level in plots of aerobic rice where lime was applied as per POP (L_1), while the pH was stabilized around six under flooded system.

4.1.2. Electrical conductivity

In situ measurement of electrical conductivity was done immediately after transplanting till the harvest of the crop under both systems of rice cultivation. The data are presented in table 5.

Table 6 a. In situ measurement of electrical conductivity (dSm^{-1}) (days after transplanting)

Days after transplanting	Aerobic rice			Flooded rice		
	L_1	L_2	L_3	L_1	L_2	L_3
1	0.12	0.13	0.13	0.08	0.09	0.10
2	0.11	0.11	0.14	0.07	0.09	0.10
3	0.12	0.12	0.13	0.06	0.08	0.09
4	0.06	0.07	0.14	0.07	0.08	0.09
5	0.04	0.06	0.14	0.06	0.07	0.08
6	0.07	0.07	0.14	0.06	0.06	0.08
7	0.08	0.05	0.14	0.06	0.06	0.08
8	0.05	0.05	0.15	0.05	0.06	0.07
9	0.05	0.05	0.15	0.05	0.06	0.07
10	0.05	0.06	0.16	0.04	0.05	0.07
11	0.05	0.05	0.16	0.05	0.05	0.07
12	0.04	0.03	0.14	0.05	0.05	0.07
13	0.04	0.02	0.14	0.05	0.05	0.07
14	0.04	0.06	0.13	0.05	0.05	0.07

Table 6 b. In situ measurement of electrical conductivity (dSm^{-1}) (weeks after transplanting)

Weeks after transplanting	Aerobic rice			Flooded rice		
	L_1	L_2	L_3	L_1	L_2	L_3
1	0.08	0.05	0.14	0.06	0.06	0.08
2	0.04	0.06	0.13	0.05	0.05	0.07
3	0.045	0.050	0.13	0.04	0.05	0.07
4	0.05	0.05	0.15	0.04	0.05	0.07
5	0.06	0.16	0.22	0.06	0.09	0.14
6	0.06	0.055	0.21	0.05	0.08	0.13
7	0.05	0.06	0.22	0.04	0.07	0.12
8	0.05	0.065	0.22	0.04	0.06	0.11
9	0.05	0.06	0.22	0.03	0.05	0.11
10	0.05	0.05	0.21	0.03	0.04	0.10
11	0.04	0.04	0.20	0.03	0.03	0.09
12	0.04	0.04	0.19	0.03	0.03	0.09
13	0.04	0.04	0.18	0.03	0.03	0.09
14	0.04	0.04	0.17	0.03	0.03	0.09

4.1.2.1 Electrical conductivity

Table 6 show the variations in electrical conductivity immediately after transplanting in daily interval up to 14 days after transplanting (6a) and in weekly interval up to harvest (6b).The data showed that EC (dSm^{-1}) increased immediately after application of lime, which was applied just before transplanting under both systems of rice cultivation. The rate of increase was in proportion to the quantity of lime applied under both the systems. However, the rate of increase was observed to be less under flooded system of rice.

4.1.3. Redox potential

The data on redox potential under aerobic and flooded systems measured from different depths immediately after transplanting till harvest of the crop are presented in table 7.

Table 7 a. In situ measurement of redox potential (mV) (days after transplanting)

Days after transplanting	Aerobic rice		Flooded rice		
	30 cm depth	45 cm depth	15 cm depth	30 cm depth	45 cm depth
1	-114.0	-6.0	14.0	-46.0	-126.0
2	-84.0	-74.0	-16.0	-66.0	-116.0
3	-126.0	-86.0	-26.0	-106.0	-166.0
4	-146.0	-166.0	-26.0	-126.0	-166.0
5	-46.0	-186.0	-16.0	-206.0	-216.0
6	214.0	-126.0	-10.0	-166.0	-186.0
7	274.0	-46.0	-16.0	-126.0	-206.0
8	354.0	-26.0	-6.0	-106.0	-206.0
9	414.0	34.0	-6.0	-146.0	-206.0
10	474.0	174.0	-94.0	-126.0	-216.0
11	474.0	174.0	-114.0	-194.0	-216.0
12	474.0	174.0	-116.0	-186.0	-166.0
13	654.0	354.0	-96.0	-146.0	-166.0
14	594.0	354.0	-96.0	-126.0	-166.0

Table 7 b. In situ measurement of redox potential (mV) (weeks after transplanting)

Weeks after transplanting	Aerobic rice		Flooded rice		
	30 cm depth	45 cm depth	15cm depth	30 cm depth	45 cm depth
1	-4.0	-98.0	-16.0	-126.0	-206.0
2	491.0	177.0	-96.0	-126.0	-166.0
3	348.0	379.0	-186.0	-206.0	-206.0
4	274.0	192.0	-124.0	-186.0	-206.0
5	278.0	170.0	-124.0	-206.0	-206.0
6	228.0	138.0	-86.0	-186.0	-186.0
7	383.0	344.0	-106.0	-166.0	-186.0
8	394.0	346.0	-116.0	-206.0	-206.0
9	394.0	172.0	-108.0	-186.0	-206.0
10	403.0	371.0	-102.0	-166.0	-192.0
11	423.0	291.0	-108.0	-186.0	-198.0
12	423.0	303.0	-102.0	-166.0	-206.0
13	474.0	283.0	-156.0	-186.0	-206.0
14	360.0	288.0	-76.0	-126.0	-144.0

4.1.3.1 Redox potential

Under flooded system, the redox potential showed a decreasing trend immediately after transplanting. The redox potential became more negative as the depth of sampling increased. The lowest redox values were recorded in this system at 45 cm depth. The redox reached a level of -156 mV, -186 mV and -206 mV at 15 cm, 30 cm and 45 cm on 13th week after transplanting.

Under aerobic system, the data showed that redox potential increased immediately after transplanting and became positive within one week after transplanting. The highest redox potential was recorded under 30 cm depth in this system consistently throughout the crop growth.

4.2. Effect of treatments on soil pH, EC and available nutrient status under aerobic and flooded systems.

The effect of applied lime and fertilizers on physicochemical properties viz. soil pH, EC, organic carbon, and available nutrient status under aerobic and flooded systems are presented here under.

4.2.1 Effect of fertilizers and lime on soil pH

The effect of fertilizers and lime on soil pH at different stages of sampling is presented in table from 8 to 10.

Table 8. Effect of fertilizers and lime on soil pH at active tillering

		Aerobic rice		
Fertilizer/Lime	L_1	L_2	L_3	**Mean**
F_1	5.1	5.3	6.9	**5.8**
F_2	5.2	5.4	6.9	**5.8**
Mean	**5.1**	**5.4**	**6.9**	**5.8**
CD. F N.S	**CD L**	**0.079**	**CD F x L**	**N. S**
		Flooded rice		
F_1	5.2	5.3	5.8	**5.5**
F_2	5.2	5.4	6.1	**5.5**
Mean	**5.2**	**5.3**	**5.9**	**5.5**
CD. F N.S	**CD L**	**0.10**	**CD F x L N. S**	
CD - pooled – N. S				

4.2.1.1 Active tillering

The data given in table 8 revealed that under both systems, the pH has increased from the initial level at active tillering stage. The quantity of lime based on lime requirement estimated by SMP buffer method resulted in increase of the pH from 4.2 to 6.9 under aerobic system, which was significantly much higher than the increase in pH resulted from the other two treatments *viz.* lime based on POP (L_1) & ΔpH (L_2). Among these two treatments, L_2 was found significantly effective in increasing the pH in comparison with that in lime as per POP (L_1).

Under flooded system of rice cultivation (table 8), the quantity of lime SMP buffer method resulted in increase the pH from 4.9 to 5.9. Lime as per POP and as per ΔpH did not differ significantly at this stage.

Table 9. Effect of fertilizers and lime on soil pH at panicle initiation

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	**Mean**
F_1	6.0	6.2	7.3	6.5
F_2	5.7	6.4	7.2	6.4
Mean	5.8	6.3	7.2	6.4
C D F N.S		CD L 1.03	CD F x L	N. S
Flooded rice				
F_1	5.4	5.9	7.0	6.1
F_2	5.4	5.8	6.8	6.0
Mean	5.4	5.9	6.9	6.1
CD. F N.S	CD L	0.13	CD F x L	0.19
CD- Pooled – N.S.				

4.2.1.2. Panicle initiation

The data on effect of lime and fertilizers on soil pH at panicle initiation stage are presented in table 9. Soil pH was found to increase from that at active tillering.

Application of lime as per SMP buffer method (L_3) was found to enhance the pH to 7.2 under aerobic system. However, lime application based on ΔpH (L_2) had a significantly better influence (pH 6.3) in neutralising the soil acidity than that of lime application based on POP (L_1). The fertilizer treatments have no significant effect in influencing pH at this stage.

Under flooded system, the significantly highest pH (6.9) was recorded in lime applied treatment as per SMP buffer method (L_3). Among the other two treatments, lime application based on ΔpH (L_2) recorded higher pH (5.9) than that of lime application based on POP (L_1, 5.4).

Among the interactions of applied lime with fertilizer, lime as per SMP buffer method with fertilizers as per POP(F_1L_3) recorded significantly higher pH (7.0), which was on par with that (6.8), in the treatment where lime as per SMP buffer method was applied with fertilizers as per soil test (F_2L_3).

Table 10. Effect of fertilizers and lime on soil pH at harvest

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	**Mean**
F_1	5.4	5.7	7.4	6.2
F_2	5.2	5.6	7.4	6.1
Mean	5.3	5.7	7.4	6.1
CD. F 0.09	**CD L**	**0.113**	**CD F x L N. S**	
Flooded rice				
F_1	5.2	5.7	6.9	6.0
F_2	5.3	5.7	7.0	6.0
Mean	5.3	5.7	7.0	6.0
CD. F N.S	**CD L**	**0.08**	**CD F x L 0.12**	
C.D pooled – N.S				

4.2.1.3. Harvest

Under aerobic system, the doses of lime had a significant effect in increasing the soil pH at this stage also (table 10). The quantity of lime applied as per SMP buffer method (L_3) was found to increase the soil pH (7.4), which was significantly much higher than the increase in pH resulted from the other two treatments. Lime applied based on ΔpH (L_2) recorded significantly higher pH (5.7), than that in lime application based on POP (L_1), (5.3).

Under flooded condition, application of lime as per SMP buffer method (L_3) was found to enhance the pH (7.0), which was significantly higher than the increase in pH resulted from the other two treatments. Lime application based on ΔpH (L_2) had a significantly better influence (5.7) in neutralising the soil acidity than that of lime application based on POP (5.3). Among the interactions, application of lime as per SMP buffer method with fertilizer as per soil test (F_2L_3) recorded highest pH of 7.0, which was on par with that of application of lime as per SMP buffer method with fertilizer as per POP (6.9).

The fertilizer treatments as per POP (F_1) and based on soil test (F_2) did not differ among themselves in increasing the pH under both systems of rice cultivation at harvest.

In general, there was no significant difference in pH under aerobic and flooded systems of rice cultivation at all the stages of sampling. The rate of increase in pH was highest in treatments where lime application based on SMP buffer method under both aerobic and flooded environment. However, increase in pH was lesser in flooded situation for the same lime treatments in comparison with that in aerobic situation.

4.2.2 Effect of fertilizers and lime on soil electrical conductivity

The influence of treatments on soil electrical conductivity at different stages of sampling is presented from table 11 to 13.

Table 11. Effect of treatments on soil electrical conductivity (dSm^{-1}) at active tillering

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	**Mean**
F_1	0.08	0.09	0.14	**0.11**
F_2	0.04	0.09	0.13	**0.09**
Mean	**0.06**	**0.09**	**0.14**	**0.10**
CD. F 0.011		**CD L 0.013**		**CD F x L 0.02**
Flooded rice				
F_1	0.06	0.10	0.16	0.10
F_2	0.07	0.09	0.21	0.12
Mean	**0.06**	**0.09**	**0.19**	**0.11**
CD. F 0.019		**CD L 0.026**		**CD F x L N.S**
C D pooled N. S.				

4.2.2.1 Active tillering

The initial EC of the soil samples under aerobic and flooded systems were 0.05 dSm^{-1} and 0.01 dSm^{-1} respectively. Applied fertilizers and lime significantly increased the electrical conductivity of the soil under both systems of rice cultivation.

Under aerobic condition, applied fertilizers as per POP (F_1) increased the EC (0.11 dSm^{-1}) of the soil at active tillering. However, fertilizers applied based on soil test (F_2) also contributed to increase the electrical conductivity of the soil (0.09 dSm^{-1}) when compared with the initial status (table 11).

Under flooded system, application of fertilizers as per soil test (F_2) significantly increased the EC of the soil at active tillering (0.12 dsm^{-1}), when compared with that of fertilizer applied as per POP (F1, 0.10 dSm^{-1}).

Under both systems of rice cultivation, lime application as per SMP buffer method (L_3) recorded significantly highest EC (0.14dSm^{-1} under aerobic system and 0.19 dSm^{-1} under flooded system) at this stage. Dose of lime as per ΔpH (L_2) also significantly increased the electrical conductivity of the soil (recorded 0.09 dSm^{-1} under both systems) when compared with that of lime as per POP (0.06 dSm^{-1} under both systems).

Interaction of fertilizers with lime also significantly increased EC under aerobic condition. Application of fertilizer as per POP with lime based on SMP buffer method (0.14 dSm^{-1}) (F_1L_3) and application of fertilizer as per soil test with lime based on SMP buffer method (0.13 dSm^{-1}) (F_2L_3) were on par and significantly higher electrical conductivity, compared with that of other interactions.

In general, there was no significant difference between aerobic and flooded conditions in influencing the electrical conductivity of the soil at this stage.

Table 12. Effect of fertilizers and lime in electrical conductivity (dSm^{-1}) of the soil at panicle initiation

Fertilizer/Lime	L_1	L_2	L_3	Mean
Aerobic rice				
F_1	0.09	0.12	0.19	**0.13**
F_2	0.10	0.12	0.21	**0.14**
Mean	**0.10**	**0.12**	**0.20**	**0.14**
CD. F 0.01	**CD L 0.01**		**CD F x L 0.04**	
Flooded rice				
F_1	0.08	0.10	0.14	**0.11**
F_2	0.07	0.09	0.20	**0.12**
Mean	**0.07**	0.09	**0.17**	**0.11**
CD. F N.S	**CD L 0.02**		**CD F x L 0.03**	
C D pooled 0.02				

4.2.2.2. Panicle initiation

The electrical conductivity of the soil was increased from active tillering under aerobic condition, while it was stabilized under flooded system.

The data presented in table 12 showed that under aerobic condition, highest EC was recorded in treatment where fertilizers applied as per soil test (0.14 dSm^{-1}) which was highest over fertilizers as per POP (0.13 dSm^{-1}).

Under both conditions, the highest electrical conductivity was recorded in the plots which were applied with lime as per SMP buffer method (L_3), recorded 0.20dSm^{-1} under aerobic condition and 0.17 dSm^{-1} under flooded system respectively.

Application of lime as per ΔpH (L_2) also significantly increased the electrical conductivity of the soil under both systems (0.12 dSm^{-1} under aerobic and 0.09 dSm^{-1} under flooded system) in comparison with the treatment where lime was applied as per POP (L_1).

Among the interactions of applied lime with fertilizer, lime as per SMP buffer method with fertilizers as per as per soil test (F_2L_3) recorded significantly higher EC (0.20 dSm^{-1}), followed by the treatment where lime as per SMP buffer method with fertilizers as per POP (F_1L_3), which recorded an EC of 0.14 dSm^{-1}.

In general, the electrical conductivity in aerobic system was significantly higher (0.14 dSm^{-1}) when compared with flooded system of rice cultivation (0.11 dSm^{-1}).

Table 13. Effect of fertilizers and lime in electrical conductivity (dSm^{-1}) of the soil at harvest of the crop

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	**Mean**
F_1	0.12	0.18	0.32	**0.21**
F_2	0.11	0.17	0.38	**0.22**
Mean	**0.12**	**0.18**	**0.35**	**0.22**
CD. F N.S	**CD L 0.019**		**CD F x L 0.027**	
Flooded rice				
F1	0.04	0.06	0.11	**0.07**
F2	0.04	0.06	0.10	**0.07**
Mean	**0.04**	**0.06**	**0.10**	**0.07**
CD. F N.S	**CD L 0.01**		**CD F x L 0.015**	
C. D. Pooled 0.08				

4.2.2.3. Harvest

The data presented in table 13 revealed that the application of lime under both systems of rice had significantly influenced the electrical conductivity of the soil.

Under both conditions, the significantly highest electrical conductivity was recorded in the plots applied with lime as per SMP buffer method (L_3) (0.35 dSm^{-1} under aerobic, and 0.11 dSm^{-1} under flooded system respectively).

Application of lime based on ΔpH (L_2) also significantly increased the EC of the soil (0.18 dSm^{-1} and 0.06 dSm^{-1} under aerobic and flooded conditions respectively) in comparison with that of the treatment where lime applied as per POP (0.12 dSm^{-1} and 0.04 dSm^{-1} under aerobic and flooded conditions respectively).

Under aerobic condition, the interaction of fertilizers applied as per soil test with lime based on SMP buffer method (F_2L_3) significantly increased the electrical conductivity of the soil (0.38 dSm^{-1}) at this stage. Under flooded condition, the interaction was not significant.

Under both systems of rice cultivation, the applied fertilizers did not significantly influence the electrical conductivity of the soil at this stage.

The highest electrical conductivity (0.22 dSm^{-1}) was recorded under aerobic system in comparison with that of flooded system (0.07 dSm^{-1}) of rice cultivation.

In general, under aerobic system, the EC showed a steady increase from initial stage to harvest. Under flooded system, the EC increased from initial status, remained constant at active tillering and panicle initiation, and then decreased at harvest.

4.2.3. Effect of fertilizers and lime on organic carbon

The influence of treatments on soil organic carbon status on at different stages of sampling is presented from table 14 to 16.

Table 14. Effect of fertilizers and lime on soil organic carbon (per cent) at active tillering

Aerobic rice				
Fertilizer/Lime	**L_1**	**L_2**	**L_3**	**Mean**
F_1	1.16	1.18	1.21	**1.18**
F_2	1.16	1.17	1.21	**1.19**
Mean	**1.16**	**1.17**	**1.21**	**1.18**
CD. F N S	**CD L**	**0.03**	**CD F x L**	**N. S**
Flooded rice				
F_1	1.02	1.08	1.13	**1.08**
F_2	1.03	1.06	1.18	**1.09**
Mean	**1.02**	**1.07**	**1.16**	**1.08**
CD. F N S	**CD L**	**0.03**	**CD F x L**	**N. S**
C. D pooled 0.08				

4.2.3.1 Active tillering

The organic carbon status of the soils under both systems of rice cultivation, were increased in all the treatment combinations because of application of cow dung at the rate of 5 tha^{-1} (as per Package of Practices Recommendations, KAU, 2011) from initial status of 0.94 per cent and 0.95 per cent under aerobic and flooded conditions respectively.

Application of lime significantly increased the organic carbon status of the soil (table 14). Highest organic carbon status of 1.21 per cent under aerobic condition and that of 1.16 per cent under flooded condition was recorded in treatment with lime applied based on SMP method of estimation (L_3) at this stage.

Under aerobic condition, dose of lime as per ΔpH (L_2) and lime as per POP (L_1) increased the organic carbon in comparison with that at the initial stage and were found on par, which were 1.18 % and 1.16 % respectively. Under flooded condition, lime as per ΔpH (L_2) recorded significantly higher organic carbon (1.07 %) than that in treatment with that of lime as per POP (L_1, 1.02 %).

The organic carbon content in aerobic rice was significantly higher (1.18 %), than that in flooded system of rice cultivation at active tillering, which was 1.08 %.

Table 15. Effect of fertilizers and lime on soil organic carbon (per cent) at panicle initiation

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	**Mean**
F_1	0.90	0.96	1.01	**0.96**
F_2	0.91	0.95	1.07	**0.98**
Mean	**0.91**	**0.96**	**1.04**	**0.97**
Flooded rice				
CD. F N S	**CD L 0.03**		**CD F x L**	**N. S**
F_1	1.03	1.05	1.08	**1.05**
F_2	1.03	1.04	1.08	**1.05**
Mean	**1.03**	**1.05**	**1.08**	**1.05**
CD. F N.S	**CD L 0.03**		**CD F x L N.S**	
C D pooled 0.07				

4.2.3.2 Panicle initiation

Under both systems of rice cultivation, doses of lime had a significant influence in increasing the organic carbon status of the soil (table 15). Highest organic carbon was recorded (1.04 % and 1.08 % under aerobic and flooded system respectively) in treatment with lime applied based on SMP method (L_3) under both systems.

Under aerobic condition, significantly higher organic carbon (0.96 %) was recorded in the treatment where lime was applied as per ΔpH (L_2) in comparison with that of lime applied as per POP (L_1, 0.91 %). However, under flooded condition, the organic carbon were on par in lime treatments as per ΔpH (L_2, 1.05 %), and as per POP (L_1, 1.03 %).

The applied fertilizers as well as their interaction with lime did not significantly influence the organic carbon status of the soil under both systems of rice cultivation.

Irrespective of the systems of cultivation, the organic carbon content decreased from that of active tillering stage in all the treatment combinations.

Flooded system of rice cultivation recorded significantly higher organic carbon content (1.05 %) than that in aerobic system of cultivation (0.97 %).

Table 16. Effect of fertilizers and lime on soil organic carbon (per cent) at harvest

		Aerobic rice		
Fertilizer/Lime	L_1	L_2	L_3	**Mean**
F_1	0.79	0.85	0.90	**0.84**
F_2	0.80	0.83	0.95	**0.86**
Mean	**0.79**	**0.84**	**0.93**	**0.85**
CD. F N S	**CD L 0.03**		**CD F x L N. S**	
		Flooded rice		
F_1	0.90	0.93	0.96	0.93
F_2	0.91	0.92	0.96	0.93
Mean	**0.91**	**0.92**	**0.96**	**0.93**
CD. F N.S	**CD L 0.03**		**CD F x L 0.05**	
C D pooled 0.08				

4.2.3.3 Harvest

The data presented in table 16 showed that, under both systems of rice cultivation, application of lime significantly influenced the organic carbon status of the soil.

Significantly highest organic carbon status of 0.93 per cent under aerobic system and 0.96 per cent under flooded system was recorded in treatment with lime applied based SMP method (L_3). Lime applied as per ΔpH (L_2) was found significantly superior (0.84 %) in improving the organic carbon under aerobic condition. Under flooded condition, lime as per ΔpH (L_2) and as per POP (L_1) was on par.

The applied fertilizers as well as their interaction with lime did not significantly differ with respect to the organic carbon status of the soil.

The organic carbon content in flooded rice recorded significantly higher (0.93 %) than that of aerobic rice (0.85 %) at harvest.

Under both systems, the organic carbon status was found to decrease from that of panicle initiation stage in all the treatment combinations. Flooded system recorded almost similar organic carbon as that of initial stage at harvest. Under aerobic system, the lowest organic carbon status was recorded at harvest stage in comparison with initial, active tillering and that at panicle initiation.

4.2. 4. Effect of fertilizers and lime on available phosphorus

The influence of treatments on soil available phosphorus status at different stages of sampling is presented from table 17 to 19.

Table 17. Effect of fertilizers and lime on available phosphorus (kg ha^{-1}) at active tillering

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	**Mean**
F_1	14.67	16.00	9.65	13.44
F_2	13.89	16.95	7.87	12.62
Mean	14.28	16.04	8.76	13.03
CD. F 0.33	**CD L 0.41**		**CD F x L 0.58**	
Flooded rice				
F_1	15.93	17.28	22.71	18.64
F_2	17.32	18.32	22.51	19.38
Mean	16.63	17.80	22.61	19.10
CD. F 0.49	**CD L 0.60**		**CD F x L 0.88**	
C. D pooled 1.25				

4.2.4.1 Active tillering

The data on available P in soil under both systems of rice cultivation, at active tillering stage are presented in table 17. The available P was found increased due to the application of fertilizers and lime from an initial status of 13.33 kg ha^{-1} and 11.35 kg ha^{-1} under aerobic and flooded systems of rice respectively.

Lime application had a significant role in changing the available P status of the soil under both systems of rice cultivation. Under aerobic rice cultivation, the treatment with lime as per ΔpH (L_2) recorded significantly higher available P status (16.04 kg ha^{-1}). Lime as per POP (L_1) also improved the available P status (14.28 kg ha^{-1}), than that of the initial value. But, application of lime as per SMP buffer method (L_3) significantly decreased the available P (8.76 kg ha^{-1}) than that of the initial status.

Under flooded condition, lime as per SMP buffer method (L_3) was found superior in increasing the available P status (22.61 kg ha^{-1}) among the three doses of lime. Lime as per ΔpH (L_2) also significantly improved the available P (17.80 kg ha^{-1}), than that of lime based on POP (L_1).

Under aerobic condition, fertilizers applied based on POP (F_1) had a significant influence in increasing the available P status of the soil (13.44 kg ha^{-1}) while, the available P decreased (12.62 kg ha^{-1}) in the treatments where the fertilizers were applied as per soil test (F_2).

Under flooded condition, fertilizer application based on soil test (F_2) was recorded the highest available P (19.38 kg ha^{-1}).

Under aerobic condition, among the interactions, fertilizer applied as per soil test with lime based on ΔpH (F_2L_2) was significantly superior in increasing the available P (16.95 kg ha^{-1}) status of the soil. But, application of fertilizer as per soil test along with lime based on SMP buffer method (F_2L_3) significantly decreased the available P status of the soil to the lowest (7.87 kg ha^{-1}), followed by fertilizer as per POP with lime as per SMP buffer method(F_1L_3) which recorded 9.65 kg available P ha^{-1}.

Under flooded system, fertilizers applied as per POP with lime based on SMP buffer method (F_1L_3) was significantly superior in increasing the available P status of the soil (22.71 kg ha^{-1}), which was on par with treatment where fertilizer as per soil test with lime as per SMP buffer method (F_2L_3) was applied (22.51 kg available P ha^{-1}).

The available P was found significantly higher in flooded rice (19.01 kg ha^{-1}) in comparison with that in aerobic rice (13.03 kg ha^{-1}).

Table 18. Effect of fertilizers and lime on available phosphorus (kg ha^{-1}) at panicle initiation

Aerobic rice				
Fertilizer/Lime	**L_1**	**L_2**	**L_3**	**Mean**
F_1	12.97	13.85	9.44	12.09
F_2	12.51	13.74	9.43	11.89
Mean	**12.74**	**13.80**	**9.44**	**11.99**
Flooded rice				
CD. F 0.19	**CD L 0.23**		**CD F x L N. S**	
F_1	17.07	20.41	9.66	15.71
F_2	17.03	21.17	11.62	16.61
Mean	**17.05**	**20.79**	**10.64**	**16.16**
CD. F 0.75	**CD L 0.92**		**CD F x L 1.29**	
C. D pooled 2.73				

4.2.4.2 Panicle initiation

The data on available P in soil, at panicle initiation are presented in table 18.

Under aerobic condition, the available P status at this stage was found decreased in comparison with that at the active tillering. Quantity of lime applied as per ΔpH (L_2) was found to improve the available P (13.80 kg ha^{-1}) significantly, followed by application of lime as per POP (12.74 kg P ha^{-1}). Lime as per SMP buffer method (L_3), significantly reduced the available P status (9.44 kg ha^{-1}) in comparison with the other two lime treatments.

Under flooded condition, quantity of lime applied as per ΔpH (L_2) improved the available P (20.79 kg ha^{-1}) significantly, followed by application of lime as per POP (L_1, 17.05 kg P ha^{-1}). These two treatments were significantly superior to application of lime as per SMP buffer method (L_3), in which the available P status of soil was 10.64 kg ha^{-1}.

Under both systems of rice cultivation, fertilizers applied as per POP (F_1) was found to increase the available P status of the soil (12.09 kg ha^{-1} and 16.61 kg ha^{-1} under aerobic and flooded condition respectively), when compared with the treatment where fertilizers were applied as per soil test (F_2).

The interactions of applied lime with fertilizers were not significant under aerobic condition at this stage. However, under flooded system, lime as per ΔpH with fertilizers as per POP (F_1L_2) recorded significantly higher available P (21.17 kg ha^{-1}), followed by the treatment where lime as per ΔpH with fertilizers as per soil test (F_2L_2), was applied (20.41 kg ha^{-1}).

The available P was found significantly higher in flooded rice (16.16 kg ha^{-1}) in comparison with aerobic rice (11.99 kg ha^{-1}) at panicle initiation.

In general, under aerobic condition, the available P status was found decreased from that of active tillering in all treatment combinations at this stage. The available P increased under flooded condition at this stage when compared with that of active tillering except in case of lime as per SMP buffer method.

Table 19. Effect of fertilizers and lime on available phosphorus (kg ha^{-1}) at harvest

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	**Mean**
F_1	16.22	19.71	21.61	19.18
F_2	16.91	18.75	21.10	18.92
Mean	**16.56**	**19.23**	**21.35**	**19.05**
CD. F N S	**CD L 0.42**		**CD F x L N.S**	
Flooded rice				
F_1	13.54	14.89	11.55	13.32
F_2	13.71	14.97	11.09	13.26
Mean	**13.62**	**14.93**	**11.32**	**13.29**
CD. F N S	**CD L 0.25**		**CD F x L N.S**	
C. D pooled 6.90				

4.2.4.3. Harvest

Under both systems of rice cultivation, applied fertilizers and lime had a significant influence on the available P status of soil at harvest (Table 19).

Under aerobic condition, the quantity of lime applied as per SMP buffer method (L_3) was found to improve the available P (21.35 kg ha^{-1}) status of the soil significantly, followed by application of lime as per ΔpH (19.23kg P ha^{-1}). However, lime applied as per POP also improved the available P status of soil (16.56 kg ha^{-1}) in comparison with that of the previous stages of soil sampling.

Under flooded condition, quantity of lime applied as per ΔpH (L_2), was found to improve the available P (14.93 kg ha^{-1}) status of the soil significantly, followed by application of lime as per POP (13.62 kg ha^{-1}). Lime applied as per SMP buffer method (L_3), recorded the lowest available P (11.32 kg ha^{-1}).

Applied fertilizers as well as their interaction with doses of lime, was not significant at this stage under both systems of rice cultivation.

The available P was found significantly higher in aerobic rice (19.05 kg ha^{-1}) in comparison with flooded rice (13.29 kg ha^{-1}) at harvest of the crop.

The available P content in aerobic rice increased substantially at harvest of the crop in comparison with that at initial, active tillering and panicle initiation stages. Under aerobic environment, the available P increased at harvest in treatments where lime was applied as per SMP buffer method. But during the earlier stages of sampling, the available P was found reduced in this treatment than that at the initial stage. Under flooded system, the available P decreased in lime treatments as per POP (L_1) and as per ΔpH (L_2) while it increased in the treatment as per SMP buffer method (L_3) at harvest.

4.2.5. Effect of fertilizers and lime on available potassium

The influence of treatments on available potassium at different stages of sampling is presented from table 20 to 22.

Table 20. Effect of fertilizers and lime on available potassium (kg ha^{-1}) at active tillering

Fertilizer/Lime	L_1	L_2	L_3	Mean
Aerobic rice				
F_1	134.73	138.78	129.03	**134.18**
F_2	131.55	132.98	127.38	**130.63**
Mean	**133.14**	**135.88**	**128.20**	**132.40**
CD. F 2.11	CD L 2.58		CD F x L	N. S
Flooded rice				
F_1	60.04	63.80	70.26	64.70
F_2	59.38	66.84	71.44	65.88
Mean	**59.71**	**65.32**	**70.85**	**65.29**
CD. F 1.01	CD L 1.24		CD F x L 1.75	
C. D pooled 7.97				

4.2.5.1 Active tillering

The data on the effect of treatments on available K at active tillering are presented in table 20. The available K was found increased from initial status of 113.3 kg ha^{-1} and 51.07 kg ha^{-1} under aerobic ad flooded systems of rice respectively.

Under both systems of rice cultivation, fertilizers applied as per POP (F_1) resulted in significant increase in available K status (134.18 kg ha^{-1} under aerobic system and 65.88 kg ha^{-1} under flooded system respectively). However, application of fertilizer based soil test (F_2) also increased the available K status of the soil (130.63 kg ha^{-1} and 64.70 kg ha^{-1} under aerobic and flooded systems respectively) in comparison with the initial values.

Under aerobic rice system, among the doses of lime, application as per ΔpH (L_2), was found superior in improving the available K status (135.88 kg ha^{-1}), followed by application based on POP (L_1), (133.14 kg ha^{-1}).

Under flooded system, available K (70.85 kg ha^{-1}) was highest and significant in the treatment of lime as per SMP buffer (L_3). Application of lime based on ΔpH (L_2) recorded available K of 65.32 kg ha^{-1}.

The interactions of applied lime with fertilizers were not significant under aerobic condition, whereas under flooded system, applied fertilizers as per soil test with lime as per SMP buffer method (F_2L_3) recorded significantly higher available K (71.44 kg ha^{-1}), which was on par with that in the treatment with fertilizers as per POP and lime as per SMP buffer method (F_1L_3, 70.26 kg ha^{-1}).

Table 21. Effect of fertilizers and lime on available potassium (kg ha^{-1}) at panicle initiation

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	**Mean**
F_1	126.50	129.34	122.83	**126.22**
F_2	128.90	131.73	124.53	**128.39**
Mean	**127.70**	**130.53**	**123.68**	**127.30**
CD. F 1.46	**CD L 1.79**		**CD F x L**	**N. S**
Flooded rice				
F_1	56.46	60.53	68.46	**61.82**
F_2	57.76	61.69	70.67	**63.37**
Mean	**57.11**	**61.11**	**69.57**	**62.59**
CD. F 1.23	**CD L 1.56**		**CD F x L**	**2.16**
C. D pooled 8.64				

4.2.5.2. Panicle initiation

The data (table 21) revealed that, under both systems of rice cultivation, the treatments did significantly influence the available K content at this stage.

Under aerobic condition, lime incorporation as per ΔpH (L_2) was found to enhance the available K (130.53 kg ha^{-1}), which was superior to the other two lime treatments. However, lime application as per POP (L_2) (127.7 kg ha^{-1}) had a significantly better influence on improving the available K in comparison with the treatment where lime applied based on SMP buffer method(L_3) (123.68 kg K ha^{-1}).

Under flooded condition, lime incorporation as per SMP buffer method (L_3) significantly enhanced the available K (69.57 kg ha^{-1}). However, lime applied as per ΔpH (L_2) also improved the available K (61.11kg ha^{-1}) in comparison with the treatment where lime was applied based on POP (L_1, 57.11 kg ha^{-1}).

Under both systems of rice cultivation, fertilizers applied as per soil test (F_2) significantly increased the available K (128.38 kg ha^{-1} and 63.37kg ha^{-1} under aerobic and flooded system respectively) in comparison with the treatment were fertilizers were applied as per POP (F_1, 126.22 kg ha^{-1} and 61.82 kg ha^{-1} under aerobic and flooded systems respectively).

Under aerobic system, the interaction of fertilizer with lime was not significant. Under flooded system, the fertilizer applied as per soil test with lime as per SMP buffer method (F_2L_3) increased the available K significantly (70.67 kg ha^{-1}).

The aerobic system of rice cultivation (127.30 kg ha^{-1}) recorded significantly higher available K than that at flooded condition (62.59 kg ha^{-1}).

The available K content in soil was found decreased under both systems in comparison with that at active tillering, but was increased than that at initial stage.

Table 22. Effect of fertilizers and lime on available potassium (kg ha^{-1}) at harvest

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	**Mean**
F_1	109.45	108.45	114.18	**109.33**
F_2	108.38	108.30	113.25	**109.64**
Mean	**108.92**	**108.33**	**113.72**	**109.48**
CD. F N. S	**CD L**	**2.15**	**CD F x L**	**3.06**
Flooded rice				
F_1	45.08	49.23	51.89	**48.73**
F_2	43.34	49.50	51.19	**48.01**
Mean	**44.21**	**49.37**	**51.54**	**48.37**
CD. F N. S.	**CD L**	**1.23**	**CD F x L**	**1.77**
C. D pooled 2.07				

4.2.5.3. Harvest

The data on available K in soil, at harvest of the crop, presented in table 22, showed that the treatments did significantly influence the available K content in soil at this stage.

Lime incorporation as per SMP buffer method (L_3) did enhance the available K under both systems of rice (113.72 kg ha^{-1} and 51.54 kg ha^{-1} under aerobic and flooded condition respectively), followed by lime application as per ΔpH (108.38 kg ha^{-1} and 49.37 kg ha^{-1} under aerobic and flooded condition) at this stage.

Under both systems, application of fertilizers did not differ significantly in improving the available K status of the soil at this stage.

Among the interactions, under both systems, fertilizers applied as per POP with lime as per SMP buffer method (F_1L_3) recorded highest available K status of the soil (114.18 kg ha^{-1} and 51.89 kg ha^{-1} under aerobic and flooded system respectively).

The aerobic system of rice cultivation recorded higher available K (109.48 kg ha^{-1}) than that at flooded system of rice cultivation (48.37 kg ha^{-1}).

In general, available K content in soil was found reduced under both systems in comparison from that at initial, active tillering and at panicle initiation stages.

4.2. 6. Effect of fertilizers and lime on available Calcium

The influence of treatments on soil available potassium status on at different stages of sampling is presented from table 23 to 25.

Table 23. Effect of fertilizers and lime on available calcium (mg kg^{-1}) at active tillering

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	Mean
F_1	117.45	122.95	304.40	**181.60**
F_2	129.58	133.48	325.90	**196.32**
Mean	**123.52**	**128.21**	**315.15**	**188.96**
CD. F 1.85	**CD L 2.27**		**CD F x L 3.22**	
Flooded rice				
F_1	140.85	233.66	394.20	**256.24**
F_2	164.28	224.54	388.29	**259.03**
Mean	**152.56**	**229.10**	**391.24**	**257.64**
CD. F N.S	**CD L 8.55**		**CD F x L 12.09**	
C D Pooled 35.21				

4.2.6.1 Active tillering

The available Ca status of the soils under aerobic and flooded conditions at initial stage was 95.6 mg kg^{-1} and 68.02 mg kg^{-1} respectively.

Under both systems of rice cultivation, liming had a significant effect in increasing Ca content of the soil (table 23). Lime applied as per SMP buffer method (L_3) recorded significantly highest available Ca under aerobic system (315.15 mg kg^{-}

$^{-1}$) and flooded systems (391.24 mg kg^{-1}). Between the other two doses of lime, application as per ΔpH (L_2) was superior in enhancing the available Ca status (128.21 mg kg^{-1} under aerobic system and 229.10 mg kg^{-1} under flooded system respectively). However, application of lime as per POP (L_1) also improved the Ca status of the soil than that at initial stage, under both systems of rice cultivation.

Application of fertilizer as per soil test (F_2) found significantly superior in increasing available Ca status of the soil (196 mg kg^{-1}) in comparison of fertilizer as per POP (F_1) under aerobic system. However, under flooded system, applied fertilizers did not significantly influence the available Ca status of the soil at this stage.

Among the interactions under aerobic system, application of fertilizer as per soil test with liming as per SMP buffer method (F_2L_3) recorded highest available Ca (325.90 mg kg^{-1}) followed by the treatment with fertilizer as per POP with lime as per SMP buffer (F_1L_3) method (304.4 mg kg^{-1}). Among the other interactions, application of fertilizer as per soil test with lime as per ΔpH (F_2L_2) was superior (133.48 mg kg^{-1}) in improving the available Ca status of the soil.

Under flooded system, fertilizer as per POP with lime based on SMP buffer (F_1L_3) method (394.20 mg kg^{-1}) and treatment with fertilizer as per soil test with lime as per SMP buffer method (F_2L_3) (388.29 mg kg^{-1}) were found on par in increasing the available Ca at this stage.

The highest available Ca was recorded under flooded condition (257.64 mg kg^{-1}) in comparison with that of aerobic condition (188.96 mg kg^{-1}). In general, the available Ca increased from the initial level at active tillering due to application of lime under both systems of rice cultivation and the rate of increase was in accordance with the quantity of lime applied.

Table 24. Effect of fertilizers and lime on available calcium (mg kg^{-1}) at panicle initiation

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	Mean
F_1	107.25	130.33	286.00	**174.53**
F_2	111.38	129.50	295.63	**178.83**
Mean	**109.31**	**129.91**	**290.81**	**176.68**
CD. F N. S	**CD L 4.98**		**CD F x L N. S**	
Flooded rice				
F_1	109.85	162.00	285.90	**185.92**
F_2	122.93	163.93	294.25	**193.70**
Mean	**116.39**	**162.96**	**290.08**	**189.81**
CD. F N.S	**CD L 9.90**		**CD F x L 14.00**	
C.D pooled 6.42				

4.2.6.2. Panicle initiation

Lime applied based on SMP buffer method (L_3) recorded significantly higher available Ca content at this stage also (290.81 mg kg^{-1} under aerobic system and 290.08 mg kg^{-1} under flooded condition) when compared with the other two treatments (Table 24). Between the other two treatments, application of lime as per ΔpH was superior in enhancing the available Ca status (129.21 mg kg^{-1} and 62.96 mg kg^{-1} under aerobic and flooded condition respectively).

Among the interactions, under flooded condition, application of fertilizer as per soil test with lime as per SMP buffer method (F_2L_3) recorded highest available Ca (193.70 mg kg^{-1}). The interactions under aerobic condition, as well as the main effect of applied fertilizers under both systems were not found significant at this stage.

Flooded system of rice cultivation recorded significantly higher available calcium (189.81 mg kg^{-1}) than that of aerobic system (176.68 mg kg^{-1}) at this stage.

In general, the available Ca decreased at panicle initiation in comparison with active tillering under both systems of rice cultivation.

Table 25. Effect of fertilizers and lime on available calcium (mg kg^{-1}) at harvest

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	Mean
F_1	105.53	110.30	283.80	**166.54**
F_2	107.10	111.25	288.60	**168.98**
Mean	**106.32**	**110.78**	**286.20**	**167.76**
C D. F N.S	**C D L 4.50**		**CD F x L 5.90**	
Flooded rice				
F_1	88.58	108.43	242.53	**146.51**
F_2	91.25	108.30	247.88	**149.14**
Mean	**89.92**	**108.37**	**245.21**	**147.83**
C D. F N. S.	**C D L**	**4.26**	**CD F x L**	**5.68**
C.D Pooled 14.09				

4.2.6.3 Harvest

Under both systems of rice cultivation, applied doses of lime were significantly influencing the available calcium in soil at harvest (table 25).

The highest available Ca (286.20 mg kg^{-1} and 245.20 mg kg^{-1} under aerobic and flooded systems respectively) was recorded in treatments with quantity of lime based on SMP buffer method (L_3) under both systems of rice cultivation. Between the other two doses of lime, application as per ΔpH (L_2) recorded significantly higher available Ca both under aerobic (110.78 mg kg^{-1}) and flooded system (108.37 mg kg^{-1}) at this stage.

Effects of applied fertilizers were not significant under both systems of rice cultivation, at this stage.

Among the interactions, fertilizer applied as per soil test with lime incorporated as per SMP buffer method (F_2L_3) recorded significantly highest available calcium under aerobic (288.60 mg kg^{-1}) and flooded (247.88 mg kg^{-1}) at this stage.

At harvest, aerobic rice recorded significantly higher available Ca (167.76 mg kg^{-1}), than that in flooded system (147.83 mg kg^{-1}).

In general, available Ca content found to increase at harvest from that of initial stage, but decreased in comparison with active tillering and panicle initiation stages.

4.2.7. Effect of fertilizers and lime on available magnesium

The influence of treatments on available magnesium status at different stages of sampling is presented from table 26 to 28.

Table 26. Effect of fertilizers and lime on available Mg (mg kg^{-1}) at active tillering

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	Mean
F_1	4.23	4.23	4.34	**4.28**
F_2	17.03	17.13	17.53	**17.23**
Mean	**10.63**	**10.68**	**10.95**	**10.75**
CD. F 0.18	**CD L 0.23**		**CD F x L 0.32**	
Flooded rice				
F_1	3.42	3.48	3.88	**3.59**
F_2	15.50	15.48	15.98	**15.65**
Mean	**9.46**	**9.48**	**9.93**	**9.63**
CD. F 2.04	**CD L 2.49**		**CD F x L N. S.**	
C D pooled 1.02				

4.2.7.1. Active tillering

The initial available Mg status of the soils under aerobic and flooded systems was 6.22 mg kg^{-1} and 8.18 mg kg^{-1} respectively.

Under both systems of rice cultivation, fertilizers applied as per soil test (F_2) increased the available Mg status of the soil, which recorded 17.23 mg kg^{-1} under aerobic condition and 15.65 mg kg^{-1} under flooded condition respectively. The data is presented in table 26.

Liming also had a significant influence in improving the available Mg status of the soil under both systems. Lime applied as per SMP buffer method (L_3) significantly increased the available Mg status of the soil (10.95 mg kg^{-1} under aerobic condition and 9.93 mg kg^{-1} under flooded condition respectively). The other two lime doses, application as per POP (L_1), and as per ΔpH (L_2) were on par in increasing the available Mg status of the soil under both systems at this stage.

Application of fertilizer as per soil test with application of lime as per SMP buffer method (F_2L_3) was significantly superior in increasing the available Mg status (17.53 mg kg^{-1}) of the soil under aerobic condition. Fertilizer as per soil test with other two lime treatments F_2L_1 and F_2L_2 were on par (recorded 17.03 mg kg^{-1} and 17.13 mg kg^{-1}). The other treatment interactions showed a decreasing trend of available Mg at this stage. The interactions were not significant under flooded condition at this stage.

Aerobic system recorded significantly higher available Mg status (10.75 mg kg^{-1}) in comparison with flooded system (9.62 mg kg^{-1}) at this stage.

Table 27. Effect of fertilizers and lime on available Mg (mg kg^{-1}) at panicle initiation

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	**Mean**
F_1	3.63	3.78	3.75	**3.72**
F_2	17.90	18.63	17.53	**18.87**
Mean	**10.76**	**11.20**	**11.91**	**11.29**
CD. F 0.29	**CD L 0.36**		**CD F x L 0.51**	
Flooded rice				
F_1	2.95	3.08	3.35	**3.13**
F_2	12.93	13.80	13.78	**13.49**
Mean	**7.94**	**8.44**	**8.57**	**8.32**
CD. F 0.56	**CD L 0.79**		**CD F X L 0.78**	
C D pooled N.S				

4.2.7.2. Panicle initiation

The data on available magnesium status in soil, at panicle initiation stage are presented in table 27.

Fertilizers applied as per soil test (F_2) significantly increased the available Mg status both under aerobic and flooded systems, (18.87 mg kg^{-1} and 13.49 mg kg^{-1} respectively) at this stage. On the other hand, fertilizer application as per POP decreased the available Mg status under aerobic and flooded systems (3.72 mg kg^{-1} and 3.13 mg kg^{-1} respectively).

Lime application also was found to enhance the available Mg status of soil. The quantity of lime applied as per SMP buffer method (L_3) was found superior in improving the available Mg content in soil (11.91 mg kg^{-1}under aerobic system and 8.57 mg kg^{-1} under flooded system respectively). Between the other two lime treatments, Application of lime as per ΔpH (L_2) was significantly better than lime applied as per POP (L_1) in improving the available Mg in comparison with the treatment in which under both systems of rice cultivation.

Among the interactions, lime as per ΔpH with fertilizers as per as per soil test (F_2L_2) and lime as per SMP buffer method with fertilizers as per as per soil test (F_2L_3) recorded almost the same available Mg content under flooded condition. In aerobic system, the treatment F_2L_2 recorded the highest available Mg content at this stage

There was no significant difference between aerobic system (11.29 mg kg^{-1}) and flooded rice cultivation system (8.48 mg kg^{-1}) in available Mg status at this stage.

Table 28. Effect of fertilizers and lime on available Mg (mg kg^{-1}) at harvest

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	**Mean**
F_1	3.28	3.43	3.58	**3.43**
F_2	16.23	17.03	17.68	**16.99**
Mean	9.76	**10.23**	**10.63**	**10.21**
CD. F 1.62	**CD L 0.19**		**CD F x L 0.28**	
Flooded rice				
F1	2.70	2.85	3.03	**2.86**
F2	11.25	11.60	13.43	**12.09**
Mean	**6.98**	**7.23**	**8.23**	**7.48**
CD. F 0.16	**CD L 0.19**		**CD F x L 0.27**	
C D pooled N. S				

4.2.7.3 Harvest

The data on available magnesium status in soil, at harvest of the crop are presented in table 28. Fertilizer applied as per soil test (F_2) significantly increased the available Mg status under aerobic system (16.98 mg kg^{-1}) as well as under flooded system (12.09 mg kg^{-1}). Fertilizer treatment as per POP (F_1) was found to decrease the available magnesium status in both the systems (3.43 mg kg^{-1} and 2.86 mg kg^{-1}).

Lime applied as per SMP buffer method (L_3) significantly increased the available Mg status of the soil under both systems, recorded 10.63 mg kg^{-1} and 8.23 mg kg^{-1} respectively under aerobic and flooded systems.

Among the interactions, fertilizer applied as per soil test with lime based on SMP buffer method (F_2L_3) recorded significantly highest available Mg under both systems at harvest of the crop followed by treatment F_2L_2. The other treatment interactions involving fertilizer application as per POP showed a decreasing trend of available Mg content at this stage also. The available Mg content at harvest was the lowest in comparison with the previous stages of soil sampling.

The pooled data of available magnesium at harvest reveal that there was no significant difference between aerobic system (10.21 mg kg^{-1}) and flooded rice cultivation system (7.48 mg kg^{-1}).

4.2.8. Effect of fertilizers and lime on available sulphur

The influence of treatments on soil available sulphur status at different stages of sampling is presented from table 29 to 31.

Table 29. Effect of fertilizers and lime on available sulphur (mg kg^{-1}) at active tillering

Aerobic rice				
Fertilizer/Lime	**L_1**	**L_2**	**L_3**	**Mean**
F_1	17.72	18.62	17.82	**18.05**
F_2	22.58	25.29	27.62	**25.16**
Mean	**20.15**	**21.96**	**22.72**	**21.61**
CD. F 0.81	**CD L**	**0.99**	**CD F x L 1.4**	
Flooded rice				
F_1	22.41	23.31	25.46	**23.73**
F_2	22.01	28.33	29.74	**26.69**
Mean	**22.21**	**25.82**	**27.60**	**25.21**
CD. F 2.04	**CD L**	**2.49**	**CD F x L**	**N. S.**
CD pooled 2.83				

4.2.8.1. Active tillering

Application of fertilizers and lime had a significant influence in increasing the available sulphur status of the soil (table 29). The available sulphur has increased from an initial status of 11.31 mg kg^{-1} under aerobic condition and 14.39 mg kg^{-1} under flooded system respectively.

The application of fertilizers as per soil test (F_2) recorded significantly higher available sulphur, recorded 25.16 mg kg^{-1} under aerobic condition and 26.69 mg kg^{-1} under flooded condition.

Application of lime as per SMP buffer method (L_3) recorded significantly higher available sulphur under both systems (22.72 mg kg^{-1} under aerobic and 27.60 mg kg^{-1} under flooded system). Between the other two lime treatments, application as per ΔpH (L_2) increased the available sulphur than in treatment as per POP (L_1) under both systems of rice cultivation.

Among the interactions, significantly highest available sulphur was recorded in treatment where application of fertilizers as per soil test with lime as per SMP buffer method (F_2L_3) under both systems of rice cultivation.

Available sulphur content under flooded system of rice cultivation was higher (25.21 mg kg^{-1}) in comparison with aerobic system (21.61 mg kg^{-1}).

Table 30. Effect of fertilizers and lime on available sulphur (mg kg^{-1}) at panicle initiation

		Aerobic rice		
Fertilizer/Lime	L_1	L_2	L_3	**Mean**
F_1	16.88	17.32	16.65	**16.95**
F_2	21.91	24.83	25.88	**24.20**
Mean	**19.39**	**21.07**	**21.27**	**20.58**
CD. F 1.19	**CD L 1.47**		**CD F x L 2.08**	
		Flooded rice		
F_1	24.25	26.31	28.65	**26.40**
F_2	29.08	31.26	32.44	**30.92**
Mean	**26.66**	**28.78**	**30.54**	**28.66**
CD. F 1.01	**CD L 1.24**		**CD F x L 1.75**	
C D pooled 4.26				

4.2.8.2. Panicle initiation

The data on effect of fertilizers and lime on available sulphur status of the soil at panicle initiation are given in table 30.

Under both systems, fertilizers applied as per soil test (F_2) significantly enhanced the available sulphur status (24.20 mg kg $^{-1}$ under aerobic condition and 30.92 mg kg^{-1} under flooded condition) in comparison with the treatment where application of fertilizer was done as per POP (F_1).

Application of lime as per SMP buffer method (L_3) was significantly superior in enhancing available sulphur status of the soil (21.27 mg kg^{-1} and 30.54 mg kg^{-1} under aerobic condition and flooded condition respectively).

Application of fertilizers as per soil test with the quantity of lime applied as per SMP buffer method (F_2L_3) recorded the highest available sulphur status under both systems of rice cultivation.

Available sulphur in flooded system was significantly higher (28.66 mg kg^{-1}) than that under aerobic system of rice cultivation (20.58 mg kg^{-1}). The available sulphur status was found improved at his stage in comparison with that at active tillering under flooded system of rice cultivation, while it got reduced under aerobic rice cultivation.

Table 31. Effect of fertilizers and lime on available sulphur (mg kg^{-1}) at harvest

Aerobic rice				
Fertilizer/Lime	L1	L2	L3	**Mean**
F_1	12.86	13.45	19.72	**15.34**
F_2	21.60	21.82	23.91	**22.44**
Mean	**17.23**	**17.63**	**21.83**	**18.89**
CD. F 0.47	**CD L** 0.57		CD F x L 0.81	
Flooded rice				
F_1	20.17	20.68	21.21	**20.69**
F_2	20.98	22.55	23.42	**22.32**
Mean	**20.58**	**21.62**	**22.32**	**21.50**
CD. F 0.63	**CD L** 0.77		**CD F x L 1.09**	
C D pooled N.S				

4.2.8.3. Harvest

The data on effect of fertilizers and lime in available sulphur status of the soil at harvest is given in table 31. Application of fertilizers and lime as well as the interactions of lime with fertilizers were found significant in influencing the available sulphur status of the soil.

Available sulphur status was significantly better in treatment with application of fertilizers as per soil test (F_2) than that in the treatment where application of fertilizer was done as per POP at this stage also.

Application of lime as per SMP buffer method (L_3) found significantly superior in enhancing available sulphur status of the soil under both systems of rice cultivation, followed by the treatment where lime was applied based on ΔpH (L_2).

The same effect was reflected in interactions also under both systems of rice cultivation.

There was no significant difference in available sulphur under aerobic and flooded systems of rice cultivation at this stage.

In general, available sulphur status was better than the initial, and then the same was reduced at harvest when compared with that in active tillering as well as in panicle initiation.

4.2.9. Effect of fertilizers and lime on available Iron

The influence of treatments on available iron status at different stages of sampling is presented from table 32 to 34.

Table 32. Effect of fertilizers and lime on available iron (mg kg^{-1}) at active tillering

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	**Mean**
F_1	54.30	51.60	47.10	**51.00**
F_2	54.53	53.43	48.13	**52.03**
Mean	**54.41**	**52.51**	47.61	**51.65**
CD. F N.S	**CD L 1.80**		**CD F x L N S**	
Flooded rice				
F_1	130.55	120.46	100.19	**117.07**
F_2	126.11	119.18	98.56	**114.62**
Mean	**128.33**	**119.82**	**99.38**	**115.84**
CD. F N. S	**CD L 4.99**		**CD F x L N S**	
C D pooled 4.56				

4.2.9.1 Active tillering

The initial status of available Fe was 56.78 mg kg^{-1} and 113.74 mg kg^{-1} under aerobic and flooded conditions respectively. Application of lime decreased the available Fe status of the soil (table 32) under both systems of rice cultivation.

Among the doses of lime, application as per SMP buffer method (L_3) significantly decreased the available Fe status of the soil (47.61 mg kg^{-1} under aerobic system and 99.38 mg kg^{-1} under flooded system). Between the other two doses of lime, application based on ΔpH (L_2) recorded lower available Fe (52.51 mg kg^{-1}) than that with application based on POP (54.41 mg kg^{-1}) under aerobic system. Applied lime as per POP (L_1) also decreased the available Fe status of the soil in comparison with the initial status under this system at active tillering. However, application of lime as per ΔpH (L_2) and POP (L_1) did not decrease the available Fe status of the soil under flooded system.

Cultivation of rice under aerobic condition (51.51 mg kg^{-1}) was significantly better than that under flooded system (115.84 mg kg^{-1}) in decreasing available Fe status. The available iron was found to decrease from the initial level in all the treatments under aerobic rice cultivation system.

Table 33. Effect of fertilizers and lime on available iron (mg kg^{-1}) at panicle initiation

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	**Mean**
F_1	52.33	50.98	44.35	**49.22**
F_2	51.35	50.75	42.03	**48.04**
Mean	**51.84**	**50.86**	**43.19**	**48.63**
CD. F N. S	**CD L 1.87**		**CD F x L 2.41**	
Flooded rice				
F_1	113.13	104.00	85.00	**100.71**
F_2	114.95	101.40	84.25	**100.20**
Mean	**114.04**	**102.70**	**84.63**	**100.45**
CD. F N. S	**CD L 3.14**		**CD F x L 4.44**	
C D pooled 9.55				

4.2.9.2 Panicle initiation

The data on effect of fertilizers and lime on available iron status of the soil at panicle initiation is given in table 33.

Under both systems of rice cultivation, application of lime was significant in decreasing the available Fe status of the soil. Among the different quantities of lime, application as per SMP buffer method (L_3) recorded the lowest available Fe (43.19 mg kg^{-1} under aerobic system and 84.63 mg kg^{-1} under flooded system). The other two doses of lime as per ΔpH (L_2) and as per POP (L_1), were found on par in decreasing the available Fe content in soil under aerobic system of rice cultivation. Under flooded system, lime based on ΔpH (L_2) recorded significantly lower available Fe (102.70 mg kg^{-1}) than that with application based on POP (114.04 mg kg^{-1}).

Among the interactions, lime as per SMP buffer method with fertilizers as per soil test (F_2L_3) recorded significantly lowest available Fe under aerobic condition (42.03 mg kg^{-1}) and under flooded condition (84.25 mg kg^{-1}) respectively.

Cultivation of rice under aerobic condition was significantly better in decreasing available Fe (48.63 mg kg^{-1}) than the flooded system (100.45 mg kg^{-1}). In general, the available Fe has decreased at panicle initiation under both systems of rice cultivation in comparison with that at active tillering.

Table 34. Effect of fertilizers and lime on available iron (mg kg^{-1}) at harvest

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	Mean
F_1	50.43	48.53	44.85	47.94
F_2	50.15	50.55	46.48	49.06
Mean	50.29	49.54	45.67	48.50
CD. F N.S	CD L 3.20		CD F x L 3.73	
Flooded rice				
F_1	94.42	90.85	74.93	86.73
F_2	89.38	85.50	72.43	82.43
Mean	91.90	88.18	73.68	84.58
CD. F N.S	CD L 4.21		CD F x L 1.32	
C D pooled 7.27				

4.2.9.3 Harvest

The data on effect of fertilizers and lime on available iron status of the soil at harvest is given in table 34.

Application of lime significantly decreased the available Fe status of the soil at harvest. Among the different quantities of lime, application as per SMP buffer method (L_3) recorded significantly the lowest available Fe status both under aerobic (45.67 mg kg^{-1}) and flooded system (73.68 mg kg^{-1}) of rice cultivation. The other two doses of lime were on par in reducing the available Fe status at this stage.

Applied fertilizers did not significantly influence the available Fe status under both systems of rice cultivation.

Among the interactions, the treatment with fertilizers as per POP and lime as per SMP buffer method (F_1L_3) recorded the lowest available Fe status (44.85 mg kg^{-1}) which was on par with fertilizers as per soil test and application of lime based on SMP buffer method (F_2L_3), (46.48 mg kg^{-1}) available Fe under aerobic rice cultivation at this stage.

Under flooded system, interaction of applied fertilizer as per soil test with lime based on SMP buffer method (F_2L_3) has significantly decreased the available Fe status (72.43 mg kg^{-1}) of soil at harvest.

Cultivation of rice under aerobic condition was significantly better in decreasing available Fe (48.50 mg kg^{-1}) than the flooded rice cultivation (84.58 mg kg^{-1}).

Available Fe was found to decrease at harvest of the crop, in comparison with other stages under flooded system. But, the available Fe recorded almost same as that at panicle initiation under aerobic system of rice at harvest of the crop.

4.2.10. Effect of fertilizers and lime on available manganese

The influence of treatments on available manganese status at different stages of sampling are presented from table 35 to 37.

Table 35. Effect of fertilizers and lime on available Mn at active tillering

Aerobic rice				
Fertilizer/Lime	**L_1**	**L_2**	**L_3**	**Mean**
F_1	26.00	25.1	22.03	**24.38**
F_2	24.28	23.35	21.20	**22.94**
Mean	**25.14**	**24.23**	**21.61**	**23.66**
CD. F N. S	**CD L 1.79**		**CD F x L N. S.**	
Flooded rice				
F_1	14.78	12.00	10.23	**12.33**
F_2	13.00	11.90	10.70	**11.87**
Mean	**13.89**	**11.95**	**10.46**	**12.10**
CD. F N.S.	**CD L 2.16**		**CD F x L N. S.**	
C D pooled 2.26				

4.2.10.1 Active tillering

The data on available manganese in soil, at active tillering, presented in table 35 showed that application of fertilizers and lime were significant in decreasing the available Mn from initial status of 29.52 mg kg^{-1} and 18.24 mg kg^{-1} under aerobic and flooded systems of rice respectively.

Quantity of lime applied as per SMP buffer method (L_3), decreased the available Mn (21.61 mg kg^{-1}) status of the soil significantly, followed by lime application based on ΔpH (24.23 mg kg^{-1}) which was superior with that of lime applied as per POP (L_1) (20.66 mg kg^{-1}) under aerobic system of rice cultivation. Similar trend was observed in flooded condition also, where lowest available Mn

(10.46 mg kg^{-1}), was recorded in lime applied as per SMP buffer method (L_3), followed by lime application based on ΔpH (11.95 mg kg^{-1}).

Applied fertilizers, as well as their interaction with doses of lime were not significant at this stage.

The data show that, cultivation of rice under flooded condition recorded lower available Mn (12.10 mg kg^{-1}) than that of aerobic rice cultivation (23.66 mg kg^{-1}).

Table 36. Effect of fertilizers and lime on available Mn at panicle initiation

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	**Mean**
F_1	20.60	20.43	17.50	**19.51**
F_2	22.73	20.80	17.35	**20.29**
Mean	**21.66**	**20.61**	**17.43**	**19.90**
CD. F N.S	**CD L 1.10**		**CD F x L 1.17**	
Flooded rice				
F_1	10.40	9.63	8.63	9.55
F_2	9.63	9.00	8.50	9.04
Mean	**10.01**	**9.31**	**8.57**	**9.30**
CD. F N. S	**CD L 0.62**		**CD F x L 0.78**	
C. D pooled 1.53				

4.2.10.2 Panicle initiation

The data on available manganese in soil, at panicle initiation, presented in table 36 showed that quantity of lime applied as per SMP buffer method (L_3) was found to decrease the available Mn significantly (17.43 mg kg^{-1} and 8.57 mg kg^{-1} under aerobic and flooded systems respectively), followed by lime applied based on ΔpH (L_2).

The effect of applied fertilizers was not significant under both systems of rice cultivation at this stage.

The interaction of applied fertilizers with doses of lime was found significant to decrease the available manganese at this stage under both systems of rice cultivation. The interaction of fertilizer applied as per soil test with lime as per lime requirement based on SMP buffer method (F_2L_3) recorded the lowest available Mn under aerobic (17.35mg kg^{-1}) and flooded system (8.50 mg kg^{-1}), which was on par with the treatment where lime as per SMP buffer method with fertilizers as per POP (F_1L_3), which recorded 17.50 mg $kg^{-1}$and 8.63 mg kg^{-1} under aerobic and flooded systems respectively.

Available Mn content was significantly lower under flooded environment (9.13 mg kg^{-1}) than that under aerobic rice (19.90 mg kg^{-1}).

The available Mn status was found decreased at this stage in comparison with that at active tillering and initial stage under both systems of rice cultivation.

Table 37. Effect of fertilizers and lime on available Mn at harvest

		Aerobic rice		
Fertilizer/Lime	**L_1**	**L_2**	**L_3**	**Mean**
F_1	21.30	20.93	18.63	20.28
F_2	20.68	19.98	18.38	19.68
Mean	**20.99**	**20.45**	**18.50**	**19.98**
CD. F N. S.	**CD L 1.20**		**CD Fx L N. S**	
		Flooded rice		
F_1	11.90	11.00	9.15	10.68
F_2	11.15	10.80	9.43	10.46
Mean	**11.53**	**10.90**	9.29	**10.57**
CD. F N. S	**CD L 0.44**		**CD F L N.S**	
C D pooled 0.74				

4.2.10.3. Harvest

The data (table 37) on available manganese in soil, at harvest of the crop showed that the quantity of lime applied as per SMP buffer method (L_3) was found to decrease the available Mn under aerobic (18.50 mg kg^{-1}) and flooded systems (9.29 mg kg^{-1}), followed by lime application based on ΔpH.

The applied fertilizers as well as the interaction of fertilizers with lime were not significant to decrease in available manganese at this stage.

However, the available manganese was found decreased from that at initial and active tillering stages, but was higher than that at panicle initiation under both systems of rice.

The content was significantly lower under flooded environment (10.57 mg kg^{-1}) than that under aerobic system (19.98 mg kg^{-1}).

The available Mn recorded at harvest under aerobic rice cultivation system was almost same as that at panicle initiation, and decreased from that at initial and active tillering. Under flooded system, the available Mn content was the lowest at harvest in comparison with the previous stages.

4.2. 11. Effect of fertilizers and lime on available zinc

The influence of treatments on available zinc status at different stages of sampling are presented from table 38 to 40.

Table 38. Effect of fertilizers and lime on available zinc (mg kg^{-1}) at active tillering

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	**Mean**
F_1	0.835	0.826	1.106	0.923
F_2	0.809	0.828	0.848	0.828
Mean	**0.822**	**0.827**	**0.977**	**0.875**
CD. F N. S	CD L 0.20		CD F x L N.S	
Flooded rice				
F_1	2.8	2.55	1.78	2.38
F_2	2.68	2.38	1.93	2.33
Mean	**2.74**	**2.46**	**1.85**	**2.35**
CD. F N. S	CD L 0.15		CD F x L N.S	
C. D pooled 0.72				

4.2.11.1. Active tillering

The initial available zinc status was 1.66 mg kg^{-1} in aerobic rice and 2.80 mg kg^{-1} in flooded rice.

The data on available zinc in soil, at active tillering (table 38) revealed that among the lime treatments, lime applied as per SMP buffer method (L_3) recorded lowest available Zn under flooded system (1.85 mg kg^{-1}), while the same treatment recorded significantly highest available Zn (0.98 mg kg^{-1}) under aerobic system.

Between the other lime treatments under aerobic system, available Zn was higher in application based on POP (0.82 mg kg^{-1}) than as per ΔpH (L_2) (0.70 mg kg^{-1}), the effect was statistically significant.

Under flooded system, lime applied as per POP (L_1) recorded significantly higher available Zn in comparison with that of lime as per ΔpH (L_2).

Applied fertilizers as well as their interaction with applied lime did not significantly influence the available Zn in soil at this stage under both systems of rice cultivation.

In general, the available Zn was found to decrease from the initial level at active tillering under both systems of rice cultivation.

The pooled analysis data on available zinc at active tillering showed that the flooded system of rice cultivation recorded significantly higher available zinc at this stage (1.85 mg kg^{-1}).

Table 39. Effect of fertilizers and lime on available zinc (mg kg^{-1}) at panicle initiation

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	**Mean**
F_1	1.19	0.90	1.22	**1.10**
F_2	0.84	0.87	0.70	**0.80**
Mean	**1.02**	**0.89**	**0.96**	**0.95**
CD. F 0.15	**CD L 0.12.**		**CD F x L**	**N.S**
Flooded rice				
F_1	1.35	1.26	1.21	**1.27**
F_2	1.37	1.28	1.24	**1.30**
Mean	**1.36**	**1.27**	**1.23**	**1.29**
CD. F N.S	**CD L 0.07**		**CD FxL**	**N. S**
C D pooled 0.16				

4.2.11.2 Panicle initiation

The data on available zinc in soil, at panicle initiation, presented in table 39 revealed that under aerobic system, applied fertilizers as per soil test (F_2) reduced the available Zn content in soil (0.80 mg kg^{-1}) than that in the treatment where fertilizers were applied as per POP (F_1, 1.10 mg kg^{-1}). Under flooded system, the effects of fertilizers were not significant at this stage.

Quantity of lime applied as per SMP buffer method (L_3) was found to decrease the available Zn under both systems of rice (0.96 mg kg^{-1} under aerobic system and 1.23 mg kg^{-1} under flooded system), which was on par with lime applied treatment based on ΔpH (L_2) (0.89 mg kg^{-1} under aerobic and 1.27 mg kg^{-1} under flooded system). Application of lime as per POP (L_1) recorded highest available Zn at this stage under aerobic (1.02 mg kg^{-1}) and flooded (1.36 mg kg^{-1}) systems respectively.

Flooded system of rice cultivation recorded significantly higher available zinc (1.29 mg kg^{-1}) than that of aerobic rice (0.95 mg kg^{-1}) at this stage

In general, the available Zn was found increased at panicle initiation in comparison with that at active tillering under aerobic system, while it decreased under flooded system of rice cultivation.

Table 40. Effect of fertilizers and lime on available zinc (mg kg^{-1}) at harvest

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	**Mean**
F_1	0.64	0.65	0.85	**0.71**
F_2	0.46	0.50	0.84	**0.60**
Mean	**0.55**	**0.58**	**0.84**	**0.66**
CD. F 0.085	**CD L 0.10**		**CD F x L**	**N.S**
Flooded rice				
F_1	1.23	1.18	1.11	**1.17**
F_2	1.25	1.19	1.09	**1.18**
Mean	**1.24**	**1.19**	**1.10**	**1.18**
CD. F N. S.	**CD L 0.23**		**CD F L**	**N. S.**
C D pooled 0.24				

4.2.11.3 Harvest

The data on available zinc in soil, at harvest, (table 40) showed that, under aerobic system, applied fertilizers as per soil test (F_2) significantly decreased the available Zn (0.60 mg kg^{-1}) than that in fertilizer as per POP (F_1) (0.71mg kg^{-1}). Under flooded system, the effect of applied fertilizers was not significant.

Lime applied as per SMP buffer method (L_3) recorded significantly the highest available Zn content (0.84 mg kg^{-1}) in soil followed by the other two treatments *viz.* lime application based on ΔpH (0.58 mg kg^{-1}) and as per POP (0.55 mg kg^{-1}) under aerobic system. Under flooded condition, applied lime as per SMP buffer method significantly decreased the available Zn (1.10 mg kg^{-1}) followed by lime application based on ΔpH (L_2) (1.19 mg kg^{-1}).

The interactions of applied fertilizers with doses of lime were not significant at this stage under both the systems.

The highest available Zn was recorded in flooded system of rice cultivation (1.18 mg kg^{-1}), in comparison with that of aerobic system (0.66 mg kg^{-1}).

In general, under both systems, the available Zn at harvest was found decreased than that of previous stages of sampling. The available Zn was reduced and became deficient (<1mg kg^{-1}) from that at active tillering to harvest of the crop under aerobic system of rice cultivation. Under flooded condition, though the available zinc was decreased, the status was sufficient for rice.

4.2.12. Effect of fertilizers and lime on available copper

The influence of treatments on available copper status at different stages of sampling are presented from table 41 to 43.

Table 41. Effect of fertilizers and lime on available copper at active tillering

		Aerobic rice		
Fertilizer/Lime	L_1	L_2	L_3	**Mean**
F_1	7.05	6.43	6.00	6.49
F_2	6.88	6.50	5.90	6.43
Mean	**6.96**	**6.43**	**5.95**	**6.46**
CD. F N. S.	**CD L 0.18**		**CD F x L N. S.**	
		Flooded rice		
F_1	4.9	4.8	4.28	4.66
F_2	4.48	4.6	4.45	4.51
Mean	**4.69**	**4.70**	**4.36**	**4.58**
CD. F N. S	**CD L N.S.**		**CD F x L N. S.**	
CD pooled 0.36				

4.2.12.1 Active tillering

The initial available copper status recorded in the experimental site of aerobic rice and flooded rice was 9.6 mg kg^{-1} and 6.10 mg kg^{-1} respectively. The available Cu was found decreased from the initial level at active tillering from the initial levels.

Under aerobic rice cultivation, lime applied as per SMP buffer method (L_3) was found to decrease the available Cu (5.95 mg kg^{-1}) status of the soil significantly, followed by lime application based on ΔpH (L_2) (6.96 mg kg^{-1}) and by lime applied as per POP (L_1 (6.43 mg kg^{-1}) in that order. Applied fertilizers as well as their interaction with lime were not found significant in influencing available Cu at this stage under aerobic rice (table 41).

Under flooded system, applied fertilizers, lime and their interactions were not significant in influencing the available Cu at this stage.

The pooled data of available copper at active tillering indicated that flooded system of rice cultivation recorded significantly lower available copper (4.58 mg kg^{-1}) in comparison with aerobic system of rice cultivation (6.46 mg kg^{-1}).

Table 42. Effect of fertilizers and lime on available copper at panicle initiation

Aerobic rice				
Fertilizer/Lime	**L_1**	**L_2**	**L_3**	**Mean**
F_1	6.10	5.97	5.57	5.88
F_2	5.98	6.20	5.53	5.90
Mean	**6.04**	**6.09**	**5.56**	**5.96**
CD. F N S	**CD L 0.15**		**CD F x L 0.21**	
Flooded rice				
F_1	3.48	3.27	3.17	3.31
F_2	3.52	3.21	3.19	3.31
Mean	**3.50**	**3.24**	**3.18**	**3.31**
CD. F N.S	**CD L 0.05**		**CDF x L N. S**	
C. D pooled 0.23				

4.2.12.2 Panicle initiation

The data on available copper in soil, at panicle initiation, presented in table 42 revealed that the fertilizers treatments were not significant at this stage under both systems of rice cultivation.

Among the different quantities of lime, application as per SMP buffer method (L_3) decreased the available copper content of the soil significantly under aerobic (5.74 mg kg^{-1}) and flooded (3.18 mg kg^{-1}) systems.

Under aerobic system, among the interactions, soil test based fertilizer application along with lime as per SMP buffer method (F_2L_3) was found significant in decreasing the available Cu status (5.53mg kg^{-1}).

The available copper content was significantly lower (3.31 mg kg^{-1}) in flooded system of rice cultivation than that under aerobic system (5.95 mg kg^{-1}). Available copper at PI was lower than that of active tillering under both systems of rice cultivation.

Table 43. Effect of fertilizers and lime on available copper at harvest

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	**Mean**
F_1	3.26	4.39	3.64	3.76
F_2	3.68	3.84	3.86	3.79
Mean	**3.45**	**3.12**	**3.75**	**3.78**
CD. F N. S	**CD L** 0.22		**CD F x L N. S**	
Flooded rice				
F_1	3.48	3.17	3.17	**3.27**
F_2	3.57	3.21	3.19	**3.32**
Mean	**3.53**	**3.19**	**3.18**	**3.30**
CD. F N. S.	**CD L 0.16**		**CD F x L N. S.**	
CD pooled 0.61				

4.2.12.3. Harvest

The data on available copper in soil, harvest (table 43) revealed that, the quantity of lime applied as per SMP buffer method (L3) recorded significantly higher available Cu (3.75 mg kg^{-1}), followed by lime based on POP (L_1, 3.45 mg kg^{-1}) under aerobic system.

However, under flooded system, lime applied as per SMP buffer method (L_3) found significant in decreasing Cu (3.18 mg kg^{-1}), which was on par with lime as per ΔpH (L_2, 3.19 mg kg^{-1}).

The pooled data of available copper at harvest indicated that flooded system of rice cultivation recorded significantly lower available copper (3.30 mg kg^{-1}) in comparison with aerobic system of rice cultivation (3.78 mg kg^{-1}).

Available copper was found decreased at harvest in comparison with that at other stages under aerobic system of rice cultivation. However, the available Cu under flooded system remained constant at harvest as that at panicle initiation, but was lower than that at active tillering.

4.2. 13. Effect of fertilizers and lime on available boron

The data on available boron status at different stages of sampling are presented from table 44 to 46.

Table 44. Effect of fertilizers and lime on available boron (mg kg^{-1}) at active tillering

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	**Mean**
F_1	0.05	0.05	0.04	**0.05**
F_2	0.65	0.69	0.60	**0.65**
Mean	**0.35**	**0.37**	**0.32**	**0.35**
CD. F 0.01	**CD L 0.02**		**CD F x L 1.4**	
Flooded rice				
F_1	0.21	0.20	0.20	**0.20**
F_2	0.84	0.85	0.51	**0.73**
Mean	**0.52**	**0.53**	**0.35**	**0.47**
CD. F 0.01	**CD L**	**0.01**	**CD F x L 0.01**	
C D pooled 0.01				

4.2.13.1 Active tillering

The initial available boron status recorded in the experimental site of aerobic rice and flooded rice was 0.07 mg kg^{-1} and 0.11 mg kg^{-1} respectively.

The data on available boron in soil, at active tillering, presented in table 44 showed that the available boron content was significantly higher in the treatments where fertilizers were applied as per soil test (F_2) under aerobic (0.65 mg kg^{-1}) and flooded systems (0.73 mg kg^{-1}). The available boron content was found to decrease from initial status (0.05 mg kg^{-1} under aerobic system and 0.20 mg kg^{-1} under flooded system respectively) in the treatment with fertilizer application as per POP (F_1).

Under aerobic system, application of lime as per ΔpH (L_2) recorded significantly the highest available boron (0.37 mg kg^{-1} under aerobic system and 0.53

mg kg^{-1} under flooded system) followed by application of lime as per POP (L_1) (0.35 mg kg^{-1}) under aerobic system. But, under flooded system, L_2 and L_1 were on par. Lime applied as per SMP buffer method (L_3) recorded the lowest available boron (0.32 mg kg^{-1}, under aerobic system and 0.35 mg kg^{-1} under flooded system respectively).

Application of fertilizers as per soil test with application of lime as per ΔpH (F_2L_2) was significantly superior in increasing the available B status under aerobic and flooded systems (0.69 mg $kg^{-1}$and 0.85 mg kg^{-1} respectively).

The available B was found to increase from the initial level at active tillering in the treatments where fertilizer was applied as per soil test (F_2), while it was decreased in treatments as per POP (F_1), under aerobic system. Under flooded system, this treatment also increased the available B in comparison with that of initial status.

The available boron was found significantly higher in flooded rice (0.47 mg kg^{-1}) in comparison with aerobic rice (0.35 mg kg^{-1}) at active tillering stage.

Table 45. Effect of fertilizers and lime on available boron at panicle (mg kg^{-1}) initiation

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	Mean
F_1	0.05	0.04	0.04	0.04
F_2	0.69	0.73	0.67	0.70
Mean	0.37	0.38	0.35	0.37
CD. F 0.01	**CD L 0.01**		**CD F x L 0.01**	
Flooded rice				
F_1	0.19	0.19	0.17	0.18
F_2	0.85	0.86	0.65	0.79
Mean	0.52	0.52	0.41	0.49
CD. F 0.004	**CD L 0.005**		**CD Fx L 0.007**	
C D pooled 0.07				

4.2.13.2 Panicle initiation

The data on available boron in soil at panicle initiation, presented in table 45 showed that the available boron content was highest and significant (0.70 mg kg^{-1}, and 0.79 mg kg^{-1} respectively under aerobic and flooded systems) in the treatments where fertilizers were applied as per soil test (F_2). The available boron content found decreased (0.04 mg kg^{-1}, and 0.18 mg kg^{-1} under aerobic and flooded system respectively) in the treatment with fertilizer application as per POP (F_1).

Under aerobic system, lime applied as per ΔpH (L_2) recorded significantly highest available boron (0.38 mg kg^{-1}) followed by application of lime as per POP (L_1) (0.37 mg kg^{-1}). Application of lime as per SMP buffer method (L_3) also resulted in an increase in available boron content (0.35 mg kg^{-1}) Under flooded condition, lime as per POP (L_1) and as per ΔpH (L_2) (0.52 mg kg^{-1}) recorded same available B, while it was decreased in treatment where lime was done as per SMP buffer method (L_3) recorded significantly lowest available boron content of 0.41 mg kg^{-1}.

Application of fertilizer as per soil test with application of lime as per ΔpH (F_2L_2) recorded the highest t available B under both systems (0.73 mg kg^{-1} and 0.86 mg kg^{-1}) aerobic and flooded systems of the soil. Under flooded system, this was on par (0.85 mg kg^{-1}) with the treatment combination F_2L_1.

The available boron was found significantly higher in flooded rice (0.49 mg kg^{-1}) in comparison with aerobic rice (0.37 mg kg^{-1}) at panicle initiation (table 127).

Under flooded system, in the treatment with fertilizer application as per POP (F_1), the available boron status was higher (0.18 mg kg^{-1}) than the initial value (0.11 mg kg^{-1}), but, was lower than that of active tillering. Under aerobic system, this treatment showed a steady decrease in available B from initial value.

Table 46. Effect of fertilizers and lime on available boron (mg kg^{-1}) at harvest

Aerobic rice					
Fertilizer/Lime		L_1	L_2	L_3	Mean
F_1		0.03	0.03	0.03	0.03
F_2		0.63	0.69	0.58	0.63
Mean		0.33	0.36	0.30	0.33
CD. F	0.009	CD L	0.011	CD F x L	0.016
Flooded rice					
F_1		0.18	0.18	0.16	0.18
F_2		0.82	0.84	0.64	0.77
Mean		0.56	0.51	0.40	0.47
CD. F	0.002	CD L	0.002	CD F L	0.003
C D pooled 0.045					

4.2.13.3 Harvest

The available boron content was highest (0.63 mg kg^{-1} and 0.77 mg kg^{-1} under aerobic and flooded systems respectively) in the treatments where fertilizers were applied as per soil test (F_2) under both systems of rice (table 46). Under aerobic system, in the treatment with fertilizer application as per POP (F_1) the available boron showed a steady decrease (0.03 mg kg^{-1}) when compared with that the initial value (0.06 mg kg^{-1}) in soil as well as with the previous stages of soil testing.

Under flooded system, the available boron found increased (0.18 mg kg^{-1}) in the treatment with fertilizer application as per POP (F_1) compared to that at initial value (0.11 mg kg^{-1}) but was lower than that at active tillering (0.20 mg kg^{-1}).

Application of lime as per ΔpH (L_2) recorded the highest available boron (0.36 mg kg^{-1} and 0.51 mg kg^{-1} under aerobic and flooded system respectively) followed by the application of lime as per POP (F_1), (0.33 mg kg^{-1}under aerobic and 0.50 mg kg^{-1} under flooded system) at this stage.

Fertilizers applied as per soil test with lime as per ΔpH (F_2L_2) recorded the highest available B under both systems at this stage (aerobic- 0.69 mg kg^{-1} and flooded - 0.84 mg kg^{-1}).

The available boron increased at this stage from that of active tillering, but decreased than that at panicle initiation in treatment where fertilizer was applied as per soil test (F_2) under both systems.

Flooded system recorded significantly higher available boron (0.47 mg kg^{-1}) in comparison with that of aerobic rice (0.33 mg kg^{-1}) at harvest.

4.3. Effect of treatments on nutrient content in rice under aerobic and flooded systems.

The effects of applied lime and fertilizers on nutrient content in rice (shoot) under aerobic and flooded systems are presented here under.

4.3.1. Effect of fertilizers and lime on nitrogen content in plant

The data on nitrogen content in plant at different stages are presented in tables from 47 to 50.

Table 47. Effect of fertilizers and lime on nitrogen content in plant (per cent) at active tillering

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	**Mean**
F_1	2.31	2.50	2.64	**2.48**
F_2	2.31	2.51	2.66	**2.49**
Mean	**2.31**	**2.51**	**2.65**	**2.49**
CD. F N S	**CD L 0.057**		**CD F x L N. S**	
Flooded rice				
F_1	2.15	2.31	2.47	**2.31**
F_2	2.29	2.43	2.53	**2.41**
Mean	**2.22**	**2.37**	**2.50**	**2.36**
CD. F 0.032	**CD L 0.039**		**CD F x L N. S**	
C D pooled 0.10				

4.3.1. 1. Active tillering

The data presented in table 47 revealed that, under both systems of rice cultivation, lime applied as per SMP buffer method (L_3) recorded highest nitrogen content in plant (2.65 % under aerobic system and 2.50 % under flooded system). Between the other two lime treatments, application as per ΔpH (L_2) recorded significantly higher nitrogen, (2.51 per cent under aerobic and 2.37 per cent under flooded system respectively) at active tillering.

The effect of applied fertilizers was not significant under aerobic system. Under flooded system, fertilizers applied as per soil test (F_2) recorded significantly higher nitrogen content in plant (2.41 %) than that of application of fertilizer as per POP (F_1) (2.31 %).

Interactions of applied lime with fertilizers were not significant under both systems were not significant at this stage.

Aerobic rice recorded significantly higher nitrogen content than flooded rice at active tillering.

Table 48. Effect of fertilizers and lime on nitrogen content in plant (per cent) at panicle initiation

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	**Mean**
F_1	3.01	2.96	3.03	**3.00**
F_2	2.56	2.73	2.91	**2.73**
Mean	**2.79**	**2.84**	**2.97**	**2.89**
CD. F 0.03	**CD L 0.04**		**CD F x L 0.06**	
Flooded rice				
F_1	1.98	2.06	2.39	**2.14**
F_2	1.88	2.11	2.61	**2.25**
Mean	**1.93**	**2.09**	**2.50**	**2.20**
CD. F N.S	**CD L 0.09**		**CD F x L 0.12**	
C D pooled 0.17				

4.3.1.2. Panicle initiation

The data presented in table 48 revealed that application of lime as per SMP buffer method (L_3) recorded the highest nitrogen content in plant under both systems of rice ((2.97 % and 2.50 % in aerobic and flooded systems respectively) than that of the other lime treatments viz. as per ΔpH (L_2), and as per POP (L_1). Between these two treatments, application as per ΔpH recorded significantly superior (2.84 % and 2.09 % under aerobic and flooded system respectively) nitrogen than that in lime as per POP.

Under aerobic system, the highest nitrogen content (3 %) was recorded in fertilizers applied as per POP (F_1) than that of application as per soil test (2.73 %) at panicle initiation. Effect of applied fertilizers was not significant under flooded system.

Under aerobic system, the combination of fertilizers applied as per POP with lime as per SMP buffer method (F_1L_3) recorded the highest nitrogen content in plant (3.03 %). Under flooded system, significantly higher N content was recorded in the treatment combination of fertilizers applied as per soil test with lime as per SMP buffer method (F_2L_3) (2.50 %).

Rice cultivation under aerobic condition recorded significantly higher nitrogen content in plant (2.89 per cent) than under flooded condition (2.20 per cent).

In general, the nitrogen content in plant was found increased at panicle initiation than that at active tillering under both systems of rice cultivation.

Table 49. Effect of fertilizers and lime on nitrogen content in straw at harvest

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	**Mean**
F_1	0.49	0.53	0.58	**0.53**
F_2	0.52	0.59	0.64	**0.58**
Mean	**0.51**	**0.56**	**0.61**	**0.56**
CD. F 0.02	**CD L 0.01**		**CD F x L 0.01**	
Flooded rice				
F_1	0.39	0.43	0.49	**0.44**
F_2	0.45	0.50	0.57	**0.51**
Mean	**0.42**	**0.47**	**0.53**	**0.47**
CD. F 0.02	**CD L 0.01**		**CD F x L 0.02**	
C D pooled 0.03				

4.3.1.3 Harvest in straw

The data presented in table 49 revealed that application of lime as per SMP buffer method (L_3) found to increase the nitrogen content in straw significantly under both systems. Between the two treatments, application of lime as per ΔpH (L_2) found significantly superior (0.56 % and 0.47 % under aerobic and flooded system respectively) in increasing the nitrogen content in plant in comparison with lime application as per POP (L_1).

Application of fertilizers as per soil test (F_2) was found to increase the N in plant significantly (0.58 % and 0.51 % under aerobic and flooded system respectively) than that of application of fertilizers as per POP (F_1).

In both the systems, the combination of fertilizers applied as per soil test with dose of lime as per SMP buffer method (F_2L_3) recorded significantly higher nitrogen content (0.64 % and 0.57 % under aerobic and flooded system respectively) than the other treatments.

Rice under aerobic condition recorded higher nitrogen in straw (0.56 %) than flooded system (0.47 %).

Table 50. Effect of fertilizers and lime on nitrogen content in grain at harvest

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	**Mean**
F_1	0.44	0.45	0.47	**0.45**
F_2	0.42	0.44	0.46	**0.44**
Mean	**0.43**	**0.44**	**0.46**	**0.44**
CD. F N S	**CD L 0.03**		**CD FxL N. S.**	
Flooded rice				
F_1	0.41	0.44	0.47	**0.44**
F_2	0.37	0.40	0.44	**0.40**
Mean	**0.39**	**0.42**	**0.45**	**0.42**
CD. F 0.01	**CD L 0.02**		**CD F x L N. S.**	
C D pooled N S				

4.3.1.4. Nitrogen in grain

The data presented in table 50 revealed that application of lime as per SMP buffer method (L_3) increased the nitrogen content in grain significantly under both the systems (0.46 % under aerobic and 0.45 % and flooded systems). The other two treatments, lime as per ΔpH (L_2) and as per POP (L_1) were found on par under aerobic system (0.44 % and 0.43 % respectively). But under flooded condition, application of lime as per ΔpH (L_2) recorded significantly higher N in grain (0.42 %), than that in lime as per POP (L_1).

Application of fertilizers as per POP (F_1) was found to increase the N in grain significantly under aerobic condition (0.44 %), while the effect of applied fertilizers were not significant under aerobic system.

The treatment with fertilizers as per POP and dose of lime as per SMP buffer method (F_1L_3) recorded significantly higher nitrogen content in both systems (0.47 % under aerobic and flooded system).

There was no significant difference between aerobic and flooded systems of rice cultivation with respect to nitrogen content in grain.

4.3.2. P content in plant

The data on P content in plant at various stages of sampling are presented in tables from 51 to 54.

Table 51. Effect of fertilizers and lime on P content in plant at active tillering

Aerobic rice				
Fertilizer/Lime	**L_1**	**L_2**	**L_3**	**Mean**
F_1	0.27	0.28	0.30	**0.28**
F_2	0.27	0.28	0.30	**0.28**
Mean	**0.27**	**0.28**	**0.30**	**0.28**
CD. F N. S	**CD L 0.007**		**CD F x L N. S**	
Flooded rice				
F_1	0.29	0.31	0.29	**0.30**
F_2	0.29	0.3	0.29	**0.30**
Mean	**0.29**	**0.31**	**0.29**	**0.30**
CD F N S	**CD L 0.002**		**C D F x LN. S**	
C. D. pooled 0.019				

4.3.2.1. Active tillering

Under aerobic rice, lime incorporated based on SMP buffer (L_3) recorded the highest phosphorus content in plant (0.30 %), followed by lime applied as per ΔpH (L2) which recorded 0.28 per cent P (table 51).

Under flooded rice, lime as per ΔpH (L_2) recorded significantly the highest phosphorus (0.31 %), followed by lime applied as per POP (L_1) which recorded 0.29 per cent P in plant.

Application of fertilizers as well as their interaction with doses of lime was not significant at this stage under both systems.

The P content in plant was found significantly higher in flooded rice (0.29 %) in comparison with aerobic rice (0.28 %) at active tillering.

Table 52. Effect of fertilizers and lime on P content in plant at panicle initiation

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	**Mean**
F_1	0.25	0.26	0.23	**0.25**
F_2	0.23	0.25	0.23	**0.24**
Mean	**0.24**	**0.25**	**0.23**	**0.24**
CD. F 0.001	**CD L 0.0015**		**CD F x L 0.002**	
Flooded rice				
F_1	0.26	0.29	0.25	**0.27**
F_2	0.26	0.30	0.25	**0.27**
Mean	**0.26**	**0.30**	**0.25**	**0.27**
CD. F N. S	**CD L 0.002**		**CD F x L N S**	
C D pooled 0.02				

4.3.2.2. Panicle initiation

The data given in table 52 revealed that, under both systems, lime incorporated based on ΔpH (L_2) recorded significantly the highest phosphorus content in plant (0.25 % and 0.30 % under aerobic and flooded systems respectively), followed by lime applied as per POP(L_1), (0.24 % and 0.26 % under aerobic and flooded systems respectively) in plant. Lime as per SMP buffer method (L_3) recorded the lowest P (0.23 % under aerobic and 0.25 % under flooded system) at this stage.

Application of fertilizers as per POP (F_1) did increase the plant P content significantly (0.25 %) than that of fertilizers as per soil test (F_2), (0.24 %) under aerobic system. Under flooded system, the effect of fertilizers was not significant.

Among the interactions of applied fertilizers with lime, fertilizers based on soil test together with lime as per ΔpH (F_2L_2) recorded highest P content (0.26 %) under aerobic and (0.30 %) flooded systems.

The P content in plant was found higher in flooded rice (0.27 %) in comparison with aerobic rice (0.24 %) at panicle initiation. In general, phosphorus content in plant was found reduced at panicle initiation than that at active tillering under both systems of rice cultivation.

Table 53. Effect of fertilizers and lime on phosphorus content in straw at harvest

Aerobic rice				
Fertilizer/Lime	**L_1**	**L_2**	**L_3**	**Mean**
F_1	0.17	0.19	0.21	**0.19**
F_2	0.18	0.18	0.21	**0.19**
Mean	**0.17**	**0.18**	**0.21**	**0.19**
CD. F 0.071	**CD L 0.050**		**CD F x L 0.061**	
Flooded rice				
F_1	0.19	0.18	0.17	**0.18**
F_2	0.18	0.19	0.17	**0.18**
Mean	**0.18**	**0.18**	**0.17**	**0.18**
CD. F N. S	**CD L**	**0.0018**	**CD F x L**	**0.0021**
C D pooled 0.024				

4.3.2.3. At harvest in straw

The data given in table 53 revealed that, under aerobic system, the amount of lime incorporated as per SMP buffer method (L_3) recorded significantly the highest phosphorus content (0.21 %), followed lime as per ΔpH (L_2, 0.19 %) in straw and was on par with lime applied as per POP (L_1, 0.18 %).

Under flooded system, incorporation of lime as per ΔpH (L_2) and as per POP (L_1) recorded the same P content (0.18 %) in straw. However, lime application as per SMP buffer method reduced the phosphorus content significantly (0.17 %).

Among the interactions, under aerobic system, the combination of lime as per SMP buffer method along with both the fertilizer recommendations recorded the highest P (0.21 per cent). Under flooded system, fertilizers based on soil test with lime as per ΔpH (F_2L_2) recorded highest P (0.187 per cent) in straw.

There was no significant difference in P content in straw at harvest between flooded rice (0.18 %) and aerobic rice (0.19 %). The P content in straw decreased at harvest than that at previous stages under both systems of rice.

Table 54. Effect of fertilizers and lime on phosphorus content in grain at harvest

	Aerobic rice			
Fertilizer/Lime	L_1	L_2	L_3	**Mean**
F_1	0.26	0.27	0.29	0.27
F_2	0.27	0.27	0.28	0.27
Mean	0.26	0.27	0.28	0.27
CD. F N. S	**CD L 0.003**		**CD F x L 0.003**	
	Flooded rice			
F_1	0.28	0.31	0.24	0.28
F_2	0.29	0.31	0.26	0.29
Mean	0.29	0.31	0.25	0.28
CD. F N. S	**CD L 0.003**		**CD F x L 0.004**	
C D pooled N S				

4.3.2.4. P content in grain

Under aerobic system, lime as per SMP buffer method (L_3) recorded the highest phosphorus content in grain (0.29 %) followed by lime applied as per ΔpH (L_2), which recorded 0.27 per cent P in grain (table 54). Under flooded system, lime as per ΔpH (L_2) recorded significantly superior phosphorus content (0.31 %) followed by lime as per POP (L_1) (0.29 % P).

The effect of applied fertilizers was not significant under both systems.

Among the interactions, under aerobic system, the treatment combination of fertilizer as per POP with lime as per SMP buffer method (F_1L_3) recorded the highest P content in grain (0.29 %). Under flooded system, interaction of lime applied as per ΔpH with both the fertilizer dose (F_1L_2 and F_2L_2) recorded the highest P (0.31 %).

There was no significant difference in P content in grain at harvest of crop between flooded rice (0.28 %) and aerobic rice (0.27 %).

4.3.3. Potassium content in plant

The data on P content in plant at various stages of sampling are presented in tables 55 to 58.

Table 55: Effect of fertilizers and lime on potassium content in plant at active tillering

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	Mean
F_1	1.91	2.12	2.34	**2.12**
F_2	1.96	2.13	2.39	**2.16**
Mean	**1.94**	**2.13**	**2.37**	**2.14**
CD. F 0.022	**CD L 0.027**		**CD F x L N. S**	
Flooded rice				
F_1	1.81	1.99	2.10	1.97
F_2	1.74	2.01	2.18	1.98
Mean	**1.77**	**2.00**	**2.14**	**1.97**
CD. F N.S	**CD L 0.018**		**CD F x L 0.03**	
CD pooled 0.13				

4.3.3.1 Active tillering

The data presented in table 55 revealed that under both systems, lime applied based on SMP buffer method (L_3) significantly increased the potassium content in plant (2.37 % and 2.14 % under aerobic and flooded systems respectively). However, lime applied based on ΔpH (L_2) was significantly superior in improving the potassium content (2.13 % under aerobic system and 2.00 % under flooded system) in comparison with the treatment where lime was applied as per POP (L_1).

Under aerobic system, fertilizers applied as per soil test (F_2) recorded significantly higher potassium content in plant (2.16 %) than that of fertilizer applied as per POP (F_1, 2.13%). Under flooded system, effect of applied fertilizers was not significant.

Among the interactions, under flooded system, fertilizers applied as per soil test with lime as per SMP buffer method (F_2L_3) was significantly superior in increasing the K content in plant (2.18 %). The interactions were not significant under aerobic system at this stage.

Significantly higher K content in plant was recorded in aerobic system (2.14 %), than that in flooded system (1.97 %).

Table 56. Effect of fertilizers and lime on potassium content in plant at panicle initiation

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	Mean
F_1	2.46	2.67	2.81	2.65
F_2	2.47	2.64	2.79	2.63
Mean	2.47	2.65	2.80	2.64
CD. F N.S	CD L 0.05		CD F x L N. S	
Flooded rice				
F_1	2.23	2.13	2.35	2.24
F_2	2.13	2.25	2.37	2.25
Mean	2.18	2.19	2.36	2.24
CD. F N.S	CD L 0.035		CD F x L N S	
C D pooled 0.21				

4.3.3.2 Panicle initiation

The data presented in table 56 showed that application of lime based on SMP buffer method (L_3) was found to increase the potassium content in plant both under aerobic (2.80 %) and flooded systems (2.36 %). The lime applied based on ΔpH (L_2) recorded significantly higher potassium content in plant (2.65 %) than that with the treatment where lime was applied as per POP (L1) under aerobic system. Under flooded system, lime based on ΔpH (L_2) and as per POP (L_1) was on par (2.19 % and 2.18 % respectively).

Effect of applied fertilizers as well as their interaction with lime was not significant under both systems of rice at this stage.

The K content in plant was significantly higher in aerobic system (2.64 %) than that in flooded condition (2.24 %). The plant K content was found increased at panicle initiation than at active tillering.

Table 57. Effect of fertilizers and lime on potassium content in straw at harvest

		Aerobic rice		
Fertilizer/Lime	L_1	L_2	L_3	**Mean**
F_1	1.04	1.08	1.19	**1.10**
F_2	1.10	1.13	1.20	**1.14**
Mean	**1.07**	**1.10**	**1.19**	**1.12**
CD. F 0.02	**CD L 0.01**		**CD F L 0.01**	
		Flooded rice		
F_1	0.96	1.03	1.11	**1.03**
F_2	0.95	1.03	1.11	**1.03**
Mean	**0.96**	**1.03**	**1.11**	**1.03**
CD. F 0.02	**CD L 0.01**		**CD F L 0.02**	
C D pooled 0.04				

4.3.3.3 Potassium content in straw at harvest

Lime applied based on SMP buffer method (L_3) recorded the highest potassium content in straw (1.19 % and 1.11 % under aerobic and flooded systems respectively). However, lime applied as per ΔpH (L_2) was significantly superior in improving the K content (1.10 % and 1.03 % under aerobic and flooded systems respectively) in straw than that of lime applied as per POP (L_1) (table 57).

Under aerobic system, fertilizers applied as per soil test significantly increased the K (1.14 %) than that with fertilizers as per POP (F_1, 1.10 %).

Among the interactions, both the fertilizer treatments lime as per SMP buffer method (F_2L_3) and fertilizers based on POP with lime as per SMP buffer method (F_1L_3) recorded highest P content in straw which were on par and significantly superior than the other treatment combinations.

Effect of fertilizers, as well as their interaction with lime was not significant in influencing the potassium content in straw under flooded system.

The aerobic system of rice cultivation was found significantly higher plant K at this stage, (1.12 %) than that in flooded system (1.03 %). However, plant K content was found decreased at harvest in straw when compared with that at panicle initiation and at active tillering under both systems.

Table 58. Effect of fertilizers and lime on potassium content in grain at harvest

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	Mean
F_1	0.23	0.25	0.29	0.26
F_2	0.23	0.27	0.31	0.27
Mean	0.23	0.26	0.30	0.26
CD. F 0.006	CD L 0.007		CD FxL	N. S
Flooded rice				
F_1	0.21	0.22	0.26	0.23
F_2	0.21	0.23	0.26	0.23
Mean	0.21	0.23	0.26	0.23
CD. F N. S	CD L 0.007		CD F x L	N S
C D pooled 0.015				

4.3.3.4 Potassium content in grain at harvest

Under both systems, application of lime based on SMP buffer method (L_3) recorded significantly higher K content in grain (0.30 % and 0.26 % under aerobic and flooded systems respectively) in comparison with that in other lime treatments (table 58).

Under aerobic system, fertilizers applied as per soil test (F_2) recorded significantly higher potassium content in grain than that of fertilizers as per POP (F_1). Effect of fertilizers applied was not significant under flooded system.

Interaction of applied fertilizers with lime was not significant in influencing potassium content in grain under both systems.

The aerobic system of rice cultivation was found significantly higher in improving K content in grain (0.26 per cent K) in comparison with that in flooded system (0.23 per cent).

4.3.4 Calcium content in plant

The data on calcium content in plant at various stages of sampling are presented in table 59 to 62.

Table 59. Effect of fertilizers and lime on calcium content in plant (mg kg^{-1}) at active tillering

Aerobic rice				
Fertilizers/ Lime	L_1	L_2	L_3	**Mean**
F_1	890.5	898.75	915.25	**901.50**
F_2	890.00	905.25	921.00	**905.00**
Mean	**890.25**	**902.00**	**918.13**	**903.46**
CD. F N.S	**CD L 4.68**		**CD F x L N. S**	
Flooded rice				
Fertilizer/Lime	**L1**	**L2**	**L3**	Mean
F_1	904.50	918.00	987.25	**936.58**
F_2	916.75	937.75	999.50	**951.33**
Mean	**910.63**	**927.88**	**993.38**	**943.96**
CD. F 3.15	**CD L 4.18**		**CD F x L N. S**	
C D pooled 38.25				

4.3.4.1 Active tillering

Under both the systems, Lime as per SMP buffer method (L_3) recorded the highest calcium content in plant (918.13 mg kg^{-1} and 993.38 mg kg^{-1} under aerobic and flooded systems respectively) (table 59). Further, lime applied based on ΔpH (L_2) recorded higher calcium content in plant than that of lime as per POP (L_1).

Under flooded condition, fertilizers as per soil test (F_2) recorded significantly higher calcium content in plant. Effect of applied fertilizers was not significant under aerobic system at this stage.

Interaction of fertilizers with doses of lime was not significant at this stage under both systems of rice cultivation.

Flooded system of rice cultivation was significantly higher with respect to calcium content (943.96 mg kg^{-1}), than that of aerobic system (903.46 mg kg^{-1}).

Table 60. Effect of fertilizers and lime on calcium content in plant (mg kg^{-1}) at panicle initiation

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	Mean
F_1	926.75	952.50	1030.25	**969.83**
F_2	935.25	947.00	1033.25	**971.83**
Mean	**931.00**	**949.75**	**1031.75**	**970.83**
CD. F N.S	**CD L 5.83**		**CD F x L 8.24**	
Flooded rice				
F_1	951.00	951.00	1092.75	**998.25**
F_2	942.00	945.00	1100.50	**995.83**
Mean	**946.50**	**948.00**	**1096.63**	**997.04**
CD. F N. S	**CD L 8.79**		**CD F x L 11.90**	
C D pooled 25.08				

4.3.4.2 Panicle initiation

The data (table 60) showed that the quantity of lime based on SMP buffer method (L_3) recorded the highest calcium content in plant under both systems (1031.75 mg kg^{-1} under aerobic system, 1096.63 mg kg^{-1} under flooded system) which were much higher than the other lime treatments. Under aerobic system, between the other treatments, lime applied based on ΔpH (L_2) recorded significantly higher Ca (949.75 mg kg^{-1}) in comparison with that in lime as per POP (L_1).While under flooded system, these two treatments were on par.

Among the interaction of fertilizers applied with doses of lime, fertilizer applied as per soil test along with lime incorporation as per SMP buffer method (F2L3) recorded significantly higher calcium content in plant at this stage under both systems (1033.25 mg kg^{-1} and 1100.5 mg kg^{-1} under aerobic and flooded system respectively).

Flooded system recorded significantly higher calcium content in plant (997 mg kg^{-1}), in comparison with aerobic system (970.83 mg kg^{-1}) at panicle initiation. However, Ca content was found increased at panicle initiation than that at active tillering under both systems of rice cultivation.

Table 61. Effect of fertilizers and lime on calcium content in straw at harvest

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	**Mean**
F_1	741.38	745.06	833.88	**773.44**
F_2	743.81	750.31	836.00	**776.71**
Mean	**742.59**	**747.69**	**834.94**	**775.07**
C D F N. S	**C D L 8.96**		**C D F x L 10.87**	
Flooded rice				
F_1	1003.58	1032.68	1150.83	**1062.36**
F_2	990.68	1033.05	1175.30	**1066.34**
Mean	**997.13**	**1032.86**	**1163.06**	**1064.35**
CD. F N S	**CD L 9.81**		**CD F x L 11.84**	
C D pooled 34.87				

4.3.4.3 Calcium content in straw at harvest

Under both systems, lime as per SMP buffer method (L_3) recorded the highest calcium content in straw (834.94 mg kg^{-1}, under aerobic and 1163.06 mg kg^{-1} under flooded system) (table 61). The other two lime treatments, viz., based on ΔpH (L_2) and as per POP (L_1) were on par. Under flooded system, lime as per ΔpH (L_2) recorded significantly higher Ca (1032.86 mg kg^{-1}) in comparison with lime applied as per POP (L_1).

Under both systems, among the interactions, fertilizers as per soil test along with lime as per SMP buffer method (F_2L_3) recorded highest calcium content in straw (836.00 mg kg^{-1} under aerobic system and 1033.25 mg kg^{-1} under flooded system).

Flooded system of rice cultivation was significantly higher in plant calcium (1064.35 mg kg^{-1}), in comparison with aerobic system of rice cultivation, (975.07 mg kg^{-1}).

The calcium content in plant was found increased at harvest than that at the previous stages, under both systems of rice cultivation.

Table 62. Effect of fertilizers and lime on calcium content in grain at harvest

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	**Mean**
F_1	128.57	139.19	144.97	**136.91**
F_2	131.99	136.16	150.08	**139.41**
Mean	**130.28**	**136.68**	**147.52**	**138.16**
CD. F 1.95	**CD L 2.39**		**CD F x L**	**N. S**
Flooded rice				
F_1	169.48	178.85	198.88	**182.40**
F_2	173.63	179.25	201.83	**185.07**
Mean	**171.55**	**179.30**	**200.35**	**183.73**
CD. F 1.95	**CD L 2.39**		**CD F x L N. S**	
C D pooled 17.84				

4.3.4.4 Calcium content in grain at harvest

The data (table 62) showed that lime as per SMP buffer method (L_3) recorded the highest calcium content under aerobic (147.52 mg kg^{-1}) and flooded systems (200.35 mg kg^{-1}). However, the amount of lime based on ΔpH (L_2) significantly increased Ca than that of lime as per POP (L_1).

Under both the systems, fertilizers applied as per soil test (F_2) recorded significantly higher Ca content in grain than that in fertilizers applied as per POP.

Among the interactions, fertilizer applied as per soil test with lime as per SMP buffer method (F_2L_3) recorded significantly the highest (150.08 mg kg^{-1} under aerobic and 201.83 mg kg^{-1} under flooded system) calcium content in grain at harvest.

Significantly higher calcium content in grain was recorded in flooded system of rice cultivation (183.73 mg kg^{-1}), when compared to that of aerobic system (138.16 mg kg^{-1}).

4.3.5 Magnesium content in plant

The data on magnesium content in plant at active tillering, panicle initiation and at harvest are presented in tables from 63 to 66.

Table 63. Effect of fertilizers and lime on magnesium content in plant (mg kg^{-1}) at active tillering

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	**Mean**
F_1	311.75	317.25	322.50	**317.18**
F_2	527.50	535.25	548.25	**537.00**
Mean	**419.65**	**426.25**	**435.38**	**427.09**
CD. F 11.75	**CD L 9.15**		**CD F x L 17.04**	
Flooded rice				
F_1	315.69	322.00	329.44	**322.75**
F_2	493.25	499.69	507.81	**500.25**
Mean	**404.47**	**410.84**	**418.63**	**411.31**
CD. F 14.13	**CD L N. S.**		**CD F X L 19.10**	
CD pooled 14.08				

4.3.5.1 Active tillering

The data presented in the table 63 revealed under aerobic system, quantity of lime applied as per SMP buffer (L_3) method recorded highest magnesium content in plant (435.38 mg kg^{-1}), followed by lime applied as per ΔpH (L_2) (426.25 mg kg^{-1}). Under flooded system, effect of doses of lime was not significant at this stage.

Under both systems of rice cultivation, fertilizers applied as per soil test (F_2) recorded the higher magnesium content in plant (537.00 mg kg^{-1} under aerobic rice and 500.25 mg kg^{-1} under flooded system) than that of fertilizers as per POP (F_1).

The interaction of applied lime based on SMP buffer method with fertilizers based on soil test (F_2L_3) was the highest in both the systems (548.25 mg kg^{-1} and 507.81 mg kg^{-1} under aerobic and flooded systems respectively).

Aerobic system of rice cultivation recorded significantly higher Mg content in plant (427.08 mg kg^{-1}) in comparison with that in flooded rice (411.31 mg kg^{-1}).

Table 64. Effect of fertilizers and lime on magnesium content in plant (mg kg^{-1}) at panicle initiation

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	**Mean**
F_1	305.75	314.00	318.75	**312.83**
F_2	516.50	529.25	537.25	**527.67**
Mean	**411.75**	**421.63**	**428.00**	**420.25**
CD. F 31.56	CD L N.S		CD F x L N. S	
Flooded rice				
F_1	299.99	306.30	313.74	**306.67**
F_2	477.55	483.99	492.11	**484.55**
Mean	**299.99**	**306.30**	**313.74**	**395.61**
CD. F 34.13	CD L N S		CD F x L N.S	
C D pooled 11.01				

4.3.5.2 Panicle initiation

The data on effect of fertilizers and lime on magnesium content in plant at panicle initiation are presented in table 64. Under both systems, the quantity of fertilizers applied as per soil test (F_2) recorded higher magnesium content in plant (527.67mg kg^{-1} under aerobic system and 484.55 mg kg^{-1} under flooded system) in comparison with that in fertilizer applied as per POP (L_1).

The quantity of lime applied, as well as their interaction with applied fertilizers was not significant in influencing the available Mg under both systems at this stage.

The magnesium content in plant was found decreased at panicle initiation than that at active tillering.

Aerobic system of rice cultivation recorded higher plant Mg status (420.25 mg kg^{-1}) in comparison with flooded rice cultivation system (395.61 mg kg^{-1}).

The plant Mg content was found reduced when compared with that at active tillering at this stage.

Table 65. Effect of fertilizers and lime on magnesium content (mg kg^{-1}) in straw at harvest

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	Mean
F_1	294.71	302.96	307.71	**301.80**
F_2	505.46	518.21	526.21	**516.63**
Mean	**400.09**	**410.59**	**416.96**	**409.21**
CD. F 12.21	**CD L N S**		**CD F x L N. S**	
Flooded rice				
F_1	268.78	274.78	280.80	**274.79**
F_2	481.28	488.80	495.78	**488.61**
Mean	**375.03**	**381.79**	**388.09**	**381.69**
CD. F 10.32	**CD L N S**		**CD F x L N S**	
C D pooled 18.63				

4.3.5.3 Magnesium content at harvest in straw

The data on effect of fertilizers and lime on magnesium content in straw (table 65) showed under both systems, fertilizers applied as per soil test (F_2) recorded significantly superior Mg content in straw (516.63 mg kg^{-1} and 488.61 mg kg^{-1} under aerobic and flooded systems respectively) in comparison with that in fertilizer applied as per POP (F_1).

The doses lime as well as their interaction with fertilizers was not significant at this stage under both systems of rice.

Aerobic system recorded higher Mg content in straw (409.21 mg kg^{-1}) in comparison with that in flooded rice cultivation system (381.69 mg kg^{-1}).

The Mg content in straw was found increased when compared with that at active tillering, but decreased when compared with that at PI at this stage.

Table 66. Effect of fertilizers and lime on magnesium content (mg kg^{-1}) in grain at harvest

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	Mean
F_1	134.85	135.33	139.35	**136.51**
F_2	162.60	165.95	175.43	**167.99**
Mean	**148.73**	**150.64**	**157.39**	**152.25**
CD. F 1.12	**CD L 1.37**		**CD F x L 1.77**	
Flooded rice				
F_1	125.28	126.68	129.28	**127.08**
F_2	149.98	156.08	159.08	**155.04**
Mean	**137.63**	**141.38**	**144.18**	**141.06**
CD. F 1.17	**CD L 1.25**		**CD F x L 1.89**	
C D pooled N S				

4.3.5.4 Magnesium content at harvest in grain

The data on effect of fertilizers and lime on magnesium content in grain (table 66) showed that under both systems, the quantity of lime applied as per SMP buffer method (L_3) recorded the highest magnesium content in grain (157.39 mg kg^{-1} and 144.18 mg kg^{-1} under aerobic and flooded systems respectively), followed by lime applied as per ΔpH (L_2).

Fertilizers applied as per soil test (F_2) recorded significantly higher magnesium content in grain (167.99 mg kg^{-1} and 155.04 mg kg^{-1}under aerobic and flooded systems respectively) than that in fertilizer applied as per POP (F_1).

The interaction effect showed that applied lime based on SMP buffer method with fertilizers based on soil test (F_2L_3) recorded the highest Mg (175.43 mg kg^{-1} under aerobic system and 159.08 mg kg^{-1} under flooded system).

Flooded (152.25 mg kg^{-1}) and aerobic system (141.06 mg kg^{-1}) did not differ significantly in improving Mg content in grain at harvest.

4.3.6 Sulphur content in plant

The influence of applied lime and fertilizers on sulphur content in plant at different stages of sampling is presented in table from 67 to 70.

Table 67. Effect of fertilizers and lime on sulphur content in plant (mg kg^{-1}) at active tillering

	Aerobic rice			
Fertilizer/Lime	L_1	L_2	L_3	Mean
F_1	720.70	724.70	730.70	**725.37**
F_2	810.20	817.20	825.30	**817.53**
Mean	**765.45**	**770.90**	**778.00**	**771.45**
CD. F 15.31	**CD L N. S**			**CD F x L 20.56**
	Flooded rice			
F_1	760.00	792.50	798.5	**783.67**
F_2	824.25	830.00	841.25	**831.83**
Mean	**792.13**	**811.25**	**819.88**	**807.75**
CD. F 12.96	**CD L 14.18**			**CD F x L 16. 67**
C D pooled 28.21				

4.3.6.1 Active tillering

The data in table 67 showed that under flooded system, lime applied based on SMP buffer method (L_3) recorded significantly the highest sulphur content in plant (819.88 mg kg^{-1}) among the different doses of lime. Between the other two doses, lime based on ΔpH (L_2) was significantly superior in enhancing sulphur (811.25 mg kg^{-1}) as presented in table 67. Under aerobic system, the effect of different doses of lime was not significant.

Under both systems, fertilizers applied as per soil test (F_2) recorded significantly higher sulphur content in plant (817. 53 mg kg^{-1} under aerobic system and 831.83 mg kg^{-1} under flooded system) in comparison with that in fertilizer applied as per POP (F_1).

Under both systems, lime incorporated as per SMP buffer method with fertilizers added based on soil test (F_2L_3) was significantly superior (825.30 under aerobic system and 841.25 mg kg^{-1} under flooded system) with respect to sulphur content.

Flooded system of rice cultivation recorded significantly higher sulphur content in plant (810.75 mg kg^{-1}) in comparison with that in aerobic system (771.45 mg kg^{-1}).

Table 68. Effect of fertilizers and lime on sulphur content in plant (mg kg^{-1}) at panicle initiation

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	Mean
F_1	718.60	722.60	728.60	723.27
F_2	808.10	815.00	823.20	815.43
Mean	763.35	768.80	775.90	769.35
CD. F 4.42	CD L 5.24		CD F x L	7.43
Flooded rice				
F_1	770.75	803.25	809.25	794.42
F_2	829.00	839.50	849.50	839.33
Mean	799.88	821.38	829.38	816.88
CD. F 4.21	CD L 5.32		CD F x L	9.86
C D pooled 26.24				

4.3.6.2 Panicle initiation

The data in table 68 showed that, under both systems, lime applied as per SMP buffer method (L_3) recorded significantly highest sulphur content (775.90 mg kg^{-1} and 829.38 mg kg^{-1} respectively under aerobic and flooded systems).

Under both systems, fertilizers applied as per soil test (F_2) recorded significantly higher sulphur content in plant (815.43 mg kg^{-1} and 839.33 mg kg^{-1} respectively under aerobic and flooded systems) in comparison with fertilizer applied as per POP (F_1).

The interaction of lime as per SMP buffer method with fertilizers based on soil test (F_2L_3) recorded significantly the highest under both systems of rice cultivation, (823.20 mg kg^{-1} under aerobic system and 849.50 mg kg^{-1} under flooded system).

Cultivation of rice under flooded condition recorded significantly more sulphur (816.88 mg kg^{-1}) than aerobic rice (769.35 mg kg^{-1}). The sulphur status was found slightly reduced at panicle initiation in comparison with active tillering.

Table 69. Effect of fertilizers and lime on sulphur content (mg kg^{-1}) in straw at harvest

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	Mean
F_1	618.65	623.40	628.90	623.65
F_2	707.90	714.55	723.50	715.32
Mean	663.27	668.97	676.20	669.48
CD. F 4.39	CD L 5.52		CD FxL 6.54	
Flooded rice				
F_1	664.50	697.00	703.00	688.17
F_2	722.75	733.25	743.25	733.08
Mean	693.63	715.13	723.13	710.63
CD. F 6.39	CD L 4.52		CD F x L 5.54	
C D pooled 25.36				

4.3.6.3 Sulphur content at harvest in straw

Lime applied as per SMP buffer method (L_3) recorded significantly the highest sulphur content in straw (676.20 mg kg^{-1} under aerobic system and 723.13 mg kg^{-1}) under flooded system under both systems of rice cultivation (table 69) .

The quantity of fertilizers applied as per soil test (F_2) recorded the higher sulphur content in straw under both systems (715.32 mg kg^{-1} under aerobic and 715.32 mg kg^{-1} under flooded system) in comparison with fertilizer applied as per POP.

The interaction of lime as per SMP buffer method with fertilizers added based on soil test (F_2L_3) was significantly superior with respect to S under both systems of rice (676.20 mg kg^{-1} and 723.50 mg kg^{-1} under aerobic and flooded system respectively).

Cultivation of rice under flooded condition recorded significantly higher sulphur (710.63 mg kg^{-1}) than that in aerobic rice (669.48 mg kg^{-1}).

Table 70. Effect of fertilizers and lime on sulphur content in grain (mg kg^{-1}) at harvest

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	Mean
F_1	629.60	633.60	636.6	633.27
F_2	679.60	683.60	690.60	684.60
Mean	654.60	658.6	663.60	658.93
CD. F 4.75	CD L 5.82		CD F x L 8.22	
Flooded rice				
F_1	676.50	709.00	715.00	700.17
F_2	734.75	744.75	752.75	744.08
Mean	705.63	726.88	733.88	722.13
CD. F 4.87	CD L 5.96		CD F x L 8.75	
C D pooled 29.16				

4.3.6.4 Sulphur content in grain

Lime applied as per SMP buffer method (L_3) recorded significantly the highest sulphur content in grain (663.60 mg kg^{-1} and 733.88 mg kg^{-1} under aerobic and flooded systems). Between the other two treatments, application of lime based on ΔpH (L_2) was significantly superior in enhancing the sulphur (658.60 mg kg^{-1} under aerobic system and 726.88 mg kg^{-1} under flooded system) in grain under both systems of rice (Table 70).

The significantly higher sulphur content under both systems was recorded in the treatment where fertilizers were applied as per soil test (684.60 mg kg^{-1} under aerobic and 744.08 mg kg^{-1} under flooded systems respectively).

The interaction of lime based on SMP buffer method with fertilizers added based on soil test (F_2L_3) recorded the highest sulphur content in grain under both systems.

Cultivation of rice under flooded condition recorded significantly higher sulphur content in grain (722.13 mg kg^{-1}) than that in aerobic condition (658.98 mg kg^{-1}).

4.3.7 Fe content in plant

The influence of lime and fertilizers on Fe content in plant at different stages of sampling is detailed in tables from 71 to 74.

Table 71. Effect of fertilizers and lime on Fe content in plant (mg kg^{-1}) at active tillering

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	Mean
F_1	1125.5	996.75	922.00	**1014.75**
F_2	1141.50	987.75	910.25	**1013.17**
Mean	**1133.50**	**992.25**	**916.13**	**1013.96**
CD. F N. S	**CD L 21.11**		**CD F x L**	**14.39**
Flooded rice				
F_1	1308.00	1234.00	1094.00	**1212.00**
F_2	1297.00	1227.00	1064.00	**1204.00**
Mean	**1302.50**	**1230.50**	**1079.00**	**1199.33**
CD. F N. S	**CD L 45.60**		**CD F L**	**20.56**
C D pooled 39.28				

4.3.7.1 Active tillering

Application of lime was found significant in decreasing the Fe content in plant (table 71). Lime applied as per SMP buffer method (L_3) recorded significantly the lowest Fe content in plant under aerobic (916.13 mg kg^{-1}) and flooded (1079 mg kg^{-1}) systems, followed by application as per ΔpH (L_2).

The quantity of fertilizers applied was not significant in influencing the Fe content in plant under both systems of rice cultivation.

The interaction of lime applied as per SMP buffer method with fertilizers based on soil test (F_2L_3) recorded the lowest Fe content in plant under both aerobic (910.25 mg kg^{-1}) and flooded system (1064 mg kg^{-1}).

The data showed that, aerobic system of rice cultivation (1013.96 mg kg^{-1}) significantly decreased the Fe content in plant in comparison with flooded system (1182.33 mg kg^{-1}).

Table 72. Effect of fertilizers and lime on Fe content in plant (mg kg^{-1}) at panicle initiation

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	**Mean**
F_1	1004.00	930.00	790.00	**908.00**
F_2	993.00	923.00	780.00	**898.67**
Mean	**998.50**	**926.50**	**785.00**	**903.35**
CD. F N.S.	**CD L 14.24**		**CD F x L 18.48**	
Flooded rice				
F_1	1031.50	969.25	859.25	**953.33**
F_2	1017.00	957.75	862.50	**945.75**
Mean	**1024.25**	**963.50**	**860.88**	**949.54**
CD. F N. S.	**CD L 10.24**		**CD F x L 14.48**	
C D pooled 26.94				

4.3.7.2 Panicle initiation

Lime applied as per SMP buffer method (L_3) recorded significantly lowest Fe content in plant under aerobic (760.00 mg kg^{-1}) and flooded systems (860.88 mg kg^{-1}) followed by application of lime as per ΔpH (L_2) (Table 72).

Effect of applied fertilizers was not significant under both the systems.

The interaction of lime as per SMP buffer method with fertilizers based on soil test (F_2L_3) was significantly superior in decreasing Fe content in plant under aerobic system (780.00 mg kg^{-1}) where as lime as per SMP buffer method with fertilizers based on POP (F_1L_3) recorded the lowest Fe under flooded system (859.25 mg kg^{-1}).

Cultivation of rice under aerobic condition was significantly superior in decreasing Fe (898.67 mg kg^{-1}) than that under flooded condition (949.54 mg kg^{-1}). However, the Fe content was found decreased at panicle initiation than that at active tillering, under both systems of rice.

Table 73. Effect of fertilizers and lime on Fe content (mg kg^{-1}) in straw at harvest

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	Mean
F_1	550.32	511.42	432.75	**498.16**
F_2	541.25	459.25	432.29	**477.60**
Mean	**545.78**	**485.34**	**432.52**	**487.88**
CD. F N. S.	CD L 14.79		CD F x LN. S.	
Flooded rice				
F_1	852.75	815.75	845.75	**838.08**
F_2	847.25	864.25	815.75	**842.17**
Mean	**850.00**	**890.00**	**830.75**	**840.12**
CD. F N. S.	CD L 17.72		CD F x L N. S.	
C D pooled	N S			

4.3.7.3 At Harvest in straw

Lime applied as per SMP buffer method (L_3) recorded significantly the lowest Fe content in straw under aerobic (432.52 mg kg^{-1}) and flooded systems (840.12 mg kg^{-1}) (table 73).

Applied fertilizers as well as their interaction with lime were not significant at this stage under both systems of rice cultivation.

Cultivation of rice under aerobic condition recorded significantly lower iron (487.88 mg kg^{-1}) than under aerobic rice (840.12 mg kg^{-1}). The content of iron in plant was found decreased at harvest in comparison with previous stages of sampling under both systems.

Table 74. Effect of fertilizers and lime on Fe content (mg kg^{-1}) in grain at harvest

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	**Mean**
F_1	258.75	221.75	151.75	**210.75**
F_2	253.25	168.25	121.75	**181.08**
Mean	**256.00**	**195.00**	**136.75**	**195.92**
CD. F 3.68	**CD L 4.52**		**CD F x L 6.3**	
Flooded rice				
F_1	347.28	318.53	308.25	**324.68**
F_2	345.65	319.55	284.30	**316.50**
Mean	**346.46**	**319.04**	**296.28**	**320.59**
CD. F N. S.	**CD L 11.60**		**CD Fx L N. S.**	
CD pooled 16.24				

4.3.7.4 Fe content in grain at harvest

Lime applied as per POP (L_1) recorded significantly the highest Fe content in grain under aerobic (256.00 mg kg^{-1}) and flooded system (346.46 mg kg^{-1}) followed by application as per ΔpH (L_2).

The quantity of fertilizers applied as per POP (F_1) significantly increased the Fe content in grain (210.75 mg kg^{-1} under aerobic and 324.68 mg kg^{-1} under flooded system) in comparison with that in application as per soil test (F_2) (181.08 mg kg^{-1} under aerobic and 316.5 mg kg^{-1} under flooded system).

The interaction of lime as per POP with fertilizers based on soil test (F_1L_1) recorded significantly the highest under aerobic (258.75 mg kg^{-1}) and under flooded system (347.28 mg kg^{-1}).

The iron content in grain was significantly higher under flooded condition was found significantly higher (320.59 mg kg^{-1}) than that in aerobic system (195.92 mg kg^{-1}).

4.3.8 Manganese content in plant

The influence of lime and fertilizers on Mn content in plant at different stages of sampling is detailed in tables from 75 to 78.

Table 75. Effect of fertilizers and lime on Mn content in plant (mg kg^{-1}) at active tillering

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	Mean
F_1	204.30	195.90	110.28	170.16
F_2	196.93	188.78	110.98	165.56
Mean	**200.62**	**192.25**	**110.63**	**167.86**
CD. F N.S	CD L 4.79		CD F x L 2.56	
Flooded rice				
F_1	296.00	286.00	247.00	276.33
F_2	292.00	283.00	253.00	276.00
Mean	**294.00**	**284.50**	**250.00**	**276.17**
CD. F N.S.	CD L 5.67		CD F x L N. S.	
C D pooled 10.93				

4.3.8.1 Active tillering

Application of lime was found significant in decreasing the Mn content in plant (table 75) under both the systems of rice. Lime applied as per SMP buffer method (L_3) recorded significantly the lowest Mn content in plant under aerobic (110.63 mg kg^{-1}) and flooded (250.00 mg kg^{-1}) systems, followed by application of lime as per ΔpH (L_2) (192.25 mg kg^{-1} and 284.50 mg kg^{-1} under aerobic and flooded systems respectively).

The effect of applied fertilizers was not significant on Mn content under both systems at this stage.

The interaction of lime as per SMP buffer method with fertilizers as per POP (F_1L_3) recorded the lowest Mn content in plant (110.28 mg kg^{-1}), which was on par with fertilizer based on soil test with lime as per SMP buffer method (F_2L_3) under aerobic system. Under flooded system, the interaction of applied lime with fertilizers was not significant.

Cultivation of rice under aerobic condition was significant in decreasing Mn content in plant (167.86 mg kg^{-1}) than the flooded system (167.86 mg kg^{-1}).

Table 76. Effect of fertilizers and lime on Mn content in plant (mg kg^{-1}) at panicle initiation

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	Mean
F_1	185.40	155.20	95.63	**145.41**
F_2	196.18	160.60	88.48	**148.42**
Mean	**190.79**	**157.90**	**92.05**	**146.92**
CD. F N. S	**CD L 11.66**		**CD F x L 16.48**	
Flooded rice				
F_1	204.08	194.08	155.06	**184.41**
F_2	200.05	191.13	161.09	**184.09**
Mean	**202.07**	**192.61**	**158.07**	**184.25**
CD. F N.S	**CD L 4.60**		**CD F x L 5.59**	
C D pooled 17.11				

4.3.8.2 Panicle initiation

The data presented in table 76 showed that the lime applied as per SMP buffer method (L_3) recorded significantly the lowest Mn content in plant under aerobic (92.05 mg kg^{-1}) and flooded (158.07 mg kg^{-1}) systems at this stage, followed by lime as per ΔpH (L_2).

Effect of applied fertilizers was not significant at this stage under both the systems.

Under aerobic system, the interaction of lime incorporated as per SMP buffer method with fertilizers based on soil test (F_2L_3) recorded the lowest Mn content in plant (88.48 mg kg^{-1}) followed by fertilizer as per POP (F_1L_3) with lime as per SMP buffer method (95.63 mg kg^{-1}). Under flooded system, lime as per SMP buffer method with fertilizers based on POP (F_1L_3) recorded lowest Mn content in plant (155.06 mg kg^{-1}).

Cultivation of rice under aerobic condition was significant in reducing plant Mn (146.89 mg kg^{-1}) than that under flooded condition (184.25 mg kg^{-1}). However, the Mn content decreased at panicle initiation than that at active tillering under both systems of rice cultivation.

Table 77. Effect of fertilizers and lime on Mn content ($mg\ kg^{-1}$) in straw at harvest

Fertilizer/Lime	L_1	L_2	L_3	Mean
Aerobic rice				
F_1	121.56	111.07	72.79	**101.81**
F_2	117.78	108.86	78.82	**101.82**
Mean	119.67	109.97	75.81	101.81
CD. F N S	CD L 11.66		CD FxL 16.48	
Flooded rice				
F_1	185.40	155.20	95.63	**145.41**
F_2	246.18	180.60	72.48	**166.42**
Mean	**215.79**	**167.90**	**84.05**	155.91
CD. F N S	CD L 14.93		CD F L 19.42	
C D pooled	15.98			

4.3.8.3 Mn at harvest in straw

The data presented in table 77 showed that lime applied as per SMP buffer method (L_3) recorded significantly the lowest Mn content, both under aerobic and flooded systems (75.81 $mg\ kg^{-1}$ and 84.05 $mg\ kg^{-1}$ respectively) followed by lime application as per ΔpH (L_2) (109.97 $mg\ kg^{-1}$under aerobic and 167.90 $mg\ kg^{-1}$ under flooded system).

Effect of applied fertilizers was not significant at this stage.

Under aerobic system, the interaction of lime as per SMP buffer method with fertilizers based on soil test (F_2L_3) recorded the lowest Mn content in plant (88.48 $mg\ kg^{-1}$) followed by fertilizer as per POP with lime (F_1L_3) (95.63 $mg\ kg^{-1}$). Under flooded system, lime as per SMP buffer method with fertilizers based on POP (F_1L_3) recorded lowest Mn content in plant (155.06 $mg\ kg^{-1}$).

The interaction of fertilizers added based on POP with lime as per SMP buffer method (F_1L_3) recorded the lowest (72.79 $mg\ kg^{-1}$ and 72.48 $mg\ kg^{-1}$ under aerobic and flooded condition) followed by fertilizer as per soil test with lime as per SMP buffer method (F_2L_3) among the interactions (78.82 $mg\ kg^{-1}$).

The Mn content in plant was significantly higher under flooded condition was significant (155.91 $mg\ kg^{-1}$) than aerobic rice (101.81mg kg^{-1}).

Table 78. Effect of fertilizers and lime on Mn content (mg kg^{-1}) in grain at harvest

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	Mean
F_1	102.83	92.84	53.81	**83.16**
F_2	98.80	89.88	59.84	**82.84**
Mean	**100.82**	**91.36**	**56.82**	**82.99**
CD. F N. S	**CD L 11.60**		**CD F x L N. S.**	
Flooded rice				
F_1	102.78	93.10	80.75	**92.18**
F_2	118.85	101.20	91.30	**103.78**
Mean	**110.78**	**97.15**	**86.03**	**97.98**
CD. F 3.68	**CD L 4.52**		**CD F x L 6.39**	
C D pooled 13.66				

4.3.8.4 Mn content in grain

The data presented in table 78 showed that, lime applied as per POP (L_1) recorded significantly highest Mn content in grain under aerobic (100.82 mg kg^{-1}) and flooded systems (110.78 mg kg^{-1}). This was followed by that in treatment with application of lime as per ΔpH (L_2) among the different doses of lime.

The effect of applied fertilizer was not significant under aerobic system. Under flooded system, fertilizer applied as per soil test recorded significantly higher Mn content in grain (103.78 mg kg^{-1}).

The treatment combination of fertilizers and lime as per POP (F_1L_1) recorded the highest Mn content under aerobic rice, while the treatment combination fertilizer as per soil test with lime as per POP (F_2L_1) recorded the highest under flooded system.

The highest Mn content was recorded under flooded system (97.98 mg kg^{-1}) than that in aerobic system (82.99 mg kg^{-1}).

4.3.9 Zinc content in plant

The data of influence of lime and fertilizers on Zn content in plant at different stages of sampling is detailed in tables from 79 to 82.

Table 79. Effect of fertilizers and lime on zinc content in plant (mg kg^{-1}) at active tillering

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	**Mean**
F_1	50.98	55.10	43.50	**49.86**
F_2	52.18	54.90	44.23	**50.43**
Mean	**51.58**	**55.00**	**43.86**	**50.15**
CD. F N. S	**CD L 0.20**		**CD F x L**	**N.S**
Flooded rice				
F_1	50.07	45.07	40.06	**45.07**
F_2	49.17	44.17	39.47	**44.27**
Mean	**49.62**	**44.62**	**39.77**	**44.67**
CD. F N. S	**CD L 4.75**		**CD F x L**	**N.S**
C D pooled 4.98				

4.3.9.1 Active tillering

Under aerobic system, lime applied as per ΔpH (L_2) significantly increased the zinc content in plant (55 mg kg^{-1}) followed by lime applied as per POP (L_1, 51.58 mg kg^{-1}). However, application of lime as per SMP buffer method (L_3) has reduced the Zn content (43.86 mg kg^{-1}) in comparison with the other treatments (table 79).

Under aerobic system, lime applied as per POP (L_1) recorded significantly the highest zinc content in plant (49.62 mg kg^{-1}) followed by lime applied as per POP (L_1 44.62 mg kg^{-1}) Application of lime as per SMP buffer method (L_3) had reduced the Zn content (39.77 mg kg^{-1}) significantly in comparison with the other lime treatments.

Applied lime, as well as their interaction with fertilizers was not significant at this stage. The aerobic system recoded significantly higher zinc content in plant at this stage, (50.15 mg kg^{-1}), than that of flooded system (44.67 mg kg^{-1}).

Table 80. Effect of fertilizers and lime on zinc content in plant (mg kg^{-1}) at panicle initiation

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	**Mean**
F_1	69.23	73.15	57.58	**66.65**
F_2	68.93	74.95	57.68	**67.18**
Mean	**69.08**	**74.05**	**57.63**	**66.92**
CD. F N.S.	**CD L 1.04**		**CD F x L N. S.**	
Flooded rice				
F_1	44.09	39.10	34.09	**39.10**
F_2	43.20	38.19	33.50	**38.30**
Mean	**43.65**	**38.65**	**33.80**	**38.70**
CD. F N. S	**CD L 3.68**		**CD F x L 5.39**	
C D pooled 10.21				

4.3.9.2 Panicle initiation

Under aerobic system, lime applied as per ΔpH (L_2) recorded significantly the highest zinc content in plant (74.05 mg kg^{-1}) followed by that in lime applied as per POP (L_1, 69.08 mg kg^{-1}). However, application of lime based on SMP buffer method (L_3) has reduced the Zn (57.63 mg kg^{-1}) (table 80). Application of fertilizers as well as their interaction with lime was not significant at this stage.

Under flooded system, lime as per POP (L_1) significantly increased the zinc content in plant (43.65 mg kg^{-1}) followed by lime applied as per ΔpH (38.65 mg kg^{-1}) Application of lime as per SMP buffer method (L3) decreased the Zn content (33.80 mg kg^{-1}) significantly in comparison with than that of other treatments.

Under flooded system, Interaction of fertilizers and lime applied as per POP (F_1L_1) recorded the highest zinc content (44.09 mg kg^{-1}) in plant at this stage.

Zn content in plant was significantly higher in aerobic system (66.92 mg kg^{-1}), than flooded system of rice cultivation was 38.70 mg kg^{-1}.

Table 81. Effect of fertilizers and lime on Zn (mg kg^{-1}) in straw at harvest

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	Mean
F_1	34.95	29.50	24.94	**29.80**
F_2	34.04	29.95	24.36	**29.45**
Mean	**34.50**	**29.73**	**24.65**	**29.62**
CD. F N. S.	**CD L 1.68**		**CD Fx L N. S.**	
Flooded rice				
F_1	26.93	28.48	22.38	**25.93**
F_2	26.83	29.15	22.40	**26.13**
Mean	**26.88**	**28.81**	**22.39**	**26.03**
CD. F N. S.	**CD L 1.41**		**CD F x L N. S.**	
C D pooled N S				

4.3.9.3 Zn in straw at harvest

The data (table 81) showed that, lime applied as per POP (L_1) significantly increased the zinc content in straw, both under aerobic (34.50 mg kg^{-1}) and flooded (26.88 mg kg^{-1}) followed by that in lime applied as per ΔpH (L_2) (29.73 mg kg^{-1} and 28.81 mg kg^{-1} respectively).

Interaction of fertilizers and lime applied as per POP (F_1L_1) recorded the highest zinc content under aerobic (34.95 mg kg^{-1}) and flooded systems (26.93 mg kg^{-1}) at this stage.

The flooded and aerobic system did not differ significantly with respect to zinc content in straw. However, the zinc content in straw decreased substantially under aerobic system at this stage in comparison with that of previous stages. Under flooded system, there was only a slight decrease in zinc in plant at harvest in comparison with that at previous stages of sampling.

Table 82. Effect of fertilizers and lime on Zn (mg kg^{-1}) in grain at harvest

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	Mean
F_1	6.49	6.59	6.69	6.59
F_2	8.24	8.66	9.03	8.64
Mean	7.37	7.63	7.86	7.62
CD. F 0.16	CD L 0.18		CD F x L N. S	
Flooded rice				
F_1	4.84	4.92	4.80	4.85
F_2	6.78	6.73	6.51	6.67
Mean	5.81	5.82	5.65	5.76
CD. F 0.14	CD L 0.078		CD F x L N. S.	
C D pooled 0.89				

4.3.9.4 Zinc content in grain

Under aerobic system, quantity of lime as per SMP buffer method (L_3) significantly increased the zinc content in grain (7.86 mg kg^{-1}) followed by lime applied as per ΔpH (L_2, 7.63 mg kg^{-1}) (table 82).Under flooded system, lime treatments, as per POP (L_1) and as per ΔpH (L_2) were on par with respect to Zn in grain (recorded 5.81 mg kg^{-1} and 5.82 mg kg^{-1} respectively). However, lime as per SMP buffer method (L_3) recorded the lowest Zn content in grain (5.65 mg kg^{-1}), which was significant.

The quantity of fertilizers applied as per soil test (F_2) did increase the Zn content in grain (8.64 mg kg^{-1} under aerobic system and 6.67 mg kg^{-1} under flooded system) significantly in comparison with that of fertilizer as per POP (F_1) (6.59 mg kg^{-1}).

Among the interactions, fertilizer as per soil test along with lime as per SMP buffer method (F_2L_3) recorded the highest Zn content in grain. But under flooded system, the treatment combination F_2L_1 recorded the highest Zn content in grain.

Aerobic system of rice cultivation found significant (7.62 mg kg^{-1}) in improving zinc content in grain.

4.3.10 Copper content in plant

The effect of lime and fertilizers on Cu content in plant at different stages of sampling is detailed in tables from 83 to 86.

Table 83. Effect of fertilizers and lime on copper content in plant (mg kg^{-1}) at active tillering

		Aerobic rice		
Fertilizer/Lime	L_1	L_2	L_3	**Mean**
F_1	2.82	2.91	2.96	**2.90**
F_2	3.25	3.34	3.99	**3.33**
Mean	*3.03*	*3.12*	*3.19*	**3.12**
CD. F 0.15	**CD L**	**0.18**	**CD F x L N S**	
		Flooded rice		
F_1	3.42	3.43	3.37	**3.40**
F_2	3.40	3.42	3.40	**3.40**
Mean	**3.41**	**3.43**	**3.38**	**3.40**
CD. F N S	**CD L 0.23**		**CD F x L N S**	
C D pooled 0.15				

4.3.10.1 Active tillering

The data (table 83) showed that under aerobic system, the quantity of lime as per SMP buffer method (L_3) recorded the highest copper content in plant (3.19 mg kg^{-1}) followed by lime applied based on ΔpH (L_2) (3.12 mg $kg^{-1}$and that in lime as per POP (L_1) in that order.

Under flooded system, lime applied as per SMP buffer method (L_3) recorded significantly lowest Cu content in plant (3.38 mg kg^{-1}) followed by application as per ΔpH (L_2) (3.43 mg kg^{-1}).

Under aerobic system, fertilizers applied as per soil test (F_2) recorded significant the higher and copper content in plant (3.33 mg kg^{-1}) in comparison with that in fertilizer as per POP (2.90 mg kg^{-1}). Effect of fertilizers was not significant under flooded system at this stage.

Under both systems, interaction of fertilizers applied with doses of lime was not significant with respect to copper content in plant.

Flooded system (3.40 mg kg^{-1}) recorded higher Cu content in plant (3.21 mg kg^{-1}) in comparison with that of Aerobic system

Table 84. Effect of fertilizers and lime on copper content in plant (mg kg^{-1}) at panicle initiation

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	**Mean**
F_1	2.40	2.33	2.30	**2.34**
F_2	2.33	2.30	2.30	**2.31**
Mean	**2.36**	**2.31**	**2.30**	**2.33**
CD. F N. S	**CD L N. S**		**CD F x L N. S**	
Flooded rice				
F_1	2.78	2.72	2.67	**2.72**
F_2	3.25	3.17	3.02	**3.14**
Mean	**3.01**	**2.94**	**2.85**	**2.93**
CD. F 0.15	**CD L 0.16**		**CD F x L N. S**	
C D pooled 0.24				

4.3.10.2 Panicle initiation

Effect of applied fertilizers, lime and their interactions were found not significant under aerobic system at this stage.

Under flooded system, lime as per POP (L_1) recorded significantly the highest copper content in plant (3.01 mg kg^{-1}) (table 84). The amount of lime applied based on ΔpH (L_2) was significantly higher in copper content in plant (2.94 mg kg^{-1}) than that of lime as per SMP buffer method (L_3). The quantity of fertilizers applied as per soil test (F_2) recorded significantly the higher Cu content in plant (3.14 mg kg^{-1}) in comparison with fertilizer applied as per POP (2.72 mg kg^{-1}). Among the interactions, fertilizers as per soil test with lime as per POP (F_2L_1) recorded significantly the highest Cu content at this stage.

Flooded system recorded significantly higher Cu content (2.93 mg kg^{-1}) in comparison with that of aerobic system (2.33mg kg^{-1}).

Table 85. Effect of fertilizers and lime on Cu (mg kg^{-1}) in straw at harvest

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	Mean
F_1	2.09	2.14	2.20	**2.14**
F_2	2.14	2.19	2.17	**2.17**
Mean	**2.12**	**2.17**	**2.19**	**2.16**
CD. F N. S	**CD L 0.05**		**CD F x L N. S**	
Flooded rice				
F_1	2.95	3.01	3.00	**2.99**
F_2	2.98	3.00	2.98	**2.99**
Mean	**2.97**	**3.01**	**2.99**	**2.99**
CD. F N S	**CD L N. S**		**CD F x L N. S.**	
C D pooled 0.21				

4.3.10.3 Cu at harvest in straw

Lime applied as per POP (L_1) significantly decreased the Cu content in straw (2.12 mg kg^{-1}), which was on par with that of lime applied as per ΔpH (L_2, 2.17 mg kg^{-1}). However, application of lime based on SMP buffer method (L_3) recorded highest Cu content in straw (2.19 mg kg^{-1}) (table 85).

Application of fertilizers, as well as their interaction with lime was not significant at this stage under both systems.

Aerobic system recorded significantly higher Cu content (2.93 mg kg^{-1}) than that of flooded system (2.33mg kg^{-1}) in straw.

Table 86. Effect of fertilizers and lime on Cu (mg kg^{-1}) in grain at harvest

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	Mean
F_1	2.80	2.85	2.91	**2.85**
F_2	3.15	3.30	3.38	**3.27**
Mean	2.98	3.07	3.14	**3.06**
CD. F 0.052	**CD L 0.064**		**CD F x L 0.090**	
Flooded rice				
F_1	2.30	2.36	2.35	**2.34**
F_2	2.33	2.35	2.33	**2.34**
Mean	2.32	2.36	2.34	**2.34**
CD. F N. S	**CD L N. S**		**CD FxL N S**	
C D pooled 0.66				

4.3.10.4 Cu in grain at harvest

The data presented in table 86 showed that, in aerobic system, lime applied as per SMP buffer method (L_3) recorded significantly the highest Cu content in grain (3.14 mg kg^{-1}) followed by that in application as per ΔpH (L_2) (3.07 mg kg^{-1}). Applied fertilizers as per soil test increased the Cu content in grain significantly. The interaction of fertilizers applied based on soil test with lime as per SMP buffer method (F_2L_3) recorded significantly the highest (3.38 mg kg^{-1}).

Under flooded system, the effect of application of fertilizers, lime as well as interaction of fertilizers applied with doses of lime was not significant in improving the copper content in grain.

Flooded system recorded significantly higher Cu content (5.07 mg kg^{-1}) in grain than that in aerobic system (4.35mg kg^{-1}).

4.3.11 Boron content in plant

The effect of treatments on boron content in plant is presented in tables from 87 to 90.

Table 87. Effect of fertilizers and lime on boron content in plant (mg kg^{-1}) at active tillering

		Aerobic rice		
Fertilizer/Lime	L_1	L_2	L_3	**Mean**
F_1	3.31	3.35	3.39	**3.35**
F_2	4.18	4.23	4.14	**4.18**
Mean	**3.75**	**3.79**	**3.77**	**3.77**
CD. F 0.01	**CD L 0.02**		**CD F x L 1.4**	
		Flooded rice		
F_1	3.42	3.52	3.62	**3.52**
F_2	5.17	5.59	5.96	**5.57**
Mean	**4.30**	**4.56**	**4.79**	**4.55**
CD. F 0.12	**CD L 0.014**		**CD F x L 0.24**	
C D pooled 0.38				

4.3.11.1 Active tillering

The data presented in the table 87 revealed that under aerobic system, the quantity of lime applied as per ΔpH (L_2) recorded significantly the highest boron content in plant (3.79 mg kg^{-1}), followed by lime as per SMP buffer method (L_3) (3.77 mg kg^{-1}).

Under flooded system, lime applied as per SMP buffer method (L_3) recorded the highest boron content in plant (4.79 mg kg^{-1}), followed by lime applied as per ΔpH (L_2) (4.56 mg kg^{-1}).

Under both the systems, fertilizers applied as per soil test (F_2) was significantly superior in increasing the boron content in plant (4.18 mg kg^{-1} and 5.57 mg kg^{-1} under aerobic and flooded systems respectively) than that of fertilizer as per POP.

Under aerobic system, the interaction of applied lime as per ΔpH with fertilizers based on soil test (F_2L_2) recorded the highest boron content (4.23mg kg^{-1}) followed by lime applied as per POP (F_2L_1) (4.18 mg kg^{-1}).

The boron content was the highest in treatment combination of applied lime as per SMP buffer method with quantity of fertilizers added based on soil test (F_2L_3) was highest (5.96 mg kg^{-1})which was followed by fertilizer as per soil test with lime applied as per ΔpH (F_2L_2) (4.56 mg kg^{-1}) under flooded system.

The boron content in plant found significantly higher in flooded rice (4.53 mg kg^{-1}) in comparison with aerobic rice (3.77 mg kg^{-1}) at active tillering stage.

Table 88. Effect of fertilizers and lime on boron content in plant (mg kg^{-1}) at panicle initiation

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	**Mean**
F_1	4.23	4.31	4.19	**4.24**
F_2	6.16	6.11	5.89	**6.06**
Mean	**5.20**	**5.21**	**5.04**	**5.15**
CD. F 0.04	**CD L 0.05**		**CD F x L 0.07**	
Flooded rice				
F_1	5.54	5.64	5.74	5.64
F_2	7.29	7.71	8.08	7.69
Mean	**6.42**	**6.68**	**6.91**	**6.67**
CD. F 0.69	**CD L 0.29**		**CD F x L 1.1**	
C D pooled 0.41				

4.3.11.2 Panicle initiation

The data presented in the table 88 revealed that, under aerobic system, lime applied as per ΔpH (L_2) recorded the highest boron content in plant (5.21mg kg^{-1}), which was on par with that of lime applied as per POP (L_1, 5.20 mg kg^{-1}). Lime applied as per SMP buffer method (L_3) recorded the lowest boron content (5.04 mg kg^{-1}) at this stage.

Under flooded system, lime applied as per SMP buffer method (L_3) recorded the highest boron content in plant (6.91mg kg^{-1}), followed by lime applied based on ΔpH (L_2) (6.68 mg kg^{-1}).

Under both the systems, fertilizers applied as per soil test (F_2) significantly enhanced the boron content in plant (6.06 mg kg^{-1} under aerobic and 7.69 mg kg^{-1} under flooded system) in comparison with that in fertilizer as per POP (4.24 mg kg^{-1} and 5.64 mg kg^{-1} under aerobic and flooded systems respectively).

Among the interactions under aerobic system, the combination of applied lime as per POP with fertilizers based on soil test (F_2L_1) recorded the highest B content (6.16 mg kg^{-1}) followed by lime applied as per ΔpH (F_2L_2) (6.11mg kg^{-1}).

Under flooded system, interaction of applied lime as per SMP buffer method with fertilizers based on soil test (F_2L_3) recorded significantly higher B content (8.08 mg kg^{-1}) than the other treatment combination.

The boron content in plant was found significantly higher in flooded rice (4.53 mg kg^{-1}) in comparison with aerobic rice (6.67 mg kg^{-1}). The boron content in plant did increase at panicle initiation than that at active tillering stage under both systems of rice cultivation.

Table 89. Effect of fertilizers and lime on boron content (mg kg^{-1}) in straw at harvest

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	Mean
F_1	3.60	3.68	3.56	3.61
F_2	5.53	5.48	5.26	5.43
Mean	4.57	4.58	4.41	4.52
CD. F 0.061	CD L 0.053		CD F x L 0.075	
Flooded rice				
F_1	7.64	7.74	7.84	7.74
F_2	9.37	9.81	10.18	9.78
Mean	8.50	8.77	9.01	8.76
CD. F 0.061	CD L 0.053		CD FxL 0.075	
C D pooled 1.21				

4.3.11.3 Boron content in straw at harvest

The data presented in the table 89 revealed that, lime applied as per ΔpH (L_2) was significantly superior in increasing boron content in straw (4.58mg kg^{-1}), which was on par with lime applied based on POP (L_1) (4.57 mg kg^{-1}) under aerobic system. Lime applied plots as per SMP buffer method (L_3) recorded the lowest B content in straw. Under flooded system, lime applied as per SMP buffer method (L_3) recorded the highest boron content in straw (9.01mg kg^{-1}), followed by lime as per ΔpH (L_2) (8.77 mg kg^{-1}); both were significantly different.

Under both the systems, fertilizers applied as per soil test (F_2) recorded significantly higher boron content in straw (5.43mg kg^{-1} under aerobic system and 9.78 mg kg^{-1} under flooded system) than that in fertilizer as per POP (3.61 mg kg^{-1} and 7.74 mg kg^{-1} under aerobic and flooded systems respectively).

Under aerobic system, interaction of applied lime as per POP with fertilizers as per soil test (F_2L_1), recorded the highest B content in straw (5.53 mg kg^{-1}) followed by fertilizer as per soil test with lime applied as per ΔpH (F_2L_2) (5.48 mg kg^{-1}).

The interaction of applied lime based on SMP buffer method with fertilizers based on soil test (F_2L_3) recorded the highest B content in straw (8.08 mg kg^{-1})

followed by fertilizer as per soil test with lime as per ΔpH (F_2L_2, 7.71 mg kg^{-1}) under flooded system.

The flooded system of rice cultivation showed significantly higher boron content in straw than that in aerobic rice.

Table 90. Effect of fertilizers and lime on boron content (mg kg^{-1}) in grain at harvest

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	**Mean**
F_1	4.84	4.92	4.80	**4.86**
F_2	6.78	6.73	6.51	6.67
Mean	**5.81**	**5.82**	**5.66**	5.76
CD. F 0.043	**CD L 0.053**		**CD F x L 0.075**	
Flooded rice				
F_1	6.49	6.59	6.69	6.59
F_2	8.24	8.66	9.03	8.64
Mean	7.37	7.63	7.86	7.62
CD. F 0.052	**CD L 0.065**		**CD F x L 0.072**	
C D pooled 0.87				

4.3.11.4 Boron content (mg kg^{-1}) in grain at harvest

The quantity of fertilizers applied as per soil test (F_2) was significantly superior in increasing the boron content in grain (6.67 mg kg^{-1} and 8.64 mg kg^{-1} under aerobic and flooded system respectively) in comparison with fertilizer applied as per POP (4.86 mg kg^{-1} and 6.59 mg kg^{-1} under aerobic and flooded system respectively). The data are presented in table 90.

Under aerobic system, the lime treatments as per ΔpH (L_2) was on par with lime applied based on POP (L_1), (5.82 mg kg^{-1} and 5.81 mg kg^{-1} respectively); both were superior than lime applied as per SMP buffer method (L_3) (5.66 mg kg^{-1}). Under flooded system, lime applied as per SMP buffer method (L_3) recorded the highest boron content in grain (7.86 mg kg^{-1}), followed by that in lime as per ΔpH (L_2) (7.63 mg kg^{-1}).

Under aerobic system, interaction of applied lime as per POP with fertilizers as per soil test (F_2L_1), recorded the highest B content in grain (6.78 mg kg^{-1}) followed by fertilizer as per soil test with lime as per ΔpH (F_2L_2) (6.73 mg kg^{-1}).

Under flooded system , the interaction of applied lime based on SMP buffer method with fertilizers based on soil test (F_2L_3) recorded the highest B content in grain (8.08 mg kg^{-1}) followed by fertilizer as per soil test with lime as per ΔpH (F_2L_2, 7.71 mg kg^{-1}).

The flooded system of rice cultivation showed significantly higher boron content in grain (9.03 mg kg^{-1}) than that under aerobic rice.

4.4 Distribution of fractions of phosphorus, correlations of P fractions with available P and P content in plant and path coefficients at different stages.

The distribution of different P fractions as percentage of total inorganic P, correlations of available P and P content in plant, as well as the path coefficients indicating the direct and indirect effects are presented hereunder.

4.4.1 P fractions expressed as percentage of total inorganic P

The distribution of different P fractions as percentage of total inorganic P, extracted at different stages is presented here under.

4.4.1.1 Percentage distribution of soluble P

The distribution of soluble P in different treatment combinations at different stages of sampling are presented in table 91.

Table 91. Percentage distribution of soluble P

Stages of sampling	Aerobic rice			Flooded rice		
	L_1	L_2	L_3	L_1	L_2	L_3
Initial	1.7	1.7	1.7	2.5	2.5	2.5
AT	3.9	4.8	4.5	5.7	6.4	9.5
PI	4.1	5.0	4.7	4.7	6.0	7.0
Harvest	6.2	7.1	6.8	3.8	4.9	5.7

Under aerobic cultivation, the soluble P fraction in the treatment with lime as per POP showed an increase from 1.7 % at in initial stage to 3.9 % at active tillering and to 4.1 % at panicle initiation and further to 6.2 at harvest (table 91).

In soils with lime applied as per ΔpH, the soluble P fraction increased to 4.8 % at active tillering, and to 5 % at panicle initiation. The soluble P fraction increased to 7.1 % at harvest of the crop. Same trend was observed in soils with lime treatment as per SMP buffer method, where the soluble P fraction showed an increase to 4.5 % at active tillering, 4.7 % to panicle initiation and to 6.8 % at harvest of the crop.

Under flooded system, in lime treatments as per ΔpH, the soluble P fraction increased from 2.5 % (initial) to 6.4 % at active tillering. The soluble P fraction was reduced to 6.0 % at panicle initiation and further to 4.9 % at harvest. Same trend was observed in soils with lime treatment as per SMP buffer method, where the soluble P fraction showed an increase to 9.5 % at active tillering and reduced to 7.0 % at panicle initiation and further to 5.7 % at harvest of the crop.

In general, under aerobic system, the soluble P fraction showed an increasing trend from initial stage to harvest with highest percentage increase in lime treatments as per ΔpH. Under flooded system, the soluble P fraction showed an increasing trend from initial to active tillering and then decreased till harvest of the crop. The highest distributions of soluble P at all stages were recorded in soils with lime treatment as per SMP buffer method.

4.4.1.2 Percentage distribution of Al-P

The distribution of Al-P in different treatment combinations at different stages of sampling are presented in table 92.

Table 92. Percentage distribution of Al-P

Stages of sampling	Aerobic rice			Flooded rice		
	L_1	L_2	L_3	L_1	L_2	L_3
Initial	11.7	11.7	11.7	12.5	12.5	12.5
AT	12.3	10.2	8.9	8.5	7.2	5.5
PI	11.8	9.3	8.1	10.6	10.0	8.7
Harvest	12.2	9.4	8.4	10.5	9.8	7.9

The Al- P fraction contributed 11.7 % initially, under aerobic system. The Al bound P fraction showed a slight increase to 12.3 % at active tillering and then reduced to 11.8% at panicle initiation in lime treatments as per POP. Al-P showed an increasing trend from panicle initiation to harvest (12.2 %) (Table 105). In lime applied treatments as per ΔpH, the percentage of Al-P decreased to 10.2 % at AT, and to 9.3 % at PI, remained almost similar at harvest (9.4 %). In the treatments where lime applied as per SMP buffer method, the distribution of Al bound P decreased to 8.9% at active tillering and to 8.1 % at panicle initiation. Further it increased to 8.4 % at harvest (table 92).

Under flooded system, the initial distribution of Al bound P was 12.5 %. The distribution of Al bound P had shown a decreasing trend in treatments where lime was applied as per POP at active tillering to 8.5 % and then it increased to 10.6 % at panicle initiation and recorded almost similar distribution (9.5 %) at harvest. In the lime treatments, as per ΔpH, the distribution of Al bound P decreased to 7.2 % at active tillering, increased to 10.0 % at panicle initiation and then slightly decreased to 9.8 % at harvest. Similar trends were recorded in lime treatments as per SMP buffer method, where the distribution of Al-P was reduced to 5.5 % at active tillering, then increased to 8.7% at panicle initiation and decreased to 7.9 % at harvest.

The Al bound P decreased from initial to active tillering and further it increased at panicle initiation and at harvest in comparison with that at active tillering under both the systems. The percentage distribution of Al bound P reduced at harvest in comparison with that of initial stage. The highest percentage reduction was recorded, recorded in lime applied treatments as per SMP buffer method under both systems.

4.4.1.3 Percentage distribution of Fe-P

The distribution of Fe-P in different treatment combinations at different stages of sampling are presented in table 93.

Table 93. Percentage distribution of Fe-P

Stages of sampling	Aerobic rice			Flooded rice		
	L_1	L_2	L_3	L_1	L_2	L_3
Initial	52.1	52.1	52.1	57.5	57.5	57.5
AT	45.4	43.1	39.6	58.1	56.2	50.4
PI	44.7	43.3	39.4	55.6	49.1	45.8
Harvest	42.8	41.9	38.5	54.9	50.2	46.9

Under aerobic system, percentage distribution of Fe bound P in the initial stage was 52.1 %. At active tillering, in the lime treatments as per POP, it decreased to 45.4 %, further to 44.7 % at panicle initiation and then to 42.8 % at harvest (Table 93). Similar decreasing trend was observed in lime treatments as per ΔpH also. At active tillering and panicle initiation, the distribution of Fe-P was 43.1 % and 43.3 % respectively. At harvest the distribution of Fe bound P was further reduced to 41.9 % under this treatment under aerobic system. In lime treatments as per SMP buffer method, the distribution of Fe bound P was decreased to 39.6 % at active tillering and to 39.4 % at panicle initiation and further to 38.5 % at harvest.

Under flooded system, the initial distribution of Fe bound P was 57.5 %. The distribution of Fe bound P had shown an increasing trend in treatments where lime was applied as per POP at active tillering to 58.1 % and then it decreased to 55.6 % at panicle initiation and further to 54.9 % at harvest of the crop. In the lime treatments, as per ΔpH, the distribution of Fe bound P decreased to 56.2 % at active tillering, and to 49.1 % at panicle initiation. At harvest of the crop, the Fe bound P showed an increasing trend to 50.2 % from that at PI. Similar trends were recorded in lime applied treatments as per SMP buffer method, where the distribution of Fe bound P was reduced to 50.4 % at active tillering, to 45.8 % at panicle initiation and then slightly increased to 46.9 % at harvest of the crop.

The Fe bound P showed a decreasing trend from initial to harvest of the crop under aerobic system and highest reduction in distribution was shown in treatments where lime applied as per SMP buffer method. Under flooded system, the same trend was observed in lime treatments as per POP. But in lime treatments as per ΔpH and SMP buffer method the distribution of Fe bound P decreased from initial stage till panicle initiation and then showed a slight increase at harvest of the crop and the highest reduction in percentage distribution was observed in treatments where lime applied as per SMP buffer method.

4.4.1.4 Percentage distribution of sesquioxide occluded P

The distribution of sesquioxide occluded P in different treatment combinations at different stages of sampling are presented in table 94.

Table 94. Percentage distribution of occluded P

Stages of sampling	Aerobic rice			Flooded rice		
	L_1	L_2	L_3	L_1	L_2	L_3
Initial	27.8	27.8	27.8	21.8	21.8	21.8
AT	28.3	29.6	30.8	18.9	19.5	18.5
PI	27.3	28.2	29.8	19.5	21.5	20.5
Harvest	25.6	26.9	27.7	18.1	19.1	18.7

Occluded P

Under aerobic system, percentage distribution of occluded P in the initial stage was 27.8 %. At active tillering, distribution of occluded P increased to 28.3 %, and then showed reduction to 27.3 % at panicle initiation and further to 25.6 % at harvest in lime treatments as per POP. Similar trends were observed in other two lime treatments also (table 94).

Under flooded condition, the distribution of occluded P showed a reduction from 21.8 % at initial stage to 18.9 % at active tillering in lime applied treatments as per POP and then an increased to 19.5 % at panicle initiation. It finally reduced to 18.1 %. Similar trends were observed in other two lime treatments.

In general, highest distribution of occluded P was observed in aerobic condition. Highest percentage of occluded P was observed in lime treated soils as per SMP buffer method under both system of rice cultivation.

4.4.1.5 Percentage distribution of Ca-P

The distribution of sesquioxide occluded P in different treatment combinations at different stages of sampling are presented in table 95.

Table 95. Percentage distribution of Ca-P

Stages of sampling	Aerobic rice			Flooded rice		
	L_1	L_2	L_3	L_1	L_2	L_3
Initial	6.6	6.6	6.6	5.7	5.7	5.7
AT	10.2	12.3	16.3	9.0	11.8	16.1
PI	12.1	14.2	18.1	9.6	14.5	18.0
Harvest	13.5	14.8	18.7	12.7	16.1	20.8

In aerobic system, the percentage distribution of Ca bound P at initial stage under aerobic rice was 6.6 %. The Ca bound P fraction of the soils with lime treated as per POP has shown an increasing trend from active tillering till harvest and recorded 10.2 %, 12.1 % and 13.5 % at active tillering, panicle initiation and harvest respectively (Table 95). In treatments where lime was applied based on ΔpH and SMP buffer method also showed the same trend but the percentage of increase was declined at panicle initiation and at harvest.

Under flooded condition, the initial distribution of Ca bound P was 5.7 %. The Ca bound P in lime treatments as per POP increased from 5.7 %, recorded almost same distribution of 9.0 % and 9.6 % at active tillering and panicle initiation respectively, increased further to 12.7 % at harvest of the crop. In the treatment where lime as per ΔpH, an increasing trend of Ca bound P was observed, and recorded 11.8 %, 14.5 % and 16.1 % at active tillering, panicle initiation and at harvest respectively. Lime application based on SMP buffer method increased the distribution of Ca bound P substantially in comparison with the other two lime treatments and recorded 16.1 % at active tillering, 18.0 % at panicle initiation and 20.8 % at harvest of the crop.

In general, under both systems, the Ca bound P has shown an increasing trend from initial to harvest of the crop. The highest increase in Ca bound P was observed in the treatments where lime was applied as per SMP buffer method, when compared with that of lime as per POP and ΔpH method.

4.4.2. Correlation coefficients and path coefficients of available P and plant P with different fractions of P under aerobic and flooded systems

The correlation coefficients and path coefficients of available P and plant P with different fractions of P under aerobic and flooded systems are presented hereunder.

4.4.2.1 Correlation coefficients of available P and plant P content with fractions of soil P at active tillering under aerobic system

Al-P (0.618**) and Fe-P (0.749**) were significantly and positively correlated with available P at active tillering. The sesquioxide occluded P (-0.449*) and Ca - P (-0.819**) were significantly and negatively correlated with available P. On the other hand P content in plant was significantly and positively correlated with sesquioxide occluded P (0.524**) and Ca - P (0.881**); and significantly negatively correlated with Al – P (-0.830**) and Fe – P (-0.881**).

4.4.2.1.1 Path coefficients of available P with fractions at active tillering under aerobic system

The path coefficients of available P with fractions at active tillering under aerobic system are presented in table 96.

Table 96. Path coefficients of available P with fractions at active tillering under aerobic system

Fractions	Al- P	Fe-P	Occluded P	Ca-P	Correlation coefficients
Al-P	**-1.652**	0.224	-0.085	2.131	0.618
Fe-P	-1.531	**0.242**	-0.089	2.128	0.749
Occluded P	1.098	-0.167	**0.123**	-1.591	-0.449
Ca- P	1.569	-0.229	0.087	**-2.245**	-0.819
(Values on diagonal are direct effects and values on horizontal lines are indirect effects)					

The direct effect of Al- P on available P was very high and negative (-1.652) as indicated by the path coefficient. The indirect effect of Al-P on available P through Ca-P was very high and positive (2.131) and through Fe-P was moderate (0.224) (table 96).

The direct effect of Fe-P on available P was moderate (0.242). The indirect effect of Fe-P on available P through Ca-P was very high and positive (2.128) and through Al - P was very high and negative (-1.531).

The direct effect of occluded P on available P was low (0.123). The indirect effect of occluded P on available P through Al-P was very high (1.098) and positive and through Ca - P was very high and negative (-1.591). The direct effect of Ca-P on available P was very high and negative (-2.245) and its indirect effect through Al-P was very high (1.569) and positive. The indirect effect of Ca- P on available P through Fe-P was moderate (-0.229) and negative.

4.4.2.1.2 Path coefficients of P content in plant with fractions at active tillering under aerobic system

The path coefficients of P content in plant with fractions at active tillering under aerobic system are presented in table 97.

Table 97. Path coefficients of P content in plant with fractions of P at active tillering under aerobic system

	Al P	Fe P	Occluded P	Ca P	Correlation coefficients
Al P	**0.179**	-0.540	0.114	-0.583	-0.830**
Fe P	0.166	**-0.583**	0.118	-0.582	-0.881**
Occluded P	-0.119	0.401	**-0.171**	0.413	0.524**
Ca P	-0.170	0.552	-0.115	**0.614**	0.881**
(Values on diagonal are direct effects and values on horizontal lines are indirect effects)					

The indirect effects of Al-P on P content in plant through Fe-P (-0.540) and through Ca-P (-0.583) were very high and negative (table 97).

The direct effect of Fe-P on P content in plant was high and negative (- 0.583) and its indirect effect through Ca-P was also high and negative (-0.582).

The indirect effects of occluded P through Fe-P and through Ca-P were very high. The direct effect of Ca-P on P content in plant was very high (0.614). The indirect effect of Ca-P through Fe-P was also high (0.552).

Significant negative correlation of Fe-P with Ca-P and its negative indirect effect through Ca-P indicate that the initially existing most dominant Fe-P was transferred to Ca-P, which in turn is absorbed by the plant.

4.4.2.2 Correlation coefficients available P and plant P content with fractions of soil P at panicle initiation under aerobic system

The Correlation coefficients of available P and plant P content with fractions of soil P at panicle initiation under aerobic system are presented hereunder

Al-P (0.579**), Fe-P (0.848**) and total P (0.492*) were significantly and positively correlated with available P at panicle initiation stage. The sesquioxide occluded P (-0.707**) and Ca-P (-0.809**) were significantly and negatively correlated with available P at this stage. P content in plant was significantly and positively correlated with Al- P (0.414*) and Fe-P (0.573*) and was significantly and negatively correlated with Ca - P (-0.592**).

4.4.2.2.1 Path coefficients of available P with fractions at panicle initiation under aerobic system

Path coefficients of available P with fractions of P at panicle initiation under aerobic rice are presented in table 98.

Table 98. Path coefficients of available P with fractions at panicle initiation

Fractions	Al -P	Fe- P	Occluded P	Ca - P	Total P	Correlation coefficients
Al - P	**-0.961**	0.454	-0.057	1.109	0.034	**0.579**
Fe - P	-0.832	**0.524**	-0.060	1.167	0.049	**0.848**
Occluded P	0.828	-0.481	**0.066**	-1.083	-0.036	**-0.707**
Ca P	0.891	-0.512	0.059	**-1.196**	-0.052	**-0.809**
Total P	-0.201	0.161	-0.015	0.384	**0.162**	**0.492**
(Values on diagonal are direct effects and values on horizontal lines are indirect effects)						

As revealed by the path analysis, the path coefficients of available P with fractions at panicle initiation (table 98) indicated that the direct effect of Al-P on available P was very high and negative (-0.961). The indirect effect of Al-P on available P through Ca-P was very high (1.109) and positive and through Fe-P was high (0.454) and positive.

The direct effect of Fe-P on available P was high (0.524). The indirect effect of Fe-P on available P through Ca-P was very high (1.167) and through Al-P was very high and negative (-0.832).

The indirect effect of occluded P on available P through Al-P was very high (0.828) and through Fe-P was very high and negative (-0.481). The indirect effect of occluded P on available P through Ca-P was very high and negative (-1.083).

The direct effect of Ca-P on available P was very high and negative (-1.196). The indirect effect of Ca-P on available P through Al-P was very high (0.891), and through Fe-P was high and negative (-0.512).

The indirect effect of total inorganic P on available P through Ca-P was high (0.384).

4.4.2.2.2 Path coefficients of P content in plant with fractions of P at panicle initiation under aerobic system

Path coefficients of P content in plant with fractions of P at panicle initiation under aerobic rice are presented in table 99.

Table 99. Path coefficients of P content in plant with fractions of P at panicle initiation

	Al-P	Fe-P	Ca-P	Correlation coefficients with plant P content
Al-P	**-1.282**	-0.999	2.695	0.414
Fe-P	-1.111	**-1.153**	2.837	0.573
Ca-P	1.189	1.126	**-2.907**	-0.592
(Values on diagonal are direct effects and values on horizontal lines are indirect effects)				

The data presented in table 99 indicated that the direct effect of Al-P on P content in plant was very high and negative (-1.282). The indirect effect of Al-P on P content in plant through Ca-P was very high (2.695) and positive and that through Fe-P was very high and negative (-0.999).

The direct effect of Fe-P (-1.153) as well as its indirect effect, through Al-P (-1.111) was very high and negative, while its indirect effect through Ca-P (2.837) was very high and positive. The direct effect of Ca-P on P content in plant was very high and negative (-2.907), while its indirect effects through Al-P (1.189) and Fe-P (1.126) were very high and positive.

4.4.2.3 Correlation coefficients available P, P content in straw and grain with fractions of soil P and path coefficients at harvest

The soluble P (0.570**), occluded P and Ca-P (0.901**) were significantly and positively correlated with available P at harvest.

The P content in straw was significantly and positively correlated with occluded P (0.843**) and Ca -P (0.941**) and was significantly and negatively correlated with Al-P (0.724**) and Fe-P (-0.880**).

P content in grain was significantly and positively correlated with occluded P (0.868**) and Ca-P (0.861**) and was significantly and negatively correlated with Al-P (-0.765**) and Fe-P (-0.914**).

4.4.2.3.1 Path coefficients of available P with fractions under aerobic rice

Path coefficients of available P with fractions of P at harvest under aerobic rice are presented in table 100.

Table 100. Path coefficients of available P with fractions of P at harvest

	Sol P	Al-P	Fe-P	Occluded P	Ca-P	Correlation coefficients
Sol P	**0.318**	0.052	0.114	0.052	0.139	0.567
Al-P	-0.229	**0.073**	-0.266	-0.090	-0.401	-0.914
Fe-P	-0.110	0.059	**-0.329**	-0.091	-0.441	-0.912
Occluded P	0.169	-0.067	0.307	**0.098**	0.436	0.942
Ca-P	0.039	-0.062	0.307	0.090	**0.471**	0.901

(Values on diagonal are direct effects and values on horizontal lines are indirect effects)

The path analysis of available P with fractions at harvest given in table 100 revealed that the direct effect of soluble P on available P was high (0.318). The indirect effects of soluble P on available P through Fe-P (0.114) and through Ca-P (0.139) were low.

The indirect effect of Al-P on available P through Ca-P was very high and negative (-0.401). The indirect effect of Al-P on available P through soluble P (-0.229) and Fe- P (-0.266) were negative and moderate.

The direct effect of Fe-P on available P was moderate (-0.329). The indirect effect of Fe-P on available P through Ca-P was high and negative (-0.441).

The indirect effect of occluded P on available P through Ca-P was very high and positive (0.436).

The direct effect of Ca-P on available P was very high (0.471). The indirect effect of Ca-P on available P through Fe-P was moderate (0.307).

4.4.2.3.2 Path coefficients of P content in straw with fractions under aerobic rice

Path coefficients of P content in straw with fractions of P at harvest under aerobic rice are presented in table 101.

Table 101. Path coefficients of P content in straw at harvest with fractions of P under aerobic system

Fractions	Al P	Fe P	Occluded P	Ca P	Correlation coefficients
Al P	**0.378**	0.052	-0.194	-0.960	-0.724
Fe P	0.306	**0.064**	-0.196	-1.055	-0.880
Occluded P	-0.349	-0.060	**0.210**	1.043	0.843
Ca P	-0.322	-0.060	0.194	**1.129**	0.941
(Values on diagonal are direct effects and values on horizontal lines are indirect effects)					

The direct effect of Al-P on P content in straw was high (0.378) and its indirect effect through Ca-P was very high and negative (-0.960) (Table 101). The indirect effect of Fe-P through Al-P (0.306) was high, and that through Ca-P was very high and negative (-1.055). The direct effect of occluded P (0.210) and its indirect effect through Al-P were moderate (-0.349), and through Ca-P was very high (1.043). The direct effect of Ca-P was very high (1.129) and its indirect effect through Al-P was high and negative (-0.322).

4.4.2.3.3 Path coefficients of P content in grain with fractions under aerobic rice

Path coefficients of P content in straw with fractions of P at harvest under aerobic rice are presented in table 102.

Table 102. Path coefficients of P content in grain with fractions of P

Fractions	Al- P	Fe - P	Occluded P	Ca - P	Correlation coefficients
Al - P	**-0.110**	0.144	0.265	0.015	-0.765**
Fe - P	0.079	**-0.200**	-0.619	0.025	-0.914**
Occluded P	0.038	-0.161	**-0.765**	-0.026	0.868**
Ca - P	-0.427	0.312	-0.214	**1.189**	0.861**
(Values on diagonal are direct effects and values on horizontal lines are indirect effects)					

The indirect effect of Al-P on P content in grain was moderate (table 102). The direct effect of Fe-P (-0.200) was also moderate while its indirect effect through occluded P was very high and negative (-0.619). The direct effect of Ca-P was very high (1.189) and its indirect effect through Al-P was high and negative.

4.4.2.4. Correlation coefficients of available P, fractions of soil P and P content in plant at active tillering under flooded system

Correlation coefficients of available P, fractions of soil P and P content in plant at different stages under flooded system at active tillering showed that the available P was significantly and positively correlated with Ca-P (0.923**) while it was significantly and negatively correlated with Al-P (-0.792**), Fe-P (-0.716**) and sesquioxide occluded P (-0.449*).

P content in plant at active tillering was significantly and positively correlated only with total P (0.862**). Hence path analysis was not done.

4.4.2.4.1 Path coefficients of available P with fractions

Path coefficients of available P with fractions of P at active tillering under flooded system are presented in table 103.

Table 103. Path coefficients of available P with fractions at active tillering under flooded system

	Al-P	Fe-P	Occluded P	Ca-P	Total P	Correlation coefficients
Al-P	**0.397**	-0.075	0.331	-0.569	-0.214	-0.792**
Fe-P	0.258	**-0.115**	-0.260	-0.432	-0.167	-0.716**
Occluded P	0.312	-0.071	**-0.420**	0.568	-0.170	-0.917**
Ca-P	-0.370	0.081	-0.391	**0.611**	0.209	0.923**
Total P	0.252	-0.057	-0.212	-0.381	**-0.380**	-0.336*
(Values on diagonal are direct effects and values on horizontal lines are indirect effects)						

The direct effect of Al-P on available P was high (0.397), while its indirect effect through Ca-P was very high and negative and through occluded P was high and positive (0.331) (Table 103).

The indirect effects of Fe-P through Al-P (0.258) and occluded P (-0.260) were moderate while that through Ca-P was very high and negative (-0.432).

The direct effect of occluded P on available P was very high (-0.420); its indirect effect through Al-P was high (0.312), and that through Ca-P was very high (0.568). The direct effect of Ca-P on available P was very high (0.611) and positive, while indirect effects through Al-P (-0.370) and that through occluded P (-0.391) were very high and negative.

4.4.2.5 Correlation coefficients of available P, fractions of soil P and P content in plant at panicle initiation under flooded system

Available P was significantly and positively correlated with Al-P (0.422*), Fe-P (0.544**), occluded P (0.509*) and total P (0.892**); was significantly and negatively correlated with soluble P (-0.611**) and Ca-P (-0.592**). The plant P content was significantly and positively correlated only with total P (0.828**).

4.4.2.5.1 Path coefficients of available P with fractions at panicle initiation

Path coefficients of available P with fractions of P at panicle initiation under flooded system are presented in table 104.

Table 104. Path coefficients of available P with fractions at panicle initiation under flooded system

Fractions	Sol-P	Al-P	Fe-P	Occluded P	Ca-P	Total P	Correlation
Sol -P	**-2.580**	3.504	0.587	-0.884	-1.201	-0.037	**-0.611******
Al -P	2.489	**-3.633**	-0.593	0.916	1.219	0.0239	**0.422***
Fe- P	2.469	-3.509	**-0.614**	0.944	1.220	0.033	**0.544****
Occluded P	2.354	-3.436	-0.598	**0.969**	1.192	0.028	**0.509***
Ca -P	-2.507	3.585	0.606	-0.934	**-1.236**	-0.031	**-0.517****
Total P	1.455	-1.312	-0.302	0.415	0.572	**0.066**	**0.892****

(Values on diagonal are direct effects and values on horizontal lines are indirect effects)

The direct effect of sol-P (-2.58) as well as its indirect effect through Ca-P (-1.201) on available P was very high and negative. The indirect effects of sol-P on available P through Al-P (3.504), Fe-P (0.587) and occluded P (-0.884) was also very high (Table 103).

The direct effect of Al-P on available P was very high and negative (-3.633) and its indirect effects through Sol-P (2.489), Ca-P (1.219) and occluded P (0.916) were very high and positive while that through Fe-P (-0.593) was very high and negative.

The direct effect of Fe-P on available P was very high and negative (-0.614) where as its indirect effects through Sol-P (2.469) and Ca-P (1.220) and occluded P (0.944) were very high and positive; the indirect effects of Fe-P on available P through Al-P (-3.509) was very high and negative.

The direct effect of occluded P on available P was high (0.969) while its indirect effects through sol-P (2.354) and Ca-P (1.192) were very high and positive. The indirect effects through Al-P (-3.436) and through Fe-P (-0.598) were very high and negative.

The direct effect of Ca-P on available P was very high and negative (-1.236). The indirect effect of Ca-P on available P through Al-P (-2.507) and occluded P (-0.934) were very high and negative, while that through Fe-P (3.585) was very high and positive.

4.4.2.6 Correlation coefficients of available P, fractions of soil P and P content in straw and grain at harvest under flooded system

Correlation coefficients of available P and P content in straw and grain with fractions of P at harvest under flooded system are presented here under. Available P was significantly and positively correlated with Al-P (0.600**), Fe-P (0.445*), occluded P (0.540**) and total P (0.828**); was significantly and negatively correlated with soluble P (-0.585**) and Ca-P (-0.495*).

P content in straw was significantly and positively correlated with Al-P (0.511*), occluded P (0.449*) and total P (0.657**) and was significantly and negatively correlated with soluble P (-0.480*) and Ca-P (-0.453*). P content in grain was significantly and positively correlated with Al-P (0.542**), occluded P (0.446*) and total P (0.848**) and was significantly and negatively correlated with soluble P (-0.556*) and Ca-P (-0.448*).

4.4.2.6.1 Path coefficients of available P with fractions at harvest

Path coefficients of available P with fractions of P at harvest under flooded system are presented in table 104.

Table 105. Path coefficients of available P with fractions at harvest under flooded system

Fraction	Sol-P	Al-P	Fe-P	Occluded P	Ca-P	Total P	Correlation coefficients
Sol-P	**-1.789**	-0.328	0.182	-0.518	2.112	-0.244	-0.585**
Al-P	1.721	**0.341**	-0.183	0.544	-2.120	0.298	0.600**
Fe-P	1.728	0.331	**-0.189**	0.533	-2.152	0.194	0.445*
Occluded P	1.626	0.325	-0.176	**0.570**	-2.044	0.239	0.540**
Ca-P	-1.747	-0.334	0.188	-0.539	**2.163**	-0.226	-0.495*
Total P	0.776	0.180	-0.065	0.242	-0.868	**0.562**	0.828**
(Values on diagonal are direct effects and values on horizontal lines are indirect effects)							

The direct effect of Sol-P on available P was very high (-1.789) and negative. The indirect effect of Sol-P on available P through Ca-P was very high and positive (2.112) while the indirect effect through Al-P (-0.328), and occluded P (-0.518) were very high and negative (table 105).

The direct effect of Al-P on available P was high (0.341). The indirect effects of Al-P on available P through sol-P (1.721) and occluded P (0.544) were very high and positive while that through Ca-P (-2.120) was very high and negative.

The indirect effects of Fe-P on available P through Sol-P (1.728) and occluded P (0.533) were very high and positive, through Al-P was moderate (0.331) and through Ca-P was very high and negative (-2.152).

The direct effect of occluded P on available P was high (0.570). The indirect effect of occluded P on available P through sol-P (1.626) was very high and positive, through Al-P (0.325) was high and through Ca-P was very high and negative (-2.044).

The direct effect of Ca-P on available P was high (2.163). The indirect effect of Ca-P on available P through sol-P (-1.747), Al-P (-0.334) and occluded P (-0.539) were very high and negative.

4.4.6.2.2 Path coefficients of P content in straw with fractions at harvest

Path coefficients of P content in straw with fractions of P at harvest under flooded system are presented in table 106.

Table 106. Path coefficients of P content in straw with fractions at harvest under flooded system

Fractions	Sol-P	Al-P	Occluded P	Ca -P	Total P	Correlation coefficients
Sol-P	**-0.326**	0.698	-0.128	-0.437	-0.287	-0.480*
Al-P	0.314	**-0.726**	0.134	0.439	0.349	0.511**
Occluded P	0.296	-0.692	**0.141**	0.423	0.281	0.449*
Ca-P	-0.318	0.711	-0.133	**-0.448**	-0.265	-0.453*
Total P	0.142	-0.384	0.056	0.178	**0.660**	0.657**
(Values on diagonal are direct effects and values on horizontal lines are indirect effects)						

The data in table 106, indicated that, the direct effect of Sol-P on plant P content was high (-0.326) and negative. The indirect effects of Sol-P on plant P through Ca-P were high and negative (-0.437) while that through Al-P was very high (0.698) and positive.

The direct effect of Al-P on plant P content was very high and negative (-0.726). The indirect effects of Al-P on plant P content through Sol-P (0.314) and Ca-P (0.439) were high and positive.

The indirect effects of occluded P on plant P content through sol-P and total P were moderate, and through Al-P (-0.692) was very high and negative. The indirect effect of occluded P on plant P content through Ca-P was high (0.423) and positive.

The direct effect of Ca-P on plant P content was high (-0.448) and negative. The indirect effect of Ca-P on pant P content through Al-P (0.711) was very high.

4.4.6.2.3 Path coefficients of P content in grain

Path coefficients of P content in grain with fractions at harvest under flooded system are presented in table 107.

Table 107. Path coefficients of P content in grain with fractions at harvest

	Sol P	Al P	Occluded P	Ca P	Total P	Correlation coefficients
Sol P	**-1.984**	0.349	-0.223	1.624	-0.322	-0.556
Al P	1.909	**-0.363**	0.234	-1.630	0.392	0.542
Occluded P	1.803	-0.346	**0.246**	-1.572	0.315	0.446
Ca P	-1.937	0.356	-0.232	**1.663**	-0.298	-0.448
Total P	0.861	-0.192	0.104	-0.667	**0.741**	0.848
(Values on diagonal are direct effects and values on horizontal lines are indirect effects)						

The direct and indirect effects of soluble P on P content in grain were very high and negative (-1.984) (table 107). The indirect effects of sol-P through Ca-P were very high and positive (1.624). The direct effect of Al bound P on P content in grain were high and negative (-0.363) while its indirect effects through sol-P (1.909) and through Ca-P (-1.630) were very high. The direct effects of occluded P were moderate (0.246) while its indirect effects through sol-P (1.803) and through Ca-P (-1.572) were very high. The direct effect of Ca bound P was very high and positive (1.663) while its indirect effect through sol-P (-1.937) was very high and negative.

4.5 Distribution of fractions of iron, correlations of Fe fractions with available Fe and Fe content in plant and path coefficients at different stages.

The distribution of different Fe fractions as percentage of total Fe, correlations of available Fe and Fe content in plant, as well as the path coefficients indicating the direct and indirect effects are presented hereunder.

4.5.1 Distribution of Fe fractions expressed as percentage of total Fe in soil

The data on Fe fractions expressed as percentage of total Fe in soil under aerobic and flooded systems of rice cultivation are presented in tables from 108 to 115. The following was the dominance of different fractions under aerobic and flooded systems initially.

Aerobic system

Residual (62.05 %) > crystalline Fe oxide occluded Fe (33.85 %) > OM occluded Fe (2.18 %) > MnO occluded Fe (0.91 %) > Water soluble + exchangeable Fe (0.57 %) > Amorphous Fe oxide occluded (0.403 %) > specifically adsorbed Fe (0.02) > acid soluble Fe (0.009 %).

Flooded system

Residual (57.64 %) > crystalline Fe oxide occluded Fe (36.71 %) > OM occluded Fe (2.52 %) > water soluble + exchangeable Fe (1.23 %) > Amorphous Fe oxide occluded (1.06 %) > MnO occluded Fe (0.84 %) > acid soluble Fe (0.0052 %) > specifically adsorbed Fe (0.005 %).

4.5.1.1 Water soluble + exchangeable Fe

Distribution of water soluble + exchangeable Fe under aerobic and flooded systems is given in table 108.

Table 108. Distribution of water soluble + exchangeable Fe expressed as percentage of total Fe in soil

Stages of sampling	Aerobic rice			Flooded rice		
	L_1	L_2	L_3	L_1	L_2	L_3
Initial	0.57	0.57	0.57	1.23	1.23	1.23
AT	0.59	0.58	0.53	1.40	1.36	1.14
PI	1.24	1.16	0.96	1.24	1.16	0.96
Harvest	0.98	0.97	0.82	0.98	0.97	0.82

The water soluble + exchangeable Fe fraction of the soils, in treatments with lime as per POP, increased to 0.59 % at active tillering and then to 1.24 % at panicle initiation and further reduced to 0.98 % at harvest.

In treatment of lime applied as per ΔpH, the water soluble + exchangeable Fe fraction increased to 0.58 % at active tillering, to 1.16 % at panicle initiation, and then reduced to 0.97 % at harvest of the crop. When lime was applied as per SMP buffer method, the water soluble + exchangeable Fe fraction showed a decrease to 0.53 % at active tillering, and then increased to 0.96 % at panicle initiation. At harvest of the crop, water soluble + exchangeable Fe recorded 0.82 %. Thus, lowest distribution of water soluble + exchangeable Fe was in the soils where dose of lime was applied as per SMP buffer method, under aerobic rice cultivation.

In flooded system, water soluble + exchangeable Fe fraction in treatment with lime as per POP showed an increase to 1.40 % at active tillering, then reduced to 1.24 % at panicle initiation. The water soluble + exchangeable Fe fraction further decreased to 0.98 % at harvest.

In lime applied treatments as per ΔpH, the water soluble + exchangeable Fe fraction increased to 1.36 % at active tillering, reduced to 1.16 % at panicle initiation, and further to 0.97 % at harvest of the crop. When lime was applied as per SMP buffer method, the water soluble + exchangeable Fe fraction steadily decreased to 1.14 % at active tillering, to 0.96 % to panicle initiation and further to 0.82 % at harvest of the crop.

In general, under aerobic rice cultivation system, the water soluble + exchangeable Fe fraction showed an increasing trend from initial stage to panicle initiation with highest percentage increase in lime treatments as per POP method and further reduced at harvest. Under flooded rice cultivation, the water soluble + exchangeable Fe fraction showed an increasing trend from initial to active tillering and then decreased till harvest of the crop in lime treatments as per POP and ΔpH, whereas in lime treatments as per SMP buffer method, this fraction showed a decreasing trend from initial stage till harvest of the crop.

4.5.1.2 Specifically adsorbed Fe

The distribution of specifically adsorbed Fe under aerobic and flooded systems is presented in table 109.

Table109. Distribution of specifically adsorbed Fe expressed as percentage of total Fe in soil

Stages of sampling	Aerobic rice			Flooded rice		
	L_1	L_2	L_3	L_1	L_2	L_3
Initial	0.02	0.02	0.02	0.005	0.005	0.005
AT	0.02	0.03	0.02	0.02	0.01	0.01
PI	0.03	0.02	0.02	0.02	0.02	0.01
Harvest	0.03	0.02	0.02	0.03	0.03	0.02

Under aerobic cultivation, the specifically adsorbed Fe fraction of the treatments applied with lime as per POP recorded same distribution as that at initial stage (0.02 %) at active tillering and then slightly increased to 0.03 % at panicle initiation and recorded same value of 0.03 % at harvest. In treatments where lime was applied as per ΔpH, the specifically adsorbed Fe fraction increased from 0.02 % at initial stage to 0.03 % at active tillering and then decreased to 0.02 % at panicle initiation and recorded same percentage at harvest. In lime treatments as per SMP buffer method, the percentage of specifically adsorbed Fe fraction remained constant throughout the stages of sampling at 0.02 %.

Under flooded system of rice cultivation, the specifically adsorbed Fe fraction in treatments applied with lime as per POP, showed an increase from 0.005 at initial stage to 0.02 % at active tillering and panicle initiation and then showed a slight increase to 0.03 % at harvest. In treatment with lime as per ΔpH, the specifically adsorbed Fe fraction steadily increased from 0.005 to 0.01 % at AT, 0.02 % at PI and to 0.03 % at harvest. In lime treated soils as per SMP buffer method, this fraction showed an increase to 0.01 % at active tillering and panicle initiation and further increased to 0.02 % at harvest of the crop.

In general, under both systems of rice cultivation, the specifically adsorbed Fe fraction did not show much variation when compared to that at initial stage.

4.5.1.3 Acid soluble Fe

The distribution of acid soluble Fe under aerobic and flooded systems is presented in table 110.

Table 110. Distribution of acid soluble Fe expressed as percentage of total Fe

Stages of sampling	Aerobic rice			Flooded rice		
	L_1	L_2	L_3	L_1	L_2	L_3
Initial	0.01	0.01	0.01	0.11	0.11	0.11
AT	0.15	0.12	0.16	0.08	0.11	0.04
PI	0.17	0.16	0.10	0.06	0.12	0.08
Harvest	0.17	0.07	0.05	0.11	0.11	0.05

Under aerobic system in treatment with lime as per POP, the acid soluble Fe fraction of the soils showed an increase from the initial value (0.01 %) to 0.15 % at active tillering and to 0.17 % panicle initiation and at harvest. In lime treatments as per ΔpH, the acid soluble Fe fraction increased to 0.12 % at active tillering, further increased to 0.16 % at panicle initiation and then decreased to 0.07 % at harvest. In lime treated soils as per SMP buffer method, the acid soluble Fe increased to 0.16 % at active tillering, then decreased to 0.10 % at panicle initiation and further decreased to 0.05 % at harvest of the crop.

Under flooded system, with lime applied as per POP, the acid soluble Fe fraction decreased to 0.08 % at active tillering and to 0.06 % at panicle initiation and was 0.11 % at harvest. In lime applied treatments as per ΔpH, the percentage contribution of acid soluble Fe fraction remained almost unaltered. In lime treated soils as per SMP buffer method, the acid soluble Fe fraction reduced to 0.04 % at active tillering and then increased to 0.08 % at panicle initiation and finally to 0.05 % at harvest.

4.5.1.4 Manganese oxide occluded Fe

The distribution of manganese oxide occluded Fe under aerobic and flooded systems is presented in table 111.

Table 111. Distribution of manganese oxide occluded Fe expressed as percentage of total Fe in soil

Stages of sampling	Aerobic rice			Flooded rice		
	L_1	L_2	L_3	L_1	L_2	L_3
Initial	0.91	0.91	0.91	0.84	0.84	0.84
AT	0.92	0.90	0.80	1.27	1.18	0.85
PI	0.89	0.88	0.79	1.15	1.07	0.54
Harvest	0.69	0.63	0.50	0.97	0.94	0.54

Under aerobic system, in treatment with lime as per POP, the manganese oxide occluded Fe fraction almost remained the same upto PI stage and then reduced to 0.69 % at harvest. Tend in treatment with lime as per ΔpH, however when lime was applied as per SMP buffer method Mn oxide occluded fraction decreased from 0.91 (initial value) to 0.50 % at harvest.

In flooded system, the lime treatment as per POP and ΔpH showed an increase in this fraction till panicle initiation stage, then a slight decrease was observed but the percentage contribution was still higher than initial value; however this fraction decreased from 0.84 % to 0.54 % at harvest.

4.5.1.5 Organic matter bound Fe

The distribution of organic matter bound Fe under aerobic and flooded systems expressed as percentage of total Fe in soil is presented in table 112.

Table 112. Distribution of Organic matter bound Fe

Stages of sampling	Aerobic rice			Flooded rice		
	L_1	L_2	L_3	L_1	L_2	L_3
Initial	2.18	2.18	2.18	2.52	2.52	2.52
AT	1.89	2.04	1.38	3.71	3.34	2.93
PI	1.90	1.93	1.64	3.20	2.24	2.08
Harvest	1.59	2.06	1.64	2.81	1.79	1.49

Under aerobic system, the organic matter bound fraction of Fe in soils applied with lime as per POP decreased from an initial value of 2.18 % to 1.59 % at harvest. Similar trends were observed when lime was applied as per ΔpH. In lime treated soils as per SMP buffer method, this fraction reduced to 1.38 % at active tillering and then increased to 1.64 % at panicle initiation and at harvest. However, highest reduction in distribution of organic matter bound Fe was recorded in the dose of lime as per SMP buffer method under aerobic rice cultivation.

Under flooded system, with lime as per POP, the organic matter bound fraction showed an increase to 3.71 % at active tillering and then decreased to 3.20 % panicle initiation. It further reduced to 2.81 % at harvest. In lime applied soils as per ΔpH, this fraction increased to 3.34 % at active tillering, decreased to 2.24 % at panicle initiation and to 1.79 % at harvest. Same trend was observed in soils with lime treated soils as per SMP buffer method, where the organic matter bound fraction showed an increase to 2.93 % at active tillering and then decreased to 2.09 % at panicle initiation and to 1.49 % at harvest of the crop.

4.5.1.6 Amorphous Fe oxide occluded Fe

The distribution of Amorphous Fe oxide occluded Fe under aerobic and flooded systems expressed as percentage of total Fe in soil is presented in table 113.

Table 113. Distribution of Amorphous Fe oxide occluded Fe

Stages of sampling	Aerobic rice			Flooded rice		
	L_1	L_2	L_3	L_1	L_2	L_3
Initial	0.40	0.40	0.40	1.06	1.06	1.06
AT	1.37	1.66	2.06	1.28	1.78	3.36
PI	1.39	1.67	2.77	2.36	3.67	5.91
Harvest	1.69	1.50	2.66	3.91	2.72	4.62

Under aerobic system, with lime as per POP, the amorphous Fe oxide occluded Fe fraction of the soils increased from 0.40 % to 1.37 % at active tillering, to 1.39 % at panicle initiation and further to 1.69 % at harvest. When lime was applied as per ΔpH, the amorphous Fe oxide occluded Fe fraction increased to 1.66 % at active tillering to 1.67 % at panicle initiation and then reduced to 1.17 % at harvest. In lime treatment as per SMP buffer method, this fraction increased from 0.40 % at initial stage to 2.06 % at active tillering and then to 2.77 % at panicle initiation and then decreased to 2.66 % at harvest. The highest increase in distribution of amorphous Fe oxide occluded Fe was recorded in the dose of lime as per SMP buffer method under aerobic rice cultivation.

Under flooded system with lime as per POP, the amorphous Fe oxide occluded Fe fraction showed an increase to 1.28 % at active tillering from 1.06 % at initial stage and further increased to 2.36 % at panicle initiation and then to 3.91 % at harvest of the crop. In treatment of lime as per ΔpH, the amorphous Fe oxide occluded Fe fraction showed an increase to 1.78 % at active tillering to 3.67 % at panicle initiation and then decreased to 2.72 % at harvest. Same trend was observed in lime treatment as per SMP buffer method, where the amorphous Fe oxide occluded Fe fraction recorded 3.36 % at active tillering, 5.61 % at panicle initiation and 4.62 % at harvest of the crop.

In general, under both systems of rice cultivation, the amorphous Fe oxide occluded Fe fraction showed an increasing trend from initial stage to panicle initiation and then decreased harvest of the crop.

4.5.1.6 Crystalline Fe oxide occluded Fe

The distribution of crystalline Fe oxide occluded Fe under aerobic and flooded systems expressed as percentage of total Fe in soil is presented in table 114.

Table 114. Distribution of crystalline Fe oxide occluded Fe

Stages of sampling	Aerobic rice			Flooded rice		
	L_1	L_2	L_3	L_1	L_2	L_3
Initial	33.85	33.85	33.85	36.71	36.71	36.71
AT	36.68	37.20	37.45	36.37	37.16	38.54
PI	36.76	37.29	37.53	36.76	37.58	38.97
Harvest	36.87	37.49	37.62	36.92	37.74	39.14

Under aerobic cultivation, with lime as per POP, the crystalline Fe oxide occluded Fe fraction increased from 33.85 % (initial) to 36.68 % at active tillering and then to 36.76 % at panicle initiation, and further to 36.87 % at harvest. In lime treatments as per ΔpH, the crystalline Fe oxide occluded Fe fraction increased to 37.20 % at active tillering and then to 37.29 % at panicle initiation and further increased to 37.49 % at harvest. When lime was applied as per SMP buffer method, the crystalline Fe oxide occluded Fe fraction increased to 37.45 % at active tillering, 37.53 % at panicle initiation and then to 37.62 % at harvest of the crop.

Under flooded system, with lime as per POP, the crystalline Fe oxide occluded Fe fraction of the soils recorded 36.37 % at active tillering, 36.76 % at panicle initiation and 36.92 % at harvest. In lime treatment as per ΔpH, the crystalline Fe oxide occluded Fe fraction recorded 37.16 % at active tillering, 37.58 % at panicle initiation and 37.74 % at harvest. In lime treatment as per SMP buffer method, this fraction increased to 38.54 % at active tillering and then to 38.97 % at panicle initiation and to 39.14 % at harvest of the crop.

In general, under both systems of rice cultivation, the crystalline Fe oxide occluded Fe fraction showed a sharp increase from initial value to active tillering and then remained almost constant.

4.5.1.7 Residual Fe

The distribution of residual Fe oxide occluded Fe under aerobic and flooded systems expressed as percentage of total Fe in soil is presented in table 115.

Table 115. Distribution of Residual Fe

Stages of sampling	Aerobic rice			Flooded rice		
	L_1	L_2	L_3	L_1	L_2	L_3
Initial	62.05	62.05	62.05	57.64	57.64	57.64
AT	57.69	57.48	58.27	58.49	57.72	56.33
PI	56.58	57.46	58.05	54.75	54.16	53.59
Harvest	60.06	58.92	59.56	55.32	56.08	55.91

Under aerobic environment with lime as per POP, the residual Fe fraction decreased from 62.05 % at initial stage to 57.69 % at active tillering and further to 56.58 % at panicle initiation and then increased to 60.06 % at harvest. In lime treatment as per ΔpH, the residual Fe fraction decreased to 57.48 % at active tillering and further to 57.46 % at panicle initiation and then increased to 58.92 % at harvest. In lime treated soils as per SMP buffer method, the residual Fe fraction decreased to 58.27 % at active tillering and to 58.05 % at panicle initiation and then increased to 59.56 % at harvest of the crop.

Under flooded system with lime as per POP, the residual Fe fraction showed a slight increase to 58.49 % at active tillering and then decreased at panicle initiation to 54.75 % . The contribution of residual Fe fraction at harvest of the crop was 55.32 %. In lime as per ΔpH, the residual Fe fraction showed a slight increase to 57.72 % at active tillering and then decreased to 54.16 % at panicle initiation. The contribution of residual Fe fraction at harvest of the crop was 56.08 %. In lime treatment as per SMP buffer method, the residual Fe fraction decreased to 56.33 % at active tillering and then to 53.59 % at panicle initiation and finally increased to 55.91 % at harvest of the crop.

In general, under both systems of rice cultivation, distribution of residual Fe fraction found decreased from that at initial stage to harvest of the crop.

4.5.2. Correlation coefficients and path coefficients of available Fe and plant Fe with different fractions of Fe under aerobic and flooded systems

The correlation coefficients and path coefficients of available Fe and plant Fe with different fractions of Fe under aerobic and flooded systems are presented hereunder.

4.5.2.1. Correlation coefficients of available Fe and Fe content in plant with fractions of Fe at active tillering of aerobic rice cultivation at active tillering

Available Fe had positive significant correlations with water soluble + exchangeable Fe (0.889*), specifically adsorbed Fe (0.518**), MnO-Fe (0.904**), OM Fe (0.656**), and amorphous Fe oxide occluded Fe (0.834**).

Fe content in plant was positively and significantly correlated with water soluble + exchangeable Fe (0.856*), MnO-Fe (0.876**), OM-Fe (0.656**), and amorphous Fe oxide occluded Fe (0.834**).

4.5.2.1.1 Path coefficients of available Fe with fractions of Fe at active tillering

Path coefficients of available Fe with fractions of Fe at active tillering under aerobic system are presented in table 116.

Table 116. Path coefficients of available Fe with fractions of Fe

Fractions	Wex-Fe	Sp. Ad-Fe	MnO-Fe	OM-Fe	AmFeO-Fe	Correlation coefficients
Ws +Exch	**0.616**	-0.101	0.286	0.291	-0.203	0.889**
Sp. Ad-Fe	0.215	**-0.342**	0.201	0.189	0.255	0.518**
MnO-Fe	0.458	0.508	**-0.156**	0.278	-0.184	0.904**
OM -Fe	0.436	-0.096	0.112	**0.201**	0.003	0.656**
AmFeO	-0.453	0.431	0.556	0.107	**0.193**	0.834**
(Values on diagonal are direct effects and values on horizontal lines are indirect effects)						

The data (table 116) indicate that the direct effect of water soluble + exchangeable Fe on available Fe was very high (0.616). The indirect effects through MnO-Fe (0.286) and OM-Fe (0.291) were positive and moderate and that through Am FeO-Fe was negative and moderate (-0.203). The direct effect of specifically adsorbed Fe was high and negative (-0.342). The indirect effects through water soluble + exchangeable Fe (0.215), MnO-Fe (0.201) and AmO-Fe (0.255) were moderate. The indirect effects of MnO-Fe through water soluble + exchangeable Fe (0.458), specifically adsorbed Fe (0.508) was very high, and that through OM-Fe (0.278) was moderate. The direct effect of OM-Fe was moderate (0.201), while its indirect effect through water soluble + exchangeable Fe (0.436) was high. The indirect effects of Am FeO- Fe through water soluble + exchangeable Fe (-0.453) was very high and negative, and that through specifically adsorbed Fe (0.431) and MnO-Fe (0.556) were very high and positive.

4.5.2.1.2 Path coefficients of Fe content in plant with fractions of Fe at active tillering

Path coefficients of Fe content in plant with fractions of Fe at active tillering under aerobic system are presented in table 117.

Table 117. Path coefficients of Fe content in plant with fractions of Fe at active tillering under aerobic system

Fractions	Ws+Exch –Fe	MnO-Fe	OM-Fe	Am FeO-Fe	correlation coefficients
Ws+ Exch - Fe	**0.149**	0.242	-0.028	0.494	0.856**
MnO-Fe	0.445	**0.389**	-0.233	0.275	0.876**
OM-Fe	0.032	0.230	**-0.043**	0.320	0.540**
Am FeO-Fe	0.041	0.306	-0.023	**0.592**	0.916**
(Values on diagonal are direct effects and values on horizontal lines are indirect effects)					

Path coefficients of different fractions of Fe indicating the direct and indirect effects on Fe content in plant at active tillering are given in the table 130. The indirect effect of water soluble + exchangeable Fe through MnO- Fe (0.242) was moderate and that through Am FeO -Fe was very high (0.494). The direct effect of MnO-Fe (0.389) was high; the indirect effects through water soluble + exchangeable Fe (0.445) was very high, through OM Fe (-0.233) was moderate and negative, and that through Am FeO- Fe was moderate and positive (0.275). The indirect effect through MnO- Fe was moderate (0.230) and that through Am FeO- Fe was high (0.320). The direct effect of Am FeO-Fe was very high (0.592), and the indirect effect through MnO-Fe (0.306) was high.

4.5.2.2 Correlation coefficients of available Fe and Fe content in plant with fractions of Fe at panicle initiation under aerobic rice cultivation

Available Fe had positive significant correlations with plant Fe (0.877**), water soluble + exchangeable Fe (0.824*), MnO-Fe (0.931**), OM-Fe (0.466**), and amorphous Fe oxide occluded Fe (0.532**).

Fe content in plant was positively and significantly correlated with water soluble + exchangeable Fe (0.876*), MnO-Fe (0.839**), OM-Fe (0.540**) and amorphous Fe oxide occluded Fe (0.721**).

4.5.2.2.1 Path coefficients of available Fe with fractions of Fe at panicle initiation

Path coefficients of available Fe with fractions of Fe at panicle initiation under aerobic system are presented in table 118.

Table 118. Path coefficients of available Fe with fractions of Fe at panicle initiation under aerobic rice cultivation

Fractions	Ws+ Exch -Fe	MnO-Fe	OM-Fe	Am FeO-Fe	correlation coefficients
Ws+ Exch -Fe	**0.687**	0.381	-0.1195	-0.051	0.898**
MnO-Fe	0.109	**0.679**	0.305	-0.156	0.937**
OM-Fe	0.468	0.0018	**0.0111**	-0.015	0.466*
Am FeO-Fe	0.531	0.029	0.101	**-0.129**	0.532**
(Values on diagonal are direct effects and values on horizontal lines are indirect effects)					

Path coefficients of different fractions of Fe indicating the direct and indirect effects on available Fe at panicle initiation are given in the table 118. The direct effect of water soluble + exchangeable Fe on available Fe was very high (0.687). The indirect effects through MnO-Fe (0.381) were high. The direct effect of MnO-Fe (0.679) was very high, through OM Fe (0.305) was high. The indirect effect of OM-Fe through water soluble + exchangeable Fe (0.468) was high. The indirect effect of AmFeO-Fe through water soluble + exchangeable Fe (0.531) was very high and that through and OM Fe was low (0.101).

4.5.2.2.2 Path coefficients of Fe content in plant with fractions of Fe at panicle initiation

Path coefficients of Fe content in plant with fractions of Fe at panicle initiation under aerobic system are presented hereunder.

Table 119. Path coefficients of Fe content in plant with fractions of Fe

Fractions	Ws+ Exch – Fe	MnO-Fe	OM-Fe	Am FeO Fe	correlation coefficient
Ws+ Exch - Fe	**0.616**	0.368	-0.164	0.056	0.876**
MnO-Fe	0.296	**0.393**	-0.158	0.308	0.839**
OM-Fe	0.147	0.177	**-0.350**	0.566	0.540**
Am FeO-Fe	0.168	0.181	-0.296	**0.669**	0.721**
(Values on diagonal are direct effects and values on horizontal lines are indirect effects)					

Path coefficients of different fractions of Fe indicating the direct and indirect effects on Fe content in plant at panicle initiation are given in the table 119. The direct effect of water soluble + exchangeable Fe on Fe content in plant was very high (0.616). The indirect effect through MnO - Fe (0.368) was high. The direct effect of MnO-Fe (0.393) was high, the indirect effect through water soluble + exchangeable Fe (0.296) was moderate, while that through AmO- Fe was high (0.566). The direct effect of OM-Fe (-0.350) was high and negative and its indirect effect through AmO-Fe was very high.

The direct effect of Am FeO - Fe was very high (0.699) and its indirect effect through OM-Fe was moderate (-0.296) and negative.

4.5.2.3. Correlation coefficients of available Fe and Fe content in straw and grain with fractions of Fe at harvest under aerobic rice

Available Fe had positive significant correlations with plant Fe (0.869**), water soluble + exchangeable Fe (0.876**), specifically adsorbed Fe (0.760**), acid soluble Fe (0.414*), MnO-Fe (0.783**) and amorphous Fe oxide occluded Fe (0.432*).

Iron content in straw was positively correlated with Fe content in grain (0.512*), water soluble + exchangeable Fe (0.869**), specifically adsorbed Fe (0.812**), acid soluble Fe (0. 638**), MnO-Fe (0.853**) and with amorphous Fe oxide occluded Fe (0.677**).

Iron content in grain was significantly and positively correlated with specifically adsorbed Fe (0.645**), MnO-Fe (0.437*) and with amorphous Fe oxide occluded Fe (0.439*).

4.5.2.3.1 Path coefficients of available Fe with fractions of Fe at harvest

Path coefficients of available Fe with fractions of Fe at harvest under aerobic system are presented in table 120.

Table 120. Path coefficients of available Fe with fractions of Fe at harvest of aerobic rice

	Ws+ Exch - Fe	Sp. Ad-Fe	Acid-sol-Fe	Mno-Fe	Am FeO-Fe	Correlation coefficients
Ws+ Exch -Fe	**0.765**	0.125	0.165	0.128	-0.307	0.876**
Sp. Ad-Fe	0.241	**-0.121**	0.35	0.169	0.121	0.760**
Acid-sol	0.409	0.005	**0.001**	0.002	-0.003	0.414*
Mno-Fe	0.577	0.109	0.129	**0.069**	-0.101	0.783**
Am FeO-Fe	0.418	0.107	0.111	0.021	**-0.225**	0.432*
(Values on diagonal are direct effects and values on horizontal lines are indirect effects)						

Path coefficients of different fractions of Fe indicating the direct and indirect effects on available Fe at harvest are given in the table 120. The direct effect of water soluble + exchangeable Fe on available Fe was very high (0.765) and its indirect effect through Am FeO -Fe was high and negative (-0.307). The indirect effect of specifically adsorbed-Fe through water soluble + exchangeable Fe (0.241) was moderate and through acid soluble Fe (0.350) was high. The indirect effect of acid soluble Fe through water soluble + exchangeable Fe (0.409) was very high. The direct effect of Am FeO - Fe was moderate and negative (-0.225), its indirect effect through water soluble + exchangeable Fe (0.418) was very high.

4.5.2.3.2 Path coefficients of Fe content in straw with fractions of Fe at harvest

Path coefficients of Fe content in straw with fractions of Fe at harvest under aerobic system are presented in table 121.

Table 121. Path coefficients of Fe content in straw with fractions of Fe at harvest

	Ws+ Exch -Fe	Sp. Ad-Fe	Acid-sol	Mno-Fe	Am FeO-Fe	Correlation coefficients
Ws+ Exch - Fe	**0.517**	-0.145	0.379	0.327	-0.209	0.869**
Sp. Ad-Fe	-0.397	**-0.145**	0.378	0.211	0.765	0.812**
Acid-sol	0.213	0.0031	**0.0889**	0.148	0.186	0.639**
Mno-Fe	0.404	0.0031	0.0482	**0.272**	0.126	0.853**
Am FeO-Fe	-0.224	0.155	0.236	0.175	**0.335**	0.677**
(Values on diagonal are direct effects and values on horizontal lines are indirect effects)						

Path coefficients of different fractions of Fe indicating the direct and indirect effects on Fe content in straw at harvest are given in the table 121. The direct effect of water soluble + exchangeable Fe on available Fe was very high (0.517). The indirect effects through acid soluble Fe (0.379) and MnO- Fe (0.327) were high. The indirect effect of specifically adsorbed iron through water soluble + exchangeable Fe (-0.397) was high and negative, while through acid soluble Fe (0.378) and AmO- Fe (0.765) were high and positive. The indirect effect of acid soluble Fe through water soluble + exchangeable Fe (0.213) was moderate. The direct effect of Mno- Fe was moderate (0.272), its indirect effect through water soluble + exchangeable Fe (0.404) was very high. The direct effect of Am FeO - Fe was high (0.335) and its indirect effect through water soluble + exchangeable Fe (-0.224) was moderate and negative, and that through acid soluble Fe (0.236) was moderate and positive.

4.5.2.4 Correlation coefficients of available Fe and Fe content in plant with fractions of Fe at active tillering of flooded rice

Available Fe had positive significant correlations with Fe content in plant, water soluble + exchangeable Fe (0.912*), acid soluble Fe (0.440*), MnO-Fe

(0.655^{**}), and was negatively and significantly correlated with amorphous Fe oxide occluded Fe (0.834**), residual Fe (-.650**) and total Fe (-0.724**).

Iron content in plant was positively correlated with water soluble + exchangeable Fe (0.620^{**}), specifically adsorbed Fe (0.616^{**}), acid soluble Fe (0.873^{**}), MnO Fe (0.912^{**}), OM-Fe (0.656^{**}), and was negatively correlated with amorphous Fe oxide occluded Fe (-0.908^{**}). Water soluble + exchangeable Fe was positively correlated with acid soluble Fe (0.440^{*}), MnO Fe (0.655^{**}) and was negatively correlated with amorphous Fe oxide occluded Fe (-0.650^{**}).

4.5.2.4.1 Path coefficients of available Fe with fractions of Fe at active tillering under flooded rice

The Path coefficients of available Fe with fractions of Fe at active tillering under flooded rice are presented in table 122.

Table 122. Path coefficients of available Fe with fractions of Fe

Fraction	Ws+ Exch - Fe	Acid-sol	Mno-Fe	Am FeO-Fe	Residual	Total	Correlation coefficients
Ws+ Exch - Fe	**0.497**	-0.239	-0.397	-0.197	0.972	0.2762	0.912**
Acid-sol	0.252	**-0.367**	-0.357	-0.126	0.779	0.259	0.44*
Mno-Fe	0.123	-0.459	**-0.574**	0.424	0.995	0.146	0.655**
Am FeO-Fe	-0.246	-0.419	-0.147	**0.076**	0.226	-0.14	-0.65**
Residual	-0.468	0.342	0.263	0.121	**-0.874**	-0.149	-0.765**
Total	0.085	-0.428	-0.268	-0.237	0.082	**0.042**	-0.724**
(Values on diagonal are direct effects and values on horizontal lines are indirect effects)							

Path coefficients of different fractions of Fe indicating the direct and indirect effects of available Fe at active tillering are given in the table 122. The direct effect of water soluble + exchangeable Fe on available Fe was very high (0.497). The indirect effects through acid soluble Fe (-0.239) was moderate and negative and through MnO- Fe (-0.397) was high and negative. The indirect effect of water soluble + exchangeable Fe through residual Fe was very high (0.972), and that through total

Fe was moderate (0.276). The direct effect of acid soluble Fe was high and negative (-0.367). The indirect effects through water soluble + exchangeable Fe (0.252) and through total Fe (0.259) were moderate, that through MnO- Fe (-0.357) was high and negative, and that through residual Fe was (0.779) was very high. The direct effect of MnO - Fe (-0.574) as well as its indirect effect through acid soluble Fe (-0.459) was very high and negative. The indirect effects of MnO-Fe through Am FeO- Fe (0.424) and residual Fe (0.995) were high.

The direct effect of Am FeO - Fe was high (0.335), its indirect effect through water soluble + exchangeable Fe (-0.224) was moderate and negative, and that through acid soluble Fe (0.236) was moderate and positive.

4.5.4.2.2 Path coefficients of Fe content in plant with fractions of Fe at active tillering under flooded rice

The Path coefficients of Fe content in plant with fractions of Fe at active tillering under flooded rice are presented in table 123.

Table 123. Path coefficients of Fe content in plant with fractions of Fe at active tillering of flooded rice cultivation

	Ws+ Exch -Fe	Sp. Ad-Fe	Acid-sol	MnO-Fe	OM-Fe	Am FeO-Fe	Correlation coefficients
Ws+ Exch. - Fe	**0.023**	-0.021	0.264	-0.303	-0.032	0.689	0.620**
Sp. Ad-Fe	0.009	**-0.057**	0.372	-0.279	-0.061	0.632	0.616**
Acid-sol	0.010	-0.036	**0.599**	-0.318	-0.080	0.698	0.873**
MnO-Fe	0.015	-0.035	0.413	**-0.462**	-0.066	1.047	0.912**
OM-Fe	0.007	-0.033	0.450	-0.283	**-0.107**	0.701	0.734**
Am FeO-Fe	-0.015	0.034	-0.395	0.457	0.071	**-1.06**	-0.908**

(Values on diagonal are direct effects and values on horizontal lines are indirect effects)

4.5.4.3.1 Path coefficients of available Fe with fractions of Fe at active tillering under flooded rice

The Path coefficients of available Fe with fractions of Fe at active tillering under flooded rice are presented in table 124.

Table 124. Path coefficients of available Fe with fractions of Fe at panicle initiation under flooded rice cultivation

	Ws+Exch-Fe	SP ad-Fe	MnO-Fe	OM-Fe	AmFeO	Res-Fe	Correlation coefficients
Ws+Exch.-Fe	**0.512**	-0.337	-0.485	-0.171	1.195	0.1762	0.890
SP.Ad-Fe	0.287	**-0.457**	-0.269	-0.025	0.976	0.063	0.575
MnO-Fe	0.323	-0.338	**-0.474**	-0.04	1.254	0.146	0.871
OM-Fe	0.206	-0.419	-0.188	**0.084**	0.903	-0.01	0.576
AmFeO-Fe	-0.581	0.411	0.387	0.018	**-0.991**	-0.123	-0.879
Res-Fe	0.197	-0.395	-0.248	0.021	0.787	0.102	0.464
(Values on diagonal are direct effects and values on horizontal lines are indirect effects)							

Path coefficients of different fractions of Fe indicating the direct and indirect effects of available Fe at panicle initiation are given in the table 124. The direct effect of water soluble + exchangeable Fe on available Fe was very high (0.512). The indirect effects through specifically adsorbed Fe (-0.337) was moderate and negative, through MnO- Fe (-0.485) was very high and negative, and that through Am FeO -Fe was very high (1.195) and positive. The direct effect of specifically adsorbed Fe was very high and negative (-0.457). The indirect effect through water soluble + exchangeable Fe (0.287) was moderate, through MnO- Fe (-0.269) was moderate and negative, and through Am FeO-Fe was high (0.976). The direct effect of MnO - Fe (-0.474) was very high and negative and its indirect effect through water soluble + exchangeable Fe (0.323) was high, that through specifically adsorbed was high and negative (-0.338), and that through Am FeO- Fe (1.254) was very high. The indirect effect of OM-Fe through water soluble + ex (0.206) was moderate, through specifically adsorbed was very high and negative (-0.419) and through Am FeO-Fe was very high and positive (0.903). The direct effect of Am FeO - Fe was very high and negative (-0.991), its indirect effect through water soluble + exchangeable Fe (-0.581) was very high and negative, and that through specifically adsorbed Fe (0.411) and MnO- Fe (0.387) were very high and positive.

4.5.4.3.2 Path coefficients of Fe content in plant with fractions of Fe at active tillering under flooded rice

The Path coefficients of Fe content in plant with fractions of Fe at active tillering under flooded rice are presented in table 125.

Table125. Path coefficients of Fe content in plant with fractions

Fractions	Ws+Exch-Fe	SP ad-Fe	MnO-Fe	OM-Fe	AmFeO-Fe	Res-Fe	Correlation coefficients
Ws+Exch-Fe	**0.591**	-0.432	-0.502	-0.051	1.295	-0.026	0.875
SP ad-Fe	0.241	**-0.569**	-0.378	-0.03	1.207	0.063	0.534
MnO-Fe	0.356	-0.265	**-0.811**	-0.04	1.554	0.07	0.864
OM-Fe	0.236	-0.199	-0.395	**-0.083**	1.004	-0.01	0.553
AmFeO-Fe	-0.36	0.404	0.742	0.049	**-1.699**	-0.073	-0.934
Res-Fe	0.19	-0.281	-0.448	0.011	0.961	0.128	0.561

(Values on diagonal are direct effects and values on horizontal lines are indirect effects)

Path coefficients of different fractions of Fe indicating the direct and indirect effects of Fe content in plant at panicle initiation are given in the table 125. The direct effect of water soluble + exchangeable Fe on Fe content in plant was very high (0.591) and its indirect effects through specifically adsorbed Fe (-0.432) and through MnO- Fe (-0.502) were very high and negative, and that through Am FeO -Fe was very high (1.295) and positive. The direct effect of specifically adsorbed Fe was very high and negative (-0.569); its indirect effect through water soluble + exchangeable Fe (0.241) was moderate, through MnO- Fe (-0.378) was high and negative, and through Am FeO-Fe was very high and positive (1.207). The direct effect of MnO -

Fe (-0.811) was very high and negative. The indirect effects of MnO- Fe through soluble + exchangeable (0.356) and through Am FeO- Fe (1.554) were very high and positive. The indirect effect of OM-Fe through AM FeO-Fe was very high and positive (1.004) and that through Mn FeO-Fe was very high and negative (-0.395).

The direct effect of Am FeO - Fe was very high and negative (-1.699), its indirect effect through water soluble + exchangeable Fe (-0.36) was high and negative, and that through specifically adsorbed Fe (0.404) and MnO- Fe (0.742) were very high.

4.5.4.4. Correlation coefficients of available Fe and Fe content in straw and grain with fractions of Fe at harvest of flooded rice cultivation

Available Fe was positively and significantly correlated with Fe content in straw (0.621**), Fe content in grain (0.627**), water soluble + exchangeable Fe (0.559**), specifically adsorbed Fe (.447*), MnO - Fe (0.421*) and amorphous Fe oxide occluded Fe (0.625**) and was negatively correlated with total Fe (-0.407*).

Iron content in straw was positively correlated with Fe content in grain (0.892**), water soluble + exchangeable Fe (0.919**), specifically adsorbed Fe (0.656**), MnO-Fe (0.782**), OM-Fe (0.690**) and with amorphous Fe oxide occluded Fe (0.827**).

Iron content in grain was positively and significantly correlated with water soluble + exchangeable Fe (0.559**), specifically adsorbed Fe (0.645**), MnO Fe (0.437*), OM Fe (693**), with amorphous Fe oxide occluded Fe (0. 825**).

4.5.4.4.1 Path coefficients of available Fe with fractions of Fe at harvest

The Path coefficients of available Fe with fractions of Fe at harvest under flooded rice cultivation is presented in table 127.

Table 126. Path coefficients of available Fe with fractions of Fe at harvest under flooded rice cultivation

	Ws+ Exch -Fe	SP.Ad. Fe	Mno-Fe	Am FeO-Fe	Total	Correlation coefficients
Ws+ Exch -Fe	**-0.533**	1.657	-0.236	0.774	-1.103	0.559
SPad	-0.387	**2.283**	-0.173	0.428	-1.704	0.448
Mno-Fe	-0.466	1.467	**-0.270**	0.635	-0.946	0.421
Am FeO-Fe	-0.392	0.927	-0.163	**1.053**	-0.801	0.624
total	-0.331	2.186	-0.143	0.474	**-1.779**	0.407
(Values on diagonal are direct effects and values on horizontal lines are indirect effects)						

Path coefficients of different fractions of Fe indicating the direct and indirect effects of available Fe at active tillering are given in the table 126. The direct effect of water soluble + exchangeable Fe on available Fe was very high and negative. The indirect effect through Am FeO- Fe (0.774) was very high and through MnO- Fe (-0.236) was moderate and negative. The indirect effect of water soluble + exchangeable Fe through total Fe was very high and negative (0.972), and that through total Fe was moderate (0.276).

4.6 Distribution of fractions of zinc, correlations of zinc fractions with available zinc and zinc content in plant and path coefficients at different stages.

The distribution of different Zn fractions as percentage of total Zn, correlations of available Zn and Zn content in plant, as well as the path coefficients indicating the direct and indirect effects are presented hereunder.

4.6.1. Distribution of Zn fractions expressed as percentage of total zinc in soil

The zinc content in fractions expressed as percentage of total zinc under aerobic and flooded systems of rice cultivation is presented in table 128 to 145.

Under both systems of rice cultivation, the dominant fraction with highest zinc content was residual fraction constituting 78.19 and 80.85 per cent in aerobic and flooded systems respectively at initial stage. The remaining per cent was distributed among the other eight fractions. Among them, Mn oxide occluded zinc was dominated with 7.45 % under aerobic method of rice cultivation and with 11.14 % under flooded system. Organic matter bound zinc constituted 6.42 and 5.75 % under aerobic and flooded condition respectively. Amorphous Fe oxide occluded Zn constituted 5.54 % under aerobic system and 6.86 % under flooded system. Crystalline Fe oxide fraction constituted about 2.79 % and 2.64 % under aerobic and flooded system of rice cultivation respectively. Specifically adsorbed fraction recorded the lowest percentage contribution, constituting with 0.51 % and 0.50 % under aerobic and flooded system respectively. Water soluble + exchangeable Zn was not detected initially under both systems of rice cultivation.

4.6.1.1 Distribution of water soluble + exchangeable Zn under aerobic and flooded systems

The percentage distributions of water soluble and exchangeable Zn fractions extracted at different stages under both systems are presented in table 127.

Table 127. Distribution of water soluble + exchangeable Zn

Stages of sampling	Aerobic rice			Flooded rice		
	L_1	L_2	L_3	L_1	L_2	L_3
Initial	ND	ND	ND	ND	ND	ND
AT	0.17	0.21	0.25	0.19	0.27	0.17
PI	0.15	0.19	0.23	0.19	0.14	0.11
Harvest	0.14	0.19	0.27	0.20	0.17	0.13

In lime treatment as per POP the water soluble + exchangeable Zn fraction increased to 0.17 % at active tillering and then decreased to 0.15% at panicle initiation and further to 0.14 % at harvest.

In soils with lime applied as per ΔpH, the water soluble + exchangeable Zn increased to 0.21 % at active tillering, and then reduced to 0.19 % both at panicle initiation and at harvest of the crop. When lime was applied as per SMP buffer method, the water soluble + exchangeable Zn fraction showed an increase to 0.25 % at active tillering, and then reduced to 0.23 % at panicle initiation. At harvest of the crop, water soluble + exchangeable Zn recorded 0.28 %. Thus, highest distribution of water soluble + exchangeable Zn was in the soils where dose of lime was applied as per SMP buffer method, under aerobic rice cultivation.

Under flooded system in lime treatment as per POP the water soluble + exchangeable Zn fraction showed an increase to 0.2 % at active tillering, and then reduced to 0.14 % at panicle initiation and further to 0.12 % at harvest.

In lime treatments as per ΔpH, the water soluble + exchangeable Zn fraction increased to 0.19 % at active tillering, reduced to 0.17 % at panicle initiation, and recorded 0.18 % at harvest of the crop. Same trend was observed in lime treatments as per SMP buffer method, where the water soluble + exchangeable Zn fraction showed an increase to 0.17 % at active tillering, reduced to 0.13 % at panicle initiation as well as at harvest of the crop.

In general, under aerobic system, the water soluble + exchangeable Zn fraction showed an increasing trend from initial stage to active tillering of the crop with highest percentage increase in lime treatments as per SMP buffer method (table 138). Under flooded system, the water soluble + exchangeable Zn fraction showed an increasing trend from initial to active tillering and then decreased till harvest of the crop. The highest contributions of water soluble + exchangeable Zn at all stages were recorded in lime treatments as per ΔpH.

4.6.1.2 Distribution of specifically adsorbed Zn under aerobic and flooded systems

Under aerobic cultivation, the specifically adsorbed Zn fraction in the treatments applied with lime as per POP decreased from 0.51 % at initial stage to 0.25 % at active tillering and then increased to 0.39% at panicle initiation and further to 0.45 % at harvest (table 128).

Table 128. Distribution of specifically adsorbed fraction

Stages of sampling	Aerobic rice			Flooded rice		
	L_1	L_2	L_3	L_1	L_2	L_3
Initial	0.51	0.51	0.51	0.50	0.50	0.50
AT	0.25	0.34	0.42	0.36	0.41	0.49
PI	0.39	0.48	0.56	0.41	0.50	0.63
Harvest	0.45	0.58	0.71	0.54	0.61	0.75

In soils where lime applied as per ΔpH, the specifically adsorbed Zn fraction decreased from 0.51 % at initial stage to 0.34 % at active tillering and then increased to 0.48 % at panicle initiation and further increased to 0.58 % at harvest. In lime treatments as per SMP buffer method, the specifically adsorbed Zn fraction showed a decrease to 0.42 % at active tillering. This fraction was found increased to 0.56% at panicle initiation and to 0.71 % at harvest of the crop. Highest distribution of specifically adsorbed Zn was recorded in the dose of lime as per SMP buffer method under aerobic rice cultivation.

Under flooded system, the specifically adsorbed Zn fraction in treatments applied with lime as per POP showed a decrease to 0.36 % at active tillering from 0.50% at initial stage. Then it showed an increase to 0.41 % at panicle initiation. The contribution of this fraction at harvest was 0.54 %. In treatments where lime as per ΔpH, the specifically adsorbed Zn fraction decreased to 0.41 % at active tillering, increased to 0.5 % and to 0.61 % at PI and harvest respectively. The same trend was observed in soils with lime treatment soils as per SMP buffer method, where the. specifically adsorbed Zn fraction showed a similar distribution at active tillering as that of initial (0.49) and then increased to 0.63 % at panicle initiation and 0.75 % at harvest of the crop.

In general, under both systems of rice cultivation, the specifically adsorbed Zn fraction showed a decreasing trend from initial stage to active tillering and then increased till the harvest of the crop (table 141) with highest percentage increase in lime treatments as per SMP buffer method.

4.6.1.3 Distribution of acid soluble Zn under aerobic and flooded systems

The distribution of acid soluble zinc at different stages under aerobic and flooded systems is presented hereunder

Table 129. Distribution of acid soluble Zn

Stages of sampling	Aerobic rice			Flooded rice		
	L_1	L_2	L_3	L_1	L_2	L_3
Initial	5.54	5.54	5.54	6.86	6.86	6.86
AT	5.73	5.83	5.99	11.19	10.59	10.11
PI	5.68	5.78	5.95	6.31	5.58	4.73
Harvest	8.56	8.99	9.29	6.68	9.26	10.68

Under aerobic cultivation, the acid soluble Zn fraction of the soils applied with lime as per POP did not vary much from the initial value which was 5.54 %, 5.73 % at active tillering and 5.68 % at panicle initiation. This fraction increased to 8.56 % at harvest. In lime treatments as per ΔpH, the acid soluble Zn fraction recorded 5.83 % at active tillering, 5.78 % at panicle initiation and increased at harvest to 8.99 % (Table 129).

In lime treatment as per SMP buffer method, the acid soluble Zn recorded 5.99 % at active tillering, 5.95 % at panicle initiation and increased further to 9.29 % at harvest of the crop. However, highest distribution of acid soluble Zn was recorded in the dose of lime as per SMP buffer method under aerobic rice cultivation.

Under flooded system of rice cultivation, the acid soluble Zn fraction of the soils applied with lime as per POP showed a increase to 11.19 % at active tillering from 6.86% at initial stage and to 6.31 % at panicle initiation. The contribution of acid soluble Zn fraction at harvest of the crop was 6.68 %.

In lime applied soils as per ΔpH, the acid soluble Zn fraction showed an increase to 10.59 % at active tillering from 6.86 % at initial stage and decreased to 5.58 % at panicle initiation. The contribution of acid soluble Zn fraction at harvest of the crop was 9.26 %. The acid soluble Zn fraction in soils with lime treatment as per

SMP buffer method recorded 10.11 % at active tillering and then decreased to 4.73 % at panicle initiation and increased to 10.68 % at harvest of the crop.

In general, under aerobic system, the distribution of this fraction did not show much variation from initial to panicle initiation, but then increased further at harvest. Under flooded system, the acid soluble Zn fraction showed a decreasing trend at active tillering and panicle initiation and then increased at harvest.

4.6.1.4 Distribution of manganese oxide occluded Zn under aerobic and flooded systems

The distribution of manganese oxide occluded zinc at different stages under aerobic and flooded systems is presented hereunder.

Table 130. Distribution of Manganese oxide occluded Zn

Stages of sampling	Aerobic rice			Flooded rice		
	L_1	L_2	L_3	L_1	L_2	L_3
Initial	7.45	7.45	7.45	12.14	12.14	12.14
AT	7.99	7.52	7.27	10.82	9.90	8.310
PI	8.96	8.49	8.13	11.56	11.16	10.41
Harvest	7.88	7.89	7.69	10.15	9.82	12.31

Under aerobic cultivation, the manganese oxide occluded Zn fraction of the soils applied with lime as per POP increased from 7.45 % at initial stage to 7.99 % at active tillering, and then to 8.96 % at panicle initiation, further decreased to 7.88 % at harvest (table 130). In lime treatment as per ΔpH, the manganese oxide occluded Zn fraction increased to 7.52 % at active tillering and to 8.49 % at panicle initiation and further decreased to 7.89 % at harvest. In lime treatment as per SMP buffer method, the manganese oxide occluded Zn fraction showed a decrease to 7.27 % at active tillering. The percentage distribution of manganese oxide occluded Zn was found increased to 8.13 % at panicle initiation and then to 7.69 % at harvest of the crop. The highest distribution of manganese oxide occluded Zn was recorded in the dose of lime as per POP under aerobic rice cultivation.

Under flooded system, the manganese oxide occluded Zn fraction of the treatment applied with lime as per POP showed a decrease to 10.82 % at active tillering from 12.14 % at initial stage and increased to 11.56 % at panicle initiation. The contribution of manganese oxide occluded Zn fraction at harvest of the crop was 10.15 %. In lime applied soils as per ΔpH, the manganese oxide occluded Zn fraction showed a decrease to 9.90 % at active tillering from 12.14 % at initial stage and further increased to 11.16 % at panicle initiation. The contribution of manganese oxide occluded Zn fraction at harvest of the crop was 9.82 %. Same trend was observed in lime treatment as per SMP buffer method, where the manganese oxide occluded Zn fraction recorded 8.31 % at active tillering and then increased to 10.41 % at panicle initiation and to 12.31 % at harvest of the crop.

In general, under aerobic rice system, the manganese oxide occluded Zn fraction showed a decreasing trend from initial stage to active tillering and then increased at PI and further increased at harvest of the crop. Under flooded system, this fraction decreased at active tillering, increased at PI and decreased at harvest in treatments L_1 and L_2

4.6.1.5 Distribution of Organic matter bound Zn under aerobic and flooded systems

The distribution of organic matter bound zinc at different stages under aerobic and flooded systems is presented hereunder.

Table 131. Distribution of Organic matter bound Zn

Stages of sampling	Aerobic rice			Flooded rice		
	L_1	L_2	L_3	L_1	L_2	L_3
Initial	6.42	6.42	6.42	5.75	5.75	5.75
AT	5.03	4.75	4.25	3.32	3.09	2.72
PI	4.97	4.67	3.97	3.13	2.73	2.39
Harvest	6.63	6.57	5.63	3.22	2.78	2.40

Under aerobic rice, the organic matter bound Zn fraction of the soil applied with lime as per POP decreased from 6.42 % at initial stage to 5.03 % at active tillering and then to 4.97 % at panicle initiation and then increased to 6.63 % at harvest (table 131). In soils with lime applied as per ΔpH, the organic matter bound fraction decreased to 4.75 % at active tillering and then to 4.67 % at panicle initiation and further increased to 6.57 % at harvest. In lime treatment as per SMP buffer method, the organic matter bound Zn fraction decreased to 4.25 % at active tillering and to 3.97 % at panicle initiation and then increased to 5.63 % at harvest of the crop. Under aerobic rice cultivation the highest reduction in distribution of organic matter bound Zn was recorded in treatment with lime as per SMP buffer method.

Under flooded system, the organic matter bound Zn fraction in the soil applied with lime as per POP showed a decrease to 3.32 % at active tillering from 5.75 % at initial stage and further to 3.13 % at panicle initiation. The contribution of this fraction at harvest of the crop was 3.22 %. In lime applied soils as per ΔpH, the organic matter bound fraction showed a decrease to 3.09 % at active tillering and further decreased to 2.73 % at panicle initiation. The contribution of organic matter bound fraction at harvest of the crop was 2.78 %. Same trend was observed in lime treated soils as per SMP buffer method, where the organic matter bound fraction recorded 2.72 % at active tillering and then decreased to 2.39 % a panicle initiation and 2.40 % at harvest of the crop.

In general, under both rice cultivation systems, the organic matter bound fraction showed a decreasing trend from initial stage to PI and then increased slightly at harvest of the crop.

4.6.1.6 Distribution of amorphous Fe oxide occluded Zn under aerobic and flooded systems

The distribution of amorphous Fe oxide occluded zinc at different stages under aerobic and flooded systems is presented hereunder.

Table 132. Distribution of amorphous Fe oxide occluded Zn

Stages of sampling	Aerobic rice			Flooded rice		
	L_1	L_2	L_3	L_1	L_2	L_3
Initial	0.59	0.59	0.59	1.40	1.40	1.40
AT	0.77	0.90	0.95	0.66	0.72	0.79
PI	0.55	0.69	0.93	1.15	0.92	1.02
Harvest	0.91	1.17	1.54	0.95	1.10	1.27

Under aerobic system, the amorphous Fe oxide occluded Zn fraction of the soils applied with lime as per POP increased from 0.59 % at initial stage to 0.77 % at active tillering and then decreased to 0.55 % at panicle initiation and further increased to 0.91 % at harvest (table 132). In lime applied soils as per ΔpH, the amorphous Fe oxide occluded Zn fraction increased to 0.90 % at active tillering and then decreased to 0.69 % at panicle initiation and further increased to 1.17 % at harvest. In lime treatment as per SMP buffer method, the amorphous Fe oxide occluded Zn fraction showed an increase to 0.95 % at active tillering. The distribution of this fraction was found to decrease to 0.93 % to panicle initiation and then increased to 1.54 % at harvest of the crop. However, the highest increase in distribution of amorphous Fe oxide occluded Zn was recorded in the dose of lime as per SMP buffer method under aerobic rice cultivation.

Under flooded system, the amorphous Fe oxide occluded Zn fraction of the soils applied with lime as per POP showed a decrease to 0.66 % at active tillering from 1.40 % at initial stage and further increased to 1.15 % at panicle initiation. The contribution of amorphous Fe oxide occluded Zn fraction at harvest of the crop was 0.95 %. In lime applied soils as per ΔpH, the amorphous Fe oxide occluded Zn fraction showed a decrease to 0.72 % at active tillering and further increased to 0.92% at panicle initiation. The contribution of amorphous Fe oxide occluded Zn fraction at harvest of the crop was 1.10 %. Same trend was observed in lime treated soils as per SMP buffer method, where the amorphous Fe oxide occluded Zn fraction showed 0.79 % at active tillering and then increased to 1.02 % to panicle initiation and 1.27 % at harvest of the crop.

In general, under aerobic rice, the amorphous Fe oxide occluded Zn fraction showed an increasing trend from initial stage to active tillering and then decreased at PI and further increased harvest of the crop. Under flooded system, in general, the amorphous Fe oxide occluded Zn fraction showed a decreasing trend from initial stage to AT; increased at PI and at harvest of the crop.

4.6.1.7 Distribution of crystalline Fe oxide occluded Zn under aerobic and flooded systems

The distribution of residual zinc under aerobic and flooded systems is presented hereunder.

Table 133. Distribution of crystalline Fe oxide fraction

Stages of sampling	Aerobic rice			Flooded rice		
	L_1	L_2	L_3	L_1	L_2	L_3
Initial	2.79	2.79	4.79	4.64	4.64	4.64
AT	4.77	4.78	4.83	4.77	5.01	5.14
PI	4.72	4.77	4.74	5.63	5.79	5.87
Harvest	4.93	4.96	4.05	5.98	6.15	6.24

Under aerobic cultivation, the crystalline Fe oxide occluded Zn fraction of the soils applied with lime as per POP increased from 2.79 % at initial stage to 4.77 % at active tillering and almost remained constant till harvest (table 134). Similar trends were observed in other lime treatments under aerobic system.

Under flooded system, irrespective of lime treatments, the crystalline Fe oxide occluded Zn fraction increased steadily from initial stage till harvest.

4.6.1.8 Distribution of residual Zn under aerobic and flooded systems

The distribution of residual zinc under aerobic and flooded systems is presented hereunder.

Table 134. Distribution of residual Zn

Stages of sampling	Aerobic rice			Flooded rice		
	L_1	L_2	L_3	L_1	L_2	L_3
Initial	77.19	70.19	70.19	80.85	80.85	80.85
AT	75.73	76.16	76. 60	68.70	70.03	72.26
PI	74.73	75.13	75.61	71.53	73.17	75.04
Harvest	74.51	74.87	75.15	72.29	70.11	66.23

Under aerobic cultivation, the residual Zn fraction of the soils applied with lime as per POP decreased from 77.19 % at initial stage to 75.13 % at active tillering and to 74.73 % at panicle initiation and remained constant till harvest (table 135). The same was the trend with the other two lime treatments under aerobic system.

Under flooded system, in all the lime treatments the residual Zn reduced substantially at active tillering.

4.6.2. Correlation coefficients and path coefficients of available Zn and Zn content in plant with fractions of Zn

The correlation coefficients and path coefficients of available Zn and plant Zn with different fractions of Zn under aerobic and flooded systems are presented hereunder.

4.6.2.1 Correlation coefficients of available Zn and Zn content in plant, with fractions of Zn at active tillering under aerobic rice cultivation

Available Zn had positive significant correlations with water soluble + exchangeable Zn (0.469*), specifically adsorbed Zn (0.552**), OM-Zn (0.627**) crystalline Fe oxide occluded Zn (0.530**) and was negatively and significantly correlated with residual Zn (-0.469*).

Zinc content in plant was positively and significantly correlated with water soluble + exchangeable Zn (0.406*), MnO occluded Zn (0.516**) and with organic matter occluded Zn (0.648**) and was negatively and significantly correlated with specifically adsorbed Zn (-0.583**) and amorphous Fe oxide occluded Zn (-0.575**).

4.6.2.1.1 Path coefficients of available Zn at active tillering under aerobic rice cultivation

The path coefficients indicating the direct and indirect effects of fractions on available Zn at active tillering under flooded system are presented in table 139.

Table 135. Path coefficients of available Zn, with fractions of Zn at active tillering of aerobic rice cultivation

	Ws+ exch -Zn	Sp ad - Zn	OM - Zn	Cr FeO - Zn	Res-Zn	correlation coefficients
Ws+ exch Zn	**0.105**	0.091	0.003	0.263	0.008	0.47*
Sp Ad.	-0.024	**-0.233**	-0.089	-0.216	0.009	-0.553**
OM Zn	0.233	0.17	**-0.164**	0.156	0.23	0.625**
Cr FeO	0.030	0.111	0.0484	**0.369**	-0.030	0.53**
Res	-0.032	-0.094	-0.068	-0.304	**0.028**	-0.469**
(Values on diagonal are direct effects and values on horizontal lines are indirect effects)						

Path coefficients of different fractions of Zn indicating the direct and indirect effects on available Zn at active tillering are given in the table 135.

None of the direct and indirect effects of water soluble Zn were found significant except its indirect effect through Cr FeO-Zn (0.263), which was moderate. The direct effect of specifically adsorbed Zn, as well as its indirect effect through Cr FeO -Zn was moderate and negative. The indirect effects of OM-Zn through Ws+ exch Zn and residual Zn were moderate. The direct effect of Cr FeO-Zn was high (0.369).

4.6.2.1.2 Path coefficients of available Zn at active tillering under aerobic rice cultivation

The path coefficients indicating the direct and indirect effects of fractions on Zn content in plant at active tillering under aerobic system are presented in table 137.

Table 136. Path coefficients of plant Zn with fractions of Zn at active tillering of aerobic rice cultivation

Fractions	Ws+exch Zn	Sp Ad Zn	MnO-Zn	OM- Zn	AM FeO-Zn	Correlation coefficients
W+ex	**0.08**	0.091	-0.023	0.263	-0.004	0.406*
Sp ad	-.0.03	**-0.239**	-0.095	-0.222	0.003	-0.583**
MnO- Zn	0.005	-0.058	**-0.392**	-0.072	0.002	.0.516*
OM- Zn	0.054	0.135	0.072	**0.393**	-0.006	0.648**
AM FeO-Zn	-0.053	-0.115	-0.089	-0.325	**0.007**	-0.575**
(Values on diagonal are direct effects and values on horizontal lines are indirect effects)						

The indirect effect of Ws+ Exch - Zn through OM-Zn was moderate (0.263). The direct effect of specifically adsorbed Zn (-0.239), and its indirect effect through OM-Zn (-0.222) were moderate and negative. The direct effect of OM-Zn was high and positive. The direct effect of MnO-Zn was very high (-0.392) and negative.

4.6.2.2 Correlation coefficients of available Zn with fractions of Zn at panicle initiation of aerobic rice cultivation

Available Zn had positive significant correlations with water soluble + exchangeable Zn (0.475*), specifically adsorbed Zn (-0.454*), acid soluble Zn (.476*) and amorphous Fe oxide occluded Zn (0.431*) and was negatively and significantly correlated with MnO occluded Zn (-.647**) and with organic matter occluded Zn (-0.405*).

4.6.2.2.1 Path coefficients of available Zn panicle initiation under aerobic rice cultivation

The path coefficients indicating the direct and indirect effects of fractions on available Zn at panicle initiation under aerobic system are presented hereunder.

Table 137. Path coefficients of available Zn with fractions of Zn at panicle initiation

Fractions	Ws+ Exch Zn	Sp ad Zn	Acid sol-Zn	MnO-Zn	OM-Zn	AM FeO-Zn	Correlation coefficients
Ws+ Exch-Zn	**0.031**	-0.179	-0.035	-0.162	0.064	-0.499	0.475*
Sp ad - Zn	-0.024	**-0.233**	0.089	-0.216	0.019	-0.089	-0.454*
Acid sol	0.208	0.145	**-0.189**	0.131	0.205	-0.025	0.476*
MnO Zn	0.050	0.131	0.068	**0.389**	-0.010	0.020	-0.647**
OM Zn	-0.292	-0.085	-0.058	-0.293	**0.309**	0.013	-0.405*
AM FeO-Zn	0.415	-0.12	0.158	0.104	0.109	**-0.235**	0.431*
(Values on diagonal are direct effects and values on horizontal lines are indirect effects)							

Path coefficients of different fractions of Zn indicating the direct and indirect effects on available Zn at panicle initiation are given in the table 137. The indirect effect of water soluble + exchangeable Zn through Am FeO-Zn was very high and positive.

The direct effect of specifically adsorbed Zn (-0.233) as well as its indirect through MnO-Zn were negative and moderate. The indirect effect of acid soluble Zn through water soluble Zn was moderate. The direct effects of MnO-Zn (0.389), OM-Zn (0.309) and Am FeO-Zn (-0.235) were very high, high and moderate respectively. The direct effect of MnO-Zn was high and that through specifically adsorbed Zn OM Zn was moderate. The direct effect of OM Zn was high. The direct effect of Am FeO- Zn was moderate and indirect effect through water soluble + exchangeable Zn was very high and negative.

4.6.2.3. Correlation coefficients of available Zn, Zn content in straw with fractions of Zn at harvest under aerobic system

Available Zn had positive significant correlations with water soluble + exchangeable Zn (0.600**), specifically adsorbed Zn (0.545**), acid soluble Zn

(0.575**) MnO occluded Zn (0.497*) and with organic matter occluded Zn (0.648**) and was negatively and significantly correlated with MnO occluded Zn (-0.501*) and total Zn (-0.562**). Zn content in straw had significant positive correlations with water soluble + exchangeable Zn (0.60**), Mno occluded Zn (0.497*) and with organic matter occluded Zn (0.648**) and was negatively and significantly correlated with specifically adsorbed Zn (-0.472**), acid soluble Zn (-0.577**) and amorphous Fe oxide occluded Zn (-0.508*).

4.6.2.3.1 Path coefficients of available Zn at harvest under aerobic system

The path coefficients indicating the direct and indirect effects of fractions on available Zn at harvest under aerobic system are presented in table 139.

Table 138. Path coefficients of available Zn with fractions of Zn

	Ws+ exch-Zn	Sp Ad-Zn	Acid sol -Zn	MnO-Zn	OM-Zn	correlation coefficients
Ws+ exch-Zn	**0.072**	0.172	0.345	-0.112	0.123	**0.600****
Sp Ad-Zn	0.18	**-0.029**	0.293	-0.012	0.113	**0.545****
Acid sol -Zn	0.269	0.206	**-0.128**	0.192	0.036	**0.575****
MnO-Zn	-0.182	-0.101	-0.164	**0.157**	-0.211	**-0.501***
OM - Zn	0.239	-0.297	-0.019	-0.073	**-0.412**	**-0.562****
(Values on diagonal are direct effects and values on horizontal lines are indirect effects)						

Path coefficients of different fractions of Zn indicating the direct and indirect effects on available Zn at panicle initiation are given in the table 138. The indirect effect of water soluble + exchangeable Zn through acid soluble Zn (0.345) was high. The indirect effect of specifically adsorbed Zn through acid soluble Zn was moderate. The indirect effects of acid soluble Zn through water soluble + exchangeable Zn and specifically adsorbed Zn were moderate. The direct effect of OM-Zn was very high and negative (-0.412).

4.6.2.3.2 Path coefficients of available Zn at harvest under aerobic system

The path coefficients indicating the direct and indirect effects of fractions Zn on Zn content in straw at harvest under aerobic system are presented hereunder.

Table 139: Path coefficients of Zn content in straw with Zn fractions at harvest

Fractions	Ws+ exch-Zn	Sp Ad-Zn	Acid Sol-Zn	MnO -Zn	OM -Zn	Am FeO -Zn	correlation coefficients
Ws+ exch-Zn	**0.145**	0.171	0.235	-0.232	0.113	0.214	**0.646****
Sp Ad-Zn	-0.201	**-0.224**	0.291	-0.112	0.105	-0.331	**-0.472***
Acid Sol-Zn	0.216	0.227	**-0.326**	-0.318	0.059	-0.435	**-0.577****
MnO -Zn	0.269	-0.362	0.312	**-0.079**	0.105	0.197	**0.442***
OM -Zn	-0.172	-0.197	0.135	0.261	**0.452**	0.084	**0.562****
Am FeO -Zn	-0.044	-0.087	0.147	-0.036	-0.087	**-0.401**	**-0.508***

(Values on diagonal are direct effects and values on horizontal lines are indirect effects)

Path coefficients of different fractions of Zn indicating the direct and indirect effects on Zn content in straw at harvest are given in the table 139. The direct effect of water soluble + exchangeable Zn was low (0.145). The indirect effects of water soluble + exchangeable Zn through acid soluble Zn (0.235), MnO- Zn (-0.232) and Am FeO-Zn (0.214) were moderate. The direct effect of specifically adsorbed Zn was moderate (-0.224), its indirect effect through Am FeO-Zn was high and negative (-0.331); that through water soluble + exchangeable Zn (0.201), and through acid soluble Zn (0.291) were moderate. The direct effect of acid soluble Zn was (-0.326) high and negative and its indirect effect through MnO-Zn (-0.318) and Am FeO-Zn (-0.435) were high and negative. The indirect effect of MnO-Zn through specifically adsorbed (-0.362) and acid soluble Zn (0.312) were high. The direct effect of OM-Zn was high (0.452). The direct effect of Am FeO-Zn was high (-0.401).

4.6.2.4. Correlation coefficients of available Zn and Zn content in plant with fractions of Zn at active tillering under flooded system

Available Zn had positive significant correlations with water soluble + exchangeable Zn (0.410*), MnO-Zn (0.613**), OM Zn (0.809**) amorphous Fe oxide occluded Zn (0.407**) and had negative significant correlations with residual Zn (-0.443*).

The zinc content in plant had positive significant correlations with MnO-Zn (0.719**), OM-Zn (0.667**), amorphous Fe oxide occluded Zn (0.602**) and total Zn (0.781**); was negatively correlated with residual Zn (-0.664*).

4.6.2.4.1 Path coefficients of available Zn at active tillering under flooded system

The path coefficients indicating the direct and indirect effects of fractions Zn available Zn at active tillering at harvest under flooded system are presented in table 141.

Table 140. Path coefficients of available Zn with fractions of Zn under flooded system

Fractions	Ws+ exch-Zn	MnO - Zn	OM -Zn	Am FeO - Zn	Total	Correlation coefficients
Ws+ exch-Zn	**0.110**	0.01	0.135	0.014	0.262	**0.410***
MnO- Zn	-0.003	**0.04**	0.146	0.117	0.31	**0.613****
OM –Zn	-0.003	0.01	**0.448**	0.008	0.342	**0.809****
Am FeO- Zn	-0.001	0.03	0.027	**0.135**	0.209	**0.407***
Total	-0.006	0.03	0.304	0.054	**0.502**	**0.884****
(Values on diagonal are direct effects and values on horizontal lines are indirect effects)						

Path coefficients of different fractions of Zn indicating the direct and indirect effects on available Zn at active tillering are given in the table 154. The direct effect of OM - Zn was very high (0.448) and its indirect effect through total Zn was very high. The direct effect of total Zn was very high (0.502).

4.6.2.4.2 Path coefficients of Zn content in plant at active tillering under flooded system

The path coefficients indicating the direct and indirect effects of fractions Zn on Zn content in straw at harvest under aerobic system are presented in table 142.

Table 141. Path coefficients of plant Zn with fractions of Zn at active tillering under flooded rice cultivation

	MnO-Zn	OM -Zn	Am FeO-Zn	Res-Zn	Total	Correlation coefficients
MnO –Zn	**0.019**	0.14	0.275	0.101	0.184	**0.719****
OM –Zn	0.014	**0.431**	0.026	-0.107	0.303	**0.667****
Am FeO –Zn	0.017	0.026	**0.395**	0.04	0.124	**0.602****
Res-Zn	-0.278	-0.154	-0.357	**0.342**	-0.217	**-0.664****
Total	0.012	0.292	0.13	0.078	**0.269**	**0.781****

(Values on diagonal are direct effects and values on horizontal lines are indirect effects)

The direct effect of OM-Zn was very high (0.431) and its indirect effect through total Zn (0.303) was also high (table 155). The direct effect of amorphous FeO occluded Zn was high (0.395).The direct effect of residual Zn was high, its indirect effect through MnO - Zn was moderate and negative (-0.278), and that through amorphous FeO occluded Zn was high and negative (-0.357).

4.6.2.5 Correlation coefficients of available Zn and Zn content in plant with fractions of Zn at panicle initiation under flooded system

Available Zn had positive significant correlations with water soluble + exchangeable Zn (0.414*), MnO-Zn (420*), OM Zn (0.454*) and amorphous Fe oxide occluded Zn (0.606**); was negatively and significantly correlated with residual Zn (-0.619*).

The zinc content in plant had positive significant correlations with water soluble + exchangeable Zn (0.941**), MnO-Zn (0.580**), OM-Zn (.927**) and amorphous Fe oxide occluded Zn (0.709**); was negatively correlated with crystalline Fe oxide occluded Zn (-0.426*) and residual Zn (-0.905*).

4.6.2.5.1. Path coefficients of available Zn with fractions of Zn at Panicle initiation under flooded system

Path coefficients of different fractions of Zn indicating the direct and indirect effects on available Zn at panicle initiation are given in the table 142.

Table 142. Path coefficients of available Zn with fractions of Zn at Panicle initiation under flooded rice cultivation

Fractions	Ws+Exch -Zn	MnO-Zn	OM-Zn	AmFeO -Zn	Res-Zn	Correlation coefficients
Ws+ exch-Zn	**0.276**	-0.255	0.269	0.485	-0.307	**0.468***
MnO –Zn	-0.154	**-0.349**	0.415	-0.168	0.676	**0.420***
OM –Zn	-0.235	-0.345	**0.282**	0.449	0.335	**0.486***
Am FeO – Zn	-0.179	-0.285	0.192	**0.729**	0.255	**0.712****
Res-Zn	-0.246	-0.387	0.157	-0.291	**0.148**	**-0.619****
(Values on diagonal are direct effects and values on horizontal lines are indirect effects)						

The direct effect of water soluble + exchangeable Zn was moderate (0.276). The indirect effects of water soluble + exchangeable Zn through MnO - Zn and through OM - Zn was moderate, that through Am FeO-Zn was very high (0.485). The direct effect of MnO-Zn was (-0.349) high. The indirect effect of MnO-Zn through OM-Zn (0.415) and residual Zn (0.676) were high. The direct effect of OM-Zn was high (0.282). The indirect effect of OM-Zn through water soluble + exchangeable Zn (-0.235) was moderate and negative that through MnO - Zn was high and negative (-0.345). The direct effect of Am FeO-Zn (0.729) was very high. The indirect effect of residual Zn t through MnO-Zn (-0.387) was very high and negative.

4.6.2.5.2 Path coefficients of Zn content in plant with fractions of Zn at Panicle initiation of flooded rice cultivation

Path coefficients of different fractions of Zn indicating the direct and indirect effects on Zn content in plant at PI are given in the table 143.

Table 143. Path coefficients of Zn content in plant with fractions of Zn at panicle initiation under flooded rice cultivation

Fractions	Ws+ exch-Zn	MnO - Zn	OM -Zn	Am FeO - Zn	Cr FeO-Zn	Residual	Correlation coefficients
Ws+ exch-Zn	**0.372**	0.198	0.399	0.137	-0.045	-0.121	**0.941****
MnO - Zn	0.179	**0.182**	0.189	0.142	-0.036	-0.076	**0.580****
OM -Zn	0.317	0.176	**0.452**	0.135	-0.056	-0.097	**0.927****
Am FeO -Zn	-0.085	0.152	0.276	**0.139**	-0.047	0.274	**0.709****
Cr FeO-Zn	-0.098	-0.156	0.139	-0.255	**-0.257**	0.201	**-0.426***
residual	-0.264	-0.137	0.156	-0.254	-0.249	**-0.157**	**-0.905****

(Values on diagonal are direct effects and values on horizontal lines are indirect effects)

The direct effect of water soluble + exchangeable Zn was very high (0.372). The indirect effect of water soluble + exchangeable Zn through OM Zn was high (0.399).

The direct effect of OM-Zn was very high (0.452) and its indirect effect of through water soluble + exchangeable Zn was very high (0.317). The direct effect of Am FeO-Zn was low and the indirect effect OM- Zn was moderate (0.276). The direct effect of crystalline Zn, as well as its indirect effect through Am FeO-Zn were moderate.

4.6.2.6 Correlation coefficients of available Zn and Zn content in straw with fractions of Zn at harvest under flooded system

Available Zn had positive significant correlations with, MnO-Zn (0.442*), and amorphous Fe oxide occluded Zn (0.703**), and it was negatively and significantly correlated with water soluble + exchangeable Zn (-0.842**), OM-Zn (-0.884**) and residual Zn (-0.458*).

The zinc content in straw had significant positive correlations with water soluble + exchangeable Zn (0.878**), MnO-Zn (0.898**) and residual Zn (0.429*) and was negatively and significantly correlated with acid soluble Zn (-.569**), OM Zn (-0.721**) and amorphous Fe oxide occluded Zn (-0.429**), crystalline Fe oxide occluded Zn (-0.426*).

4.6.2.6.1 Path coefficients of available Zn with fractions of Zn at harvest under flooded system

Path coefficients of different fractions of Zn indicating the direct and indirect effects on available Zn at harvest are given in the table 144.

Table 144. Path coefficients of available Zn with fractions of Zn at harvest of flooded rice cultivation

Fraction	Ws+ exch-Zn	Acid sol-Zn	MnO -Zn	OM - Zn	residual	Correlation coefficients
Ws+ exch-Zn	**-0.430**	0.104	-0.521	-0.077	0.082	-0.842**
Acid sol-Zn	0.242	**-0.184**	0.402	0.049	-0.068	0.703**
MnO –Zn	-0.354	0.117	**-0.633**	-0.082	0.0684	0.442*
OM –Zn	0.282	-0.077	0.441	**0.117**	-0.06	-0.884**
Residual	-0.26	0.092	-0.321	-0.052	**0.134**	-0.458*
(Values on diagonal are direct effects and values on horizontal lines are indirect effects)						

The direct effect of water soluble + exchangeable Zn was very high and negative (-0.430) and its indirect effect through MnO- Zn was very high (-0.521).

The indirect effect of acid soluble Zn through MnO-Zn was very high. The direct effect of MnO-Zn was very high and negative (-0.633) and its indirect effect through water soluble Zn was high (-0.354). The indirect effect of OM- Zn through MnO-Zn was very high (0.441). The indirect effect of residual Zn through MnO-Zn was high and negative (-0.321).

4.6.2.6.2 Path coefficients of Zn content in straw with fractions of zn at harvest under flooded rice cultivation

Path coefficients of different fractions of Zn indicating the direct and indirect effects on Zn content in straw at harvest are given in the table 145.

Table 145. Path coefficients of Zn content in straw with fractions of Zn at harvest under flooded rice cultivation

Fractions	Ws+ exch-Zn	Acid sol Zn	MnO -Zn	OM-Zn	Am FeO -Zn	Res-Zn	Correlation coefficients
Ws+ exch-Zn	**0.450**	0.049	0.402	0.036	0.058	-0.118	**0.878**
Acid sol Zn	-0.254	**-0.087**	-0.308	-0.023	0.005	0.098	**-0.569**
MnO –Zn	0.372	0.055	**0.487**	0.038	0.045	-0.099	**0.898**
OM –Zn	-0.295	-0.036	-0.339	**-0.054**	-0.084	0.087	**-0.721**
Am FeO –Zn	-0.107	0.002	-0.09	-0.019	**-0.244**	0.029	**-0.429**
Residual	0.272	0.043	0.248	0.024	0.037	**-0.195**	**0.429**
(Values on diagonal are direct effects and values on horizontal lines are indirect effects)							

The direct effect of water soluble + exchangeable Zn was very high (0.450) and its indirect effect through MnO-Zn was high (0.402). The indirect effect of acid soluble Zn through Ws+ExCh-Zn was moderate and negative, and that through MnO-Zn was high and negative (-0.308). The direct effect of MnO-Zn (0.487), as well as its indirect effect through Ws+ExCh-Zn (0.372) was high. The indirect effect of OM-Zn through Ws+ExCh-Zn (-0.295) was moderate and negative. The direct effect of Am FeO-Zn was moderate and negative.

4.7 Distribution of fractions of boron, correlations of boron fractions with available boron and boron content in plant and path coefficients at different stages.

The distribution of different B fractions as percentage of total B, correlations of available B and B content in plant, as well as the path coefficients indicating the direct and indirect effects are presented hereunder.

4.7.1 Percentage distribution of boron under aerobic and flooded systems of rice

The fractions of boron expressed as percentage of total boron under aerobic and flooded systems of rice is given in tables 147 to 151. Under both systems of rice, the dominant fraction with highest boron content was residual boron which constituted 91.55 and 90.45 per cent in aerobic and flooded systems respectively at initial stage. The remaining was distributed among other four fractions. Among them, oxide bound boron was dominated with 5.26 % under aerobic and 6.07 % under flooded system. This was followed by organic matter bound boron with 2.86 % in aerobic and 3.09 % in flooded system. Specifically adsorbed fraction constituted 0.24 % and 0.27 % under aerobic and flooded systems respectively. Readily soluble fraction was the one with least percentage contribution with 0.08 % and 0.12 % under aerobic and flooded systems respectively.

4.7.1.1 Readily soluble Boron

Application of fertilizers as per soil test increased the soluble B under both systems of rice cultivation and recorded 0.62 % and 1.62 % under aerobic and anaerobic systems respectively at active tillering stage (table 146).

Table 146. Distribution of readily soluble boron under aerobic and flooded systems

Stages of sampling	Aerobic rice					Flooded rice				
	F_1	F_2	L_1	L_2	L_3	F_1	F_2	L_1	L_2	L_3
Initial	0.08	0.08	0.08	0.08	0.08	0.11	0.11	0.11	0.11	0.11
AT	0.06	0.62	0.35	0.35	0.31	0.09	1.62	0.87	0.87	0.82
PI	0.04	0.67	0.36	0.37	0.34	0.09	1.63	0.87	0.88	0.82
Harvest	0.03	0.70	0.37	0.38	0.35	0.06	1.54	0.82	0.86	0.80

The distribution of boron in readily soluble fraction decreased in treatments where fertilizers were applied as per POP in both systems and recorded 0.06% under aerobic and 0.09 % under flooded system at this stage.

At panicle initiation, the distribution of boron in readily soluble pool remained almost similar under flooded system (0.09 %) whereas, it was decreased to 0.04 % under aerobic system in treatments where fertilizers were applied as per POP. In treatment with fertilizers as per soil test, it increased to 0.67 % under aerobic system, while it remained almost similar (1.63 %) under flooded system.

The distribution of readily soluble boron increased in treatments where fertilizers applied as per soil test at harvest also with 0.70 % (aerobic condition) and it decreased under flooded system (1.54 %). Application of fertilizers as per POP decreased the distribution of boron in readily soluble pool to 0.03 % and 0.06 % under aerobic and flooded conditions respectively.

Application of different doses of lime also changed the distribution of readily soluble boron under both systems of rice cultivation. Under aerobic system, the RS-B was found increased with lime application at active tillering when compared with that at initial stage. The highest increase of 0.35 % was observed in both lime treatments (*i.e.*) as per ΔpH and as per POP. Similar trends were observed at panicle initiation and at harvest with an increasing trend at each dose of lime.

Under flooded situation, application of different doses of lime showed a different trend. In all the lime treatments, the percentage of RS-B increased at active tillering stage and remained almost constant throughout the cropping period.

4.7.1.2 Specifically adsorbed boron

Application of fertilizers as per soil test increased the specifically adsorbed boron under both systems of rice cultivation; recorded 0.32 % and 0.39% under aerobic and anaerobic systems respectively at active tillering stage. The distribution of in specifically adsorbed boron decreased under both systems from active tillering to harvest stages (table 147).

Table 147. Distribution of specifically adsorbed boron under aerobic and flooded systems

Stages of sampling	Aerobic rice					Flooded rice				
	F_1	F_2	L_1	L_2	L_3	F_1	F_2	L_1	L_2	L_3
Initial	0.24	0.24	0.24	0.24	0.24	0.27	0.27	0.27	0.27	0.27
AT	0.20	0.32	0.25	0.25	0.27	0.25	0.39	0.34	0.32	0.31
PI	0.09	0.28	0.18	0.19	0.18	0.19	0.36	0.24	0.26	0.22
Harvest	0.07	0.23	0.14	0.15	0.15	0.09	0.30	0.21	0.21	0.19

Under both systems of rice cultivation, irrespective of lime application the distribution of specifically adsorbed boron recorded a slight increase under aerobic environment and a substantial increase under flooded environment at active tillering stages, further in both systems it showed a decreasing trend.

4.7.2.3 Oxide bound boron

The percentage contribution of oxide bound boron showed an increasing trend under both aerobic and flooded environment in treatments with fertilizers as well as with lime. Among the fertilizer treatments the increase was more conspicuous with fertilizers applied as per soil test. Thus, the highest percentage of this fraction was recorded in treatment F_2 at harvest (8.95 % under aerobic and 12.17 % under flooded system) (Table148).

Table 148. Distribution of oxide bound boron under aerobic and flooded systems

Stages of sampling	Aerobic rice					Flooded rice				
	F_1	F_2	L_1	L_2	L_3	F_1	F_2	L_1	L_2	L_3
Initial	5.26	5.26	5.26	5.26	5.26	6.08	6.08	6.08	6.08	6.08
AT	5.67	6.13	5.79	5.91	5.99	5.83	7.03	6.26	6.39	6.64
PI	6.04	8.32	6.88	7.16	7.51	6.50	8.46	7.31	7.49	7.63
Harvest	6.73	8.95	7.56	7.95	8.01	7.16	12.17	9.26	9.65	10.07

Comparison of different lime treatments indicated that oxide bound boron increased gradually from initial to harvest stages; the increase was more pronounced in the case of lime treatment as per SMP buffer method. Thus the percentage contribution of oxide bound boron increased from 5.26 to 8.01 % in aerobic system and from 6.08 to10.07 % under flooded system in lime treatment as per SMP buffer method.

4.7.2.4 Organic matter bound boron

The distribution of organic matter bound boron under both systems is presented hereunder.

Table 149. Distribution of organic matter bound boron under aerobic and flooded systems

Stages of sampling	Aerobic rice					Flooded rice				
	F_1	F_2	L_1	L_2	L_3	F_1	F_2	L_1	L_2	L_3
Initial	2.87	2.87	2.87	2.87	2.87	3.09	3.09	3.09	3.09	3.09
AT	4.27	5.33	4.62	4.74	5.01	3.57	4.77	4.03	4.18	4.30
PI	3.90	4.75	4.18	4.13	4.48	3.28	4.44	3.77	3.85	3.90
Harvest	3.64	4.33	3.89	3.97	4.09	3.01	4.00	3.36	3.52	3.63

Application of fertilizers as per soil test increased the organic matter bound boron under both systems of rice cultivation; recorded 5.33 % and 4.77 % under aerobic and anaerobic systems respectively at active tillering stage (table 149). The distribution of boron in organic matter bound pool increased in treatments where fertilizers were applied as per POP in both systems and recorded 4.27 % under aerobic and 3.57 % under flooded system at this stage in comparison with that at initial. The contribution of organic matter bound boron decreased in treatments where fertilizers were applied as per soil test at PI with 4.75 % (aerobic condition) and 4.44 % (flooding). The same trend was observed at harvest also in treatments where fertilizers applied as per soil test with 4.33 % (aerobic condition) and 4.0 % (flooding). Application of fertilizers as per POP decreased the distribution of boron in specifically adsorbed pool to 3.64 % and 3.01 % under aerobic and flooded condition.respectively at harvest.

Application of different doses of lime also influenced the distribution of organic matter bound boron under both systems. The organic matter bound B increased with lime application at active tillering when compared with that at initial stage. Under aerobic rice system, the highest increase of 5.01 % was observed in lime applied treatments as per SMP buffer method, followed by lime as per ΔpH (4.74 %). At panicle initiation and at harvest the organic matter bound boron was found reduced. Under flooded rice system, same increasing trend from initial to active tillering and then declining till harvest was noticed with highest percentage reduction in lime applied plots as per POP.

In general, the distribution of organic matter bound boron was shown an increasing trend at active tillering and then decreased till harvest under both systems.

4.7.2.5 Residual boron

Application of fertilizers as per soil test decreased the residual boron slightly under both systems of rice cultivation; recorded 89.81% and 90.26 % under aerobic and anaerobic systems respectively at active tillering stage (table 150).

Table 150. Distribution of residual boron under aerobic and flooded systems

	Aerobic rice					Flooded rice				
	F_1	F_2	L_1	L_2	L_3	F_1	F_2	L_1	L_2	L_3
Initial	91.55	91.55	91.55	91.55	91.55	90.45	90.45	90.45	90.45	90.45
AT	87.61	89.81	89.90	88.72	88.42	86.19	90.26	88.50	88.43	87.93
PI	85.98	89.93	88.39	87.97	87.49	85.12	90.02	87.82	87.52	87.37
Harvest	85.81	89.53	88.31	87.56	87.40	81.99	89.68	86.35	85.82	85.34

The distribution of boron in residual pool decreased in treatments where fertilizers applied as per POP in both systems and recorded 87.61 % under aerobic and 86.19 % under flooded system at this stage in comparison with that at initial stage. The percentage contribution of residual boron increased in treatments where fertilizers applied as per soil test at PI to 89.93 % (aerobic condition) and decreased to 90.02 % under flooded system. At harvest, in treatments where fertilizers applied as per soil test recorded almost similar pattern of distribution as that in PI stage (89.53 % in aerobic condition and 89.68 % under flooding). Application of fertilizers as per POP decreased the contribution of boron in residual pool to 85.98 % at PI and 85.81% at harvest under aerobic condition; and 85.12 % and 81.99 % at harvest under flooded condition.

Application of different doses of lime also influenced the distribution of residual boron under both systems of rice cultivation. Under both systems of rice cultivation, the residual B gradually decreased with lime application from active tillering till harvest.

4.7.3.1 Correlations of available B with fractions of B at active tillering of aerobic rice

The available B had significant positive correlation with RS-B (0.963**), OX-B (0.911**) and total boron (0.919**).

The B content in plant was significantly and positively correlated with RS-B (0.997), SA-B (0.974), OX-B (0.929) and total B (0.939).

4.7.3.1.1 Path coefficients of available B with fractions at Active tillering under aerobic rice

Path coefficients of different fractions of B indicating the direct and indirect effects on available B at active tillering are given in the table 151.

Table 151. Path coefficients of available B with fractions at active tillering under aerobic rice

	RS-B	SA-B	OX-B	Total B	Correlation coefficients
RS-B	**1.072**	-0.140	0.110	-0.044	**0.998****
SA-B	1.037	**-0.145**	0.117	-0.046	**0.963****
OX-B	0.976	-0.140	**0.112**	-0.046	**0.911****
Total B	0.991	-0.141	0.117	**-0.048**	**0.919****
(Values on diagonal are direct effects and values on horizontal lines are indirect effects)					

The direct effect of RS-B on hot water extractable B at active tillering was very high (1.072). The indirect effect of SA-B through RS-B was very high (1.037). The indirect effects of OX-B and Total-B through RS-B were very high.

4.7.3.1.2 Path coefficients of B content in plant with fractions of B at active tillering under aerobic rice

The direct and indirect effects of B content in plant with fractions of B at active tillering are presented in table 152.

Table 152. Path coefficients of B content in plant with fractions of B at active tillering of aerobic rice

	RS-B	SA-B	OX-B	RES-B	Correlation coefficients
RS-B	**0.929**	-0.132	0.130	0.070	**0.997****
SA-B	0.899	**-0.137**	0.138	0.074	**0.974****
OX-B	0.846	-0.132	**0.143**	0.073	**0.929****
Total B	0.859	-0.133	0.138	**0.076**	**0.939****
(Values on diagonal are direct effects and values on horizontal lines are indirect effects)					

The data showed that the direct effect of RS-B on B content in plant was very high and positive (0.929). The indirect effects of SA-B, OX-B and total B through RS-B was very high

4.7.3.2 Correlations of available B and B content in plant with fractions of P at panicle initiation under aerobic system

Hot water extractable B had high significant correlation with RS-B (0.999**), OX-B (0.953**) RES-B (0.831**) and total B (0.940**).

B content in plant was significantly and positively correlated with RS-B (0.996), OX-B (0.933), RES-B (0.916) and total B (0.922).

4.7.3.2.1 Path coefficients of available B with fractions at panicle initiation under aerobic rice

The direct as well as the indirect effects of different fractions of soil B on available B content in the soil at panicle initiation are presented in table 153.

Table 153. Path coefficients of available B with fractions at panicle initiation under aerobic system

	RS-B	OX-B	RES-B	Total B	Correlation coefficients
RS-B	**0.960**	-0.308	-2.424	2.771	0.999**
OX-B	0.917	**-0.322**	-2.255	2.911	0.953**
RES-B	0.901	-0.318	**-2.584**	2.937	0.935**
Total B	0.906	-0.319	-2.584	**2.937**	0.941**
(Values on diagonal are direct effects and values on horizontal lines are indirect effects)					

Table 153 shows the direct as well as the indirect effects of different fractions of soil B on available B content in the soil at panicle initiation.

The direct effect of readily soluble boron (0.960) and its indirect effects through oxide bound boron (-0.308), through residual boron (-2.424) and through total boron (2.771) were high

The direct effect of OX B on available B was high and negative (-0.322); its indirect effects through RS B (0.917) was very high, and that through residual (-2.255) was very high and negative.

RES-B had a high direct negative effect on available B at PI (-2.584); its indirect effects through other fractions were also very high.

4.7.3.2.2 Path coefficients of B content in plant with fractions of B at panicle initiation under aerobic system

The direct and indirect effects of B content in plant with fractions of B at panicle initiation are presented in table 154.

Table 154. Path coefficients of B content in plant with fractions of B at panicle initiation under aerobic rice

	RS-B	OX-B	RES-B	Total B	Correlation coefficients
RS-B	**1.287**	-0.025	2.686	-2.952	0.997**
OX-B	1.230	**-0.026**	2.830	-3.101	0.974**
RES-B	1.207	-0.025	**2.863**	-3.129	0.929**
Total B	1.214	-0.025	2.863	**-3.129**	0.939**
(Values on diagonal are direct effects and values on horizontal lines are indirect effects)					

The data showed that the direct effect of RS B on B content in plant were very high (1.287). The indirect effect of RS B through RES B was very high (2.686), and that through total B was very high and negative (-2.952). The indirect effects of oxide bound boron through other fractions were very high. The direct and indirect effects of RES-B were very high except that through OX-B. The direct and indirect effects of total B were very high and negative.

4.7.3.3 Correlations of available B and boron content in plant with fractions of B under aerobic rice at harvest

Hot water extractable B had high significant correlation with RS B (0.997**), OX-B (0.973**) RES-B (0.909**) and total B (0.921**).

The boron content in plant was significantly and positively correlated with RS-B (0.838), OX-B (0.977), RES-B and total B (0.762).

The boron content in grain was significantly and positively correlated with RS B (0.994**), OX B (0.958), RES B (0.898) RS-B had significant correlation with SA-B (0.911**), OX-B (0.848**), and RES-B (0.666**).

4.7.3.3.1 Path coefficients of available B with fractions at harvest

The path coefficients indicating the direct and indirect effects on available B at harvest are presented hereunder.

Table 155. Path coefficients of available B with fractions at harvest

	RS-B	OX-B	RES-B	Total B	Correlation coefficients
RS-B	**1.073**	0.942	5.535	-6.553	0.997**
OX-B	1.047	**0.965**	5.824	-6.8642	0.973**
RES-B	0.990	0.937	**5.999**	-7.0167	0.909**
Total B	1.001	0.943	5.996	**-7.0202**	0.921**

(Values on diagonal are direct effects and values on horizontal lines are indirect effects)

Table 155 shows the direct as well as the indirect effects of different fractions of soil B on available B content in the soil at harvest. Readily soluble B had very high direct effect (1.073) on available B; its indirect effects through OX-B, RES-B and total B were very high. OX-B had a very high direct effect (0.965) on available B and its indirect effects through other fractions were also very high and negative. So also is the case with residual and total boron.

4.7.3.3.2 Path coefficients of B content in plant with fractions of B at harvest in straw

The direct and indirect effects of B content in straw with fractions of B at harvest are presented in table 157.

Table 156. Path coefficients of B content in plant with fractions of B at harvest in straw

	RS-B	OX-B	RES-B	Correlation coefficients
RS-B	**0.903**	-0.3104	0.2451	0.838**
OX-B	0.6886	**-0.4072**	0.6958	0.977**
RES-B	0.2648	-0.3389	**0.8361**	0.762*
(Values on diagonal are direct effects and values on horizontal lines are indirect effects)				

The data (156) showed that the direct effect of RS-B on B content in straw was very high (0.903), its indirect effect through OX-B and that through residual B were high (negative) and moderate respectively. The direct effects of OX- B (-0.4072) and residual boron (0.8361) on P content in straw were very high.

4.7.3.3. 3 Path coefficients of B content in plant with fractions of B at harvest in grain

The direct and indirect effects of B content in grain with fractions of B at harvest are presented in table 158.

Table 157. Path coefficients of B content in plant with fractions of B at harvest in grain

	RS-B	OX-B	RES-B	Correlation coefficients
RS-B	**1.243**	-0.232	-0.017	**0.994**
OX-B	1.214	**-0.238**	-0.018	**0.958****
RES- B	1.147	-0.231	**-0.018**	**0.898***
(Values on diagonal are direct effects and values on horizontal lines are indirect effects)				

The data (157) showed that the direct effect of RS-B as well as the indirect effects OX-B and RES-B through RS-B were also very high on B content in grain was very high. The direct effect of OX- B on B content in grain was moderate.

4.7.3.3 Correlations of available B with fractions of B at active tillering under flooded rice

Hot water extractable B had very high positive correlation with RS-B (0.933**), SA-B (0.947), OX-B (0.815**) and total boron (0.714**).

Boron content in shoot had very high positive correlation with RS-B (0.963**), SA-B (0.939), OX-B (0.989**) residual boron (0.789**) and total B (0.819).

4.7.3.3.1 Path coefficients of available B with fractions of B of flooded rice at active tillering

The direct and indirect effects of hot water extractable B with fractions of B at active tillering are presented in table 158.

Table 158. Path coefficients of available B with fractions of B of flooded rice at active tillering

	RS-B	SA-B	OX-B	Total B	Correlation coefficients
RS-B	**4.020**	-1.491	-1.602	0.006	0.933**
SA-B	3.994	**-1.500**	-1.553	0.006	0.947**
OX-B	3.873	-1.402	**-1.663**	0.007	0.815**
Total B	3.263	-1.182	-1.386	**0.008**	0.704**

(Values on diagonal are direct effects and values on horizontal lines are indirect effects)

The data showed that the direct effects of RS-B(4.020), SA-B(-1.500) and OX-B(-1.663) were very high. The indirect effects of all these fractions through the other fractions except that through total B were very high.

4.7.3.3.2 Path coefficients of B content in shoot with fractions of B of flooded rice at active tillering

The direct and indirect effects of B content in plant with fractions of B at active tillering are presented in table 159.

Table 159. Path coefficients of B content in shoot with fractions of B of flooded rice at active tillering

	RS-B	SA-B	OX-B	RES-B	Total B	Correlation coefficients
RS-B	**-1.139**	0.311	-0.237	-0.199	0.299	0.963**
SA-B	-1.231	**0.316**	-0.229	0.069	0.137	0.939**
OX-B	-1.194	0.295	**-0.246**	0.104	0.052	0.989**
RES-B	-0.969	0.239	-0.198	**0.429**	1.287	0.789**
Total B	-1.006	0.249	-0.205	0.594	**1.187**	0.819**

(Values on diagonal are direct effects and values on horizontal lines are indirect effects)

The data showed that the direct effect of RS-B on B content in plant was very high and negative (-1.139). The direct effect of SA-B (0.316) on B content in plant was high, and its indirect effect through RS-B, was very high and negative (-1.231). The direct effects of OX-B was moderate and negative and that of residual boron was very high

4.7.3.4 Correlations of available B with fractions of B of flooded rice at panicle initiation

Hot water extractable B had very high positive correlation with RS-B (0.981**), SA-B (0.980), OX-B (0.937**) and residual boron (0.925**).

Boron content in shoot had significant positive correlation with RS-B (0.744**), SA-B (0.862), OX-B (0.994**) and residual boron (0.874**).

Readily soluble B was significantly and positively correlated with SA-B (0.993**), OX-B (0.984**) and RES-B (0.972**).

4.7.3.4.1 Path coefficients of available B with fractions of B of flooded rice at panicle initiation

The direct and indirect effects of hot water extractable B with fractions of B at panicle initiation are presented in table 160.

Table 160. Path coefficients of available B with fractions of B of flooded rice at panicle initiation

	RS-B	SA-B	OX-B	RES-B	Correlation coefficients
RS-B	**1.756**	0.156	-1.257	0.326	**0.981****
SA-B	1.745	**0.157**	-1.241	0.320	**0.980****
OX-B	1.728	0.153	**-1.277**	0.333	**0.937****
RES-B	1.706	0.150	-1.266	**0.335**	**0.925****

(Values on diagonal are direct effects and values on horizontal lines are indirect effects)

The data showed that the direct effect of RS-B on available B was very high (1.756) and its indirect effect through OX-B (-1.257) was very high and negative and through residual boron was high (0.326). The indirect effects of SA-B through RS-B, OX-B and RES-B were very high or high. The direct effect of OX- B was found very high and negative (-1.277). The direct effect of RES B was high (0.335).

4.7.3.4.2 Path coefficients of B content in shoot with fractions of B under flooded rice at panicle initiation

The data on Path coefficients of B content in shoot with fractions of B of flooded rice at panicle initiation are presented hereunder.

Table 161. Path coefficients of B content in shoot with fractions of B under flooded rice at panicle initiation

	RS-B	SA-B	OX-B	RES-B	Correlation coefficients
RS-B	**-0.7613**	0.5113	1.1203	-0.1266	0.744**
SA-B	-0.7490	**0.5196**	1.2628	-0.1712	0.862**
OX-B	-0.5889	0.4402	**1.4481**	-0.3054	0.994**
RES-B	-0.2722	0.2513	1.2493	**-0.3540**	0.874**
(Values on diagonal are direct effects and values on horizontal lines are indirect effects)					

The data (table 161) showed that the direct effects of RS-B as well as its indirect effects through SA-B, OX-B and RES-B were very high. The direct effect of SA B on B content in plant as well as, its indirect effect through OX-B were very high and positive while the indirect effects through RS-B was high and negative. The direct effect of OX- B was very high. The direct effect of RES-B on B content in shoot was high and negative.

4.7.3. 5. Correlations of available B, B content in straw, grain with fractions of B under flooded rice at harvest

The hot water extractable B had very high positive correlation with RS-B (0.982**), SA-B (0.989), OX-B (0.945**) and residual boron (0.925**).

The boron content in straw had very high positive correlation with RS-B (0.961**), SA-B (0.951), OX-B (0.989**) residual boron (0.969**) and total B (0.974).

The boron content in grain had very high positive correlation with RS-B (0.963**), SA-B (0.953) and OX-B (0.989**).

4.7.3.5.1 Path coefficients of available B with fractions of B of flooded rice at harvest

The direct and indirect effects of hot water extractable B with fractions of B at harvest are presented in table 162.

Table 162. Path coefficients of available B with fractions of B of flooded rice at harvest

	RS-B	SA-B	OX-B	RES-B	Correlation coefficients
RS-B	**0.352**	1.182	-0.630	0.079	**0.982****
SA-B	0.351	**1.185**	-0.624	0.078	**0.989****
OX-B	0.347	1.157	**-0.639**	0.080	**0.945****
RES-B	0.341	1.133	-0.630	**0.081**	**0.925****
(Values on diagonal are direct effects and values on horizontal lines are indirect effects)					

The data showed that the direct effect of RS-B on available B was high and positive; its indirect effect through SA B was very high and positive and that through OX-B was very high and negative. The direct effect of SA-B on B hot water extractable B as well as, its indirect effect through RS-B, and OX-B were very high. The direct effect of OX- B was very high and negative while its indirect effect through RS-B and SA-B were very high and positive, so also is the case with OX-B.

4.7.3.5.2 Path coefficients of B content in straw with fractions of B of flooded rice at harvest

The data (table 163) showed that the direct and indirect effects of RS-B on B content in straw were high, either negative or positive.

Table 163. Path coefficients of B content in straw with fractions of B of flooded rice at harvest

	RS-B	SA-B	OX-B	RES-B	Total B	Correlation coefficients
RS-B	**-0.805**	0.371	2.711	5.157	-6.474	0.961**
SA-B	-0.802	**0.372**	2.685	5.089	-6.393	0.951**
OX-B	-0.793	0.363	**2.749**	5.246	-6.576	0.989**
RES-B	-0.779	0.355	2.710	**5.322**	-6.639	0.969**
Total B	-0.784	0.358	2.722	5.320	**-6.642**	0.974**
(Values on diagonal are direct effects and values on horizontal lines are indirect effects)						

The direct effect of SA-B as well as its indirect effect through RS-B, OX-B and RES-B was very high. The direct and indirect effects of OX- B were very high. The direct and indirect effects of RES- B on B content in straw were also very high. The same is the case with the direct and indirect effect of total B on B content in straw.

4.7.3.5.3 Path coefficients of B content in grain with fractions of B under flooded rice at harvest

The data on path coefficients of B content in grain with fractions of B under flooded rice at harvest are presented in table 164.

Table 164. Path coefficients of B content in grain with fractions of B under flooded rice at harvest

	RS-B	SA-B	OX-B	Correlation coefficients
RS-B	**-0.601**	0.767	0.765	0.931**
SA-B	**-0.799**	**0.359**	1.393	0.953**
OX-B	-0.590	**0.330**	**1.250**	0.990**
(Values on diagonal are direct effects and values on horizontal lines are indirect effects)				

The data (Table 164) showed that the direct and indirect effects of RS-B on B content in plant were very high. Similarly the direct as well as indirect effects of SA-B well as OX-B were also high

4.8 Yield attributes, yield and physiological parameters under aerobic and flooded systems

The yield and yield attributes under aerobic and flooded systems are presented hereunder.

4.8.1 Yield attributes under aerobic and flooded systems

The yield attributes viz. number of tillers per hill, number of panicles per hill, number of grains per panicle, thousand grain weight, fresh root CEC and apparent free space are presented in the table from 165 to 169.

Table 165. Effect of fertilizers and lime on number of tillers per hill at active tillering

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	**Mean**
F_1	12.75	13.00	13.50	**13.08**
F_2	15.25	15.00	13.50	**14.58**
Mean	**14.00**	**14.00**	**13.50**	**13.83**
C D F 1.40	**CD L N. S**		**C D FxL1.57**	
Flooded rice				
F_1	8.00	9.75	12.00	**9.92**
F_2	10.00	13.00	9.00	**10.67**
Mean	**9.00**	**11.38**	**10.50**	**10.29**
C D F NS	**CD L 2.14**		**C D F x L 2.32**	
C D pooled 0.21				

4.8.1.1. Number of tillers per hill at active tillering

The data presented in table 165 showed that application of fertilizers as per soil test (F_2) found significant in increasing the number of tillers per hill at active tillering under aerobic rice (14.58), while the effect of fertilizers was not significant under flooded system. Liming did not show any significant difference in increasing number of tillers per hill at active tillering under aerobic system. But, under flooded system, liming as per ΔpH (L_2) was significant (11.38) in improving number of tillers per hill, followed by liming (L_3) as per SMP buffer method (10.50) and both were on par.

Among the interactions under aerobic rice, application of fertilizers as per soil test with lime based on POP (F_2L_1) was found significantly superior in improving number of tillers per hill at active tillering in aerobic rice (15.25), followed by F_1L_2, (15). Under flooded rice, application of fertilizers as per soil test with lime based on ΔpH (F_2L_2), recorded the highest number of tillers per hill (13.00), followed by application of fertilizers as per POP with lime based on SMP buffer (F_1L_3) (12 number of tillers per hill).

Aerobic rice recorded significantly higher number of tillers per hill (13.96) at active tillering stage in comparison with that of flooded system (10.29).

Table 166: Effect of fertilizers and lime on number of tillers per hill at panicle initiation

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	Mean
F_1	13.50	13.00	13.50	**13.33**
F_2	14.75	15.25	14.25	**14.75**
Mean	**14.13**	**14.13**	**13.88**	**14.04**
CD F 1.35	C D L N S		C D Fx L 1.56	
Flooded rice				
F_1	6.00	7.50	9.50	7.67
F_2	7.50	9.75	7.00	**8.08**
Mean	**6.75**	**8.63**	**8.25**	**7.88**
CD F N S	**C D L 1.89**		**C D Fx L 1.69**	
C D pooled 3.56				

4.8.1.2 Number of tillers per hill at panicle initiation

The data presented in table 166 showed that application of fertilizers as per soil test (F_2) was found significant in increasing number of tillers under aerobic rice cultivation (14.75), in comparison with that of treatment as per POP (13.33). Effect of applied fertilizers was not significant under flooded system.

Under flooded system, lime as per ΔpH (L_2) was significant in improving number of tillers per hill (8.63), followed by that in lime as per SMP buffer method (L_3) (8.25) and both were on par. Effect of doses of lime was not significant under aerobic rice at this stage.

Among the interaction of applied lime with fertilizers under aerobic rice, application of fertilizers as per ΔpH with lime based on POP (F_2L_2) recorded significantly higher number of tillers per hill (15.25), followed by that with application of fertilizers as per POP with lime based on (F_2L_1), (14.75).

Under flooded system, fertilizers as per soil test with lime based on ΔpH (F_2L_2) was found significant with respect to number of tillers (9.75) when compared with other treatments, followed by application of fertilizers as per POP with lime based on SMP buffer method (F_1L_3), which recorded 9.50 number of tillers per hill and were on par.

Aerobic rice recorded significantly higher number of tillers per hill (14.04) in comparison with that of flooded system (7.88). However, the tiller count reduced at panicle initiation than that at active tillering under flooded system.

Table 167: Effect of fertilizers and lime on number of panicles per hill

Aerobic rice				
	L_1	**L_2**	**L_3**	**Mean**
F_1	11.75	11.5	12	**11.75**
F_2	11.75	12	12.75	**12.17**
Mean	**11.75**	**11.75**	**12.38**	**11.96**
CD F N.S	CDL N.S		CD F x L N.S	
Flooded rice				
F_1	4.75	5.5	6.5	**5.58**
F_2	6.25	6.75	5.25	**6.08**
Mean	**5.5**	**6.13**	**5.87**	**5.83**
CD F N S	CD L 0.52		CD FxL1.65	
C D pooled 3.15				

4.8.1.3 Number of panicles per hill

The data presented in table 167 revealed that there was no significant difference in number of panicles due to fertilizers and lime under aerobic system. Under flooded system, application of lime as per ΔpH (L_2) recorded significantly higher number of panicles per hill (6.13), which was on par with that of application of lime as per SMP (L_3) buffer method (5.87).

The effect of applied fertilizers was not significant under flooded rice cultivation. The treatment combinations of F_2L_2 and F_2L_1, 6.25 were on par.

Aerobic rice recorded significantly higher number of panicles per hill (11.96) in comparison with that in flooded system (5.88).

Table 168: Effect of fertilizers and lime on number of grains per panicle

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	Mean
F_1	75.75	81.25	85.25	**80.75**
F_2	78.25	84.25	90.25	**84.25**
Mean	**77.00**	**82.75**	**87.75**	**82.50**
C D F 1.59	**C D L1.95**		**C D FxL 2.76**	
Flooded rice				
F_1	77.55	79.25	81.62	79.47
F_2	76.92	79.12	81.72	79.26
Mean	**77.24**	**79.19**	**81.67**	**79.37**
C D F NS	**C D L 1.24**		**C D FxL 3.00**	
C D pooled 2.95				

4.8.1.4 Number of grains per panicle

The data presented in table 168 showed that, under aerobic system, fertilizers applied as per soil test (F_2) recorded significantly higher number of grains per panicle (84.25) than that in fertilizers based on POP (80.75). Among the different doses of lime, application as per SMP buffer method (L_3) recorded significantly the highest number of grains per panicle (87.75).

Application of fertilizers as per soil test with lime as per SMP buffer method (F_2L_3) recorded significantly higher number of grains per panicle (90.25), followed by the treatment where fertilizers were applied as per POP with lime based on SMP buffer method (F_1L_3, 85.25).

Under flooded system, fertilizers treatments did not have any significant difference in increasing the number of grains per panicle. Application of lime as per SMP buffer method (L_3) recorded the highest number of grains per panicle (81.68). Among the treatment combinations, fertilizers applied as per soil test with lime based on SMP buffer method (F_2L_3) recorded significantly the highest number of grains per panicle (81.73) followed by that in fertilizers as per POP with lime as per SMP buffer method (F1L3) (81.63).

Aerobic condition (82.50) recorded significantly higher number of grains per panicle than that under flooded system (79.37).

Table 169: Effect of fertilizers and lime on thousand grain weight (g)

		Aerobic rice		
Fertilizer/lime	L_1	L_2	L_3	Mean
F_1	27.75	27.67	28.20	27.88
F_2	27.85	28.37	29.25	28.49
Mean	27.80	28.03	28.73	28.18
C D F 0.52	C D L 0.64		C D FxL 0.91	
		Flooded rice		
F_1	27.33	27.63	27.00	27.32
F_2	26.90	27.40	26.73	27.01
Mean	27.12	27.51	26.86	27.16
C D F NS	C D L 0.608		C D FxL 0.86	
C D pooled N S				

4.8.1.5 Thousand grain weight

Under aerobic system, applied fertilizers as per soil test (F_2) recorded significantly higher 1000 grain weight (28.49 g) in comparison with that in fertilizer applied as per POP (F_1, 27.88 g) (table 169). Under flooded system, effect of applied fertilizers was not significant.

Under aerobic system, lime as per SMP buffer method (L_3) recorded the highest 1000 grain weight (28.73 g), followed by that by application as per ΔpH (L_2, 28.03 g). Application of fertilizers did not show any significant difference in enhancing 1000 grain weight

Under flooded system, lime as per ΔpH (L_2) recorded higher 1000 grain weight (27.51g), followed by lime as per POP (L_1) (27.12 g) and both were found on par.

Under aerobic system, among the interactions of applied lime with fertilizers, 1000 grain weight recorded in treatments F_2L_3 and F_2L_2 were on par, and was significantly superior to the other treatment combinations.

Under flooded system, fertilizers applied as per POP with lime based on ΔpH (F_1L_2) recorded significantly the highest 1000 grain weight (27.63 g), followed by that in fertilizers as per soil test with lime based on ΔpH (F_2L_2), (27.40 g).

There was no significant difference in 1000 grain weight between aerobic system (28.18 g) and under flooded system (27.16 g).

4.8.2. Yield

Effect of treatments on grain and straw yield under aerobic and flooded systems are presented in tables 170 and 171.

Table 170. Effect of fertilizers and lime on Grain yield (t ha^{-1})

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	**Mean**
F_1	5.94	6.02	6.18	**6.04**
F_2	6.10	6.30	6.84	**6.41**
Mean	**6.02**	**6.16**	**6.51**	**6.23**
C D F 0.3	**CD L 0.4**		**C D FxL 0.6**	
Flooded rice				
F_1	4.82	5.12	5.19	**5.04**
F_2	5.21	5.29	5.11	**5.20**
Mean	**5.01**	**5.21**	**5.15**	**5.12**
C D F N S	**CD L 0.20**		**C D F x L 0.35**	
C D pooled 0.41				

4.8.2.1 Grain yield

The data presented in table 170 showed that, under aerobic system, among the doses of lime, application based on SMP buffer method (L_3) recorded a grain yield of 6.51 tha^{-1}, followed by lime application as per ΔpH (L_2), which recorded 6.16 t ha^{-1}, were on par. On the other hand, under flooded system, lime based on ΔpH (L_2) recorded a grain yield of 5.21 tha^{-1}, which was on par with lime as per SMP buffer method (L_3), (5.15 t ha^{-1}).

Under both the systems, application of fertilizers as per soil test found significant in increasing the grain yield (6.41 kg plot^{-1} and 5.21 mg kg^{-1} under aerobic and flooded systems respectively), in comparison with that of fertilizer treatment as per POP (6.04 kg $plot^{-1}$ and 5.04 kg $plot^{-1}$ under aerobic and flooded systems respectively).

Under aerobic system, fertilizers as per soil test with lime based on SMP buffer method (F_2L_3) recorded significantly the highest grain yield (6.84 kg $plot^{-1}$) which was significantly higher than in treatment combination of fertilizers as per soil test with lime as per ΔpH (F_2L_2, 6.30 t ha^{-1}). Under flooded system, the interaction of fertilizers as per soil test with lime based ΔpH (F_2L_2) recorded significantly the highest grain yield (5.21t ha^{-1}), followed by the treatment where fertilizers as per soil test with lime as per POP (F_2L_1) (5.01 tha^{-1}).

Cultivation of rice under aerobic system recorded significantly higher grain yield (6.23 t ha^{-1}) than that under flooded system (5.12 tha^{-1}).

Table 171. Effect of fertilizers and lime on straw yield (t ha^{-1})

Aerobic rice				
Fertilizer/Lime	L_1	L_2	L_3	**Mean**
F_1	6.2	6.25	6.4	6.3
F_2	6.15	6.4	6.9	6.5
Mean	**6.2**	**6.35**	**6.65**	**6.4**
C D F N.S	**CD L 0.51**		**CD F x L 0.68**	
Flooded rice				
F_1	5.19	5.69	5.44	5.44
F_2	6.44	5.5	4.87	5.60
Mean	**5.81**	**5.59**	**5.15**	**5.52**
C D F NS	**CD L 1.06**		**C D F x L 1.35**	
C D pooled 0.21				

4.8.2.2 Straw yield

The data presented in table 171 showed that application fertilizer did not have any significant effect in increasing the straw yield under both the systems.

Under aerobic system, application of lime as per SMP buffer method (L_3) recorded significantly higher straw yield (6.65 tha^{-1}) among different doses of lime. But, under flooded system, lime as per POP recorded the highest straw yield (5.81t ha^{-1}).

Under aerobic system, application of fertilizers as per soil test with lime based on SMP buffer method (F_2L_3) recorded significantly the highest straw yield of 6.9 t ha^{-1}, followed by the treatment where fertilizers as per POP with lime as per SMP buffer method (F_2L_2) (6.4 t ha^{-1}).

Under flooded system, application of fertilizers as per soil test with lime based on POP (F_2L_1) recorded significantly the highest straw yield of 6.44 t ha^{-1}, followed by the treatment where fertilizers as POP with lime as per ΔpH (F_1L_2) (5.59 t ha^{-1}).

Cultivation of rice under aerobic system recorded significantly highest straw yield (6.4 t ha^{-1}) than that of flooded system (5.52 t ha^{-1}).

4.8.3. Root cation exchange capacity and apparent free space

The root cation exchange capacity and apparent free space under both systems of rice are discussed hereunder.

Table 172. Effect of fertilizers and lime on fresh root CEC (cmol (+) kg^{-1} root)

Aerobic rice				
Fertilizer /Lime	L_1	L_2	L_3	**Mean**
F_1	2.53	1.53	1.76	**1.94**
F_2	1.64	1.36	1.20	**1.40**
Mean	**2.09**	**1.45**	**1.48**	**1.67**
C D F 0.015	**CD L 0.018**		**CD Fx L0.026**	
Flooded rice				
F_1	1.13	0.88	1.26	**1.09**
F_2	1.03	0.81	1.26	**1.03**
Mean	**1.08**	**0.85**	**1.26**	**1.06**
C D F 0.015	**CD L 0.018**		**CD Fx L 0.025**	
C D pooled 0.53				

4.8.3.1 Fresh root CEC

Under both systems, (table 172) the application of fertilizers as per POP (F_1) was found significant in increasing the fresh root CEC (1.94 c mol (+) kg^{-1} root under aerobic system and 1.09 c mol (+) kg^{-1} under flooded system), in comparison with that of treatment as per soil test (1.49 c mol (+) kg^{-1} root and 1.03 c mol (+) kg^{-1} root under aerobic and flooded system respectively).

Under aerobic system, lime application based on POP (L_1) recorded significantly higher fresh root CEC (2.09 c mol (+) kg^{-1} root), followed by lime as per SMP buffer method (L_3), which recorded 1.48 c mol (+) kg^{-1} root.

Under flooded system, among the doses of lime, application based on SMP buffer method (L_3) recorded significantly the highest root CEC (1.26 c mol (+) kg^{-1}), followed by lime application as per POP (L_1, 1.08 c mol (+) kg^{-1}).

Under aerobic system, applied fertilizers and lime based POP (F_1L_1) recorded significantly the highest fresh root CEC (2.53 c mol (+) kg^{-1}) followed by the treatment where fertilizers as per POP with lime as per SMP buffer method (F_1L_3) (1.76 c mol (+) kg^{-1}).

Under flooded system, treatment F_1L_3 and F_2L_3 were on par and significantly. Aerobic rice recorded significantly higher fresh root CEC (1.67 c mol (+) kg^{-1}) than that under flooded system (1.06 c mol (+) kg^{-1}).

Table 173. Effect of fertilizers and lime on apparent free space (cm^3 g^{-1})

Aerobic rice				
Fertilizer /Lime	L_1	L_2	L_3	**Mean**
F_1	3.00	4.07	3.65	3.57
F_2	3.20	3.95	3.58	3.58
Mean	3.10	4.01	3.61	3.57
C D F N.S:	C D L 0.28		C D FxL 0.32	
Flooded rice				
F_1	2.90	3.60	3.60	3.34
F_2	3.10	3.50	3.30	3.30
Mean	2.98	3.53	3.45	3.32
CD F N.S:	C D L 0.24		C D FxL N.S	
C. D pooled N.S.				

4.8.2.7 Apparent free space

The data presented in table 173 showed that application of fertilizers did not show any significant difference in increasing apparent free space under both systems.

Among the doses of lime, under both the systems, application based on ΔpH (L_2) recorded significantly superior apparent free space (4.01 $cm^3\ g^{-1}$ and 3.53 $cm^3\ g^{-1}$ under aerobic and flooded system), followed by lime application as per SMP buffer method (L_3), (3.61 $cm^3\ g^{-1}$ under aerobic and 3.45 $cm^3\ g^{-1}$ under flooded system).

Under aerobic system, applied fertilizers as per POP and lime based on ΔpH (F_1L_2) recorded significantly the highest apparent free space (4.07 $cm^3\ g^{-1}$) followed by fertilizer application as per soil test with lime based on ΔpH (F_2L_2) with an apparent free space of 3.95 $cm^3\ g^{-1}$. Interaction effect was not significant under flooded system.

There was no significant difference in apparent free space between aerobic and flooded systems.

Table 174. Other Biometric observations at active tillering

Growing condition	Shoot mass	Root mass	Root volume	Root length
Aerobic rice	210.97g	18.60 g	30.00cm^3	55.00 cm
Flooded rice	172.61g	13.90g	23.50 cm^3	29.00 cm

The parameters shoot mass, root mass, root length and root volume were higher under aerobic system (table 174).

Physiological traits under aerobic and flooded system viz. Chlorophyll content and aerenchyma formation are discussed here under.

4.9. The effect of fertilizers and lime on Chlorophyll 'a'content in flag leaf

The chlorophyll content (Chlorophyll a, b and total chlorophyll) in flag leaf under aerobic and flooded systems are presented in table 175 to 177.

Table 175. The effect of fertilizers and lime on chlorophyll 'a' content in flag leaf ($mg\ g^{-1}$)

Aerobic rice				
Fertilizer /Lime	L_1	L_2	L_3	Mean
F_1	1.85	1.87	1.88	**1.86**
F_2	1.86	1.87	1.87	**1.87**
Mean	**1.85**	**1.87**	**1.87**	**1.86**
C D F N.S	C D L 0.28		C D FxL N S	
Flooded rice				
F_1	1.83	1.82	1.82	**1.82**
F_2	1.81	1.81	1.82	**1.81**
Mean·	**1.82**	**1.81**	**1.82**	**1.81**
CD F N.S	C D L N. S		C D FxL N.S	
C. D pooled 0.04				

4.9.1 Chlorophyll a content in flag leaf

The data presented in table 175 revealed that the effect of applied lime and fertilizers as well as their interaction was not significant under both systems of rice cultivation. However, aerobic rice recorded higher chlorophyll a than that under flooded system.

Table 176. The effect of fertilizers and lime on chlorophyll 'b' content in flag leaf ($mg\ g^{-1}$)

Aerobic rice				
Fertilizer /Lime	L_1	L_2	L_3	Mean
F_1	0.55	0.56	0.55	**0.55**
F_2	0.56	0.55	0.54	**0.55**
Mean	**0.55**	**0.55**	**0.54**	**0.55**
C D F N.S	C D L N S		C D FxL N. S	
Flooded rice				
F_1	0.54	0.51	0.52	**0.52**
F_2	0.54	0.53	0.53	**0.53**
Mean	**0.54**	**0.52**	**0.52**	**0.52**
CD F N.S	C D L N S		C D FxL N.S	
C. D pooled N S				

4.9.2 Chlorophyll b content in flag leaf

The data presented in table 177 revealed that the effect of applied lime and fertilizers as well as their interaction was not significant under both systems of rice cultivation.

Table 177.The effect of fertilizers and lime on total chlorophyll content in flag leaf (mg g^{-1})

Aerobic rice				
Fertilizer /Lime	L_1	L_2	L_3	**Mean**
F_1	2.4	2.43	2.43	**2.41**
F_2	2.4	2.43	2.43	**2.41**
Mean	**2.4**	**2.43**	**2.43**	**2.41**
C D F N.S	C D L N S		C D FxL N. S	
Flooded rice				
F_1	2.37	2.33	2.34	**2.34**
F_2	2.35	2.34	2.35	**2.34**
Mean	**2.36**	**2.33**	**2.34**	**2.34**
CD F N.S	C D L N S		C D FxL N.S	
C. D pooled N S				

4.9.3 Total chlorophyll content in flag leaf

The data presented in table 177 revealed that the effect of applied lime and fertilizers as well as their interaction was not significant under both systems of rice cultivation.

4.10 Aerenchyma development in roots under aerobic and flooded systems

The cross section of the rice roots from both the systems were studied to observe the difference if any, in aerenchyma tissue development. Well developed aerenchyma tissues were observed under flooded system in comparison with that in aerobic rice, where it was not well developed.

4.11 Total water requirement by the crop

The data on total water requirement by the crop is presented in table 178.

Table 178. Total water requirement by the crop

System of rice cultivation	Depth of irrigation	Duration of irrigation	No of days of irrigations	Total water requirement (L)	Yield (kg)	Water requirement to produce 1kg rice
Aerobic rice	4cm	Once in two days	47	18.8×10^6	6230	3018L
Flooded rice	5cm	Daily	87	43.5×10^6	5120	8497L

The water requirement of the crop under both systems was calculated for the crop duration of 94 days, from transplanting one week prior to harvest of the crop. Under flooded system, 5 cm of standing water was maintained in the field from throughout the crop growth. Under aerobic system 4cm irrigation (800 Lm^2) was given on alternate days. A reduction of 57 per cent in water requirement was recorded for rice under aerobic condition.

Table 179. Cost of cultivation under aerobic and flooded systems

Cost of cultivation									
Treatments	Urea (Rs 6 kg^{-1})	Factomphos (Rs.8.5 kg^{-1})	MOP (Rs 12 kg^{-1})	$MgSO_4$ Rs. 20 kg^{-1}	Borax (Rs. 70 kg^{-1})	CaO (Rs 9 kg^{-1})	Labour charges Rs	Plant protection Rs	Total Rs (a)
Aerobic rice									
F_1L_1	586.8	1912	900	0	0	5400	24645	2000	35443.8
F_1L_2	586.8	1912	900	0	0	6984	24645	2000	37027.8
F_1L_3	586.8	1912	900	0	0	76500	24645	2000	106543.8
F_2L_1	516.5	1798	954	1600	700	5400	24645	2000	37613.48
F_2L_2	516.5	1798	954	1600	700	6984	24645	2000	39197.48
F_2L_3	516.5	1798	954	1600	700	76500	24645	2000	108713.5
Flooded rice									
F_1L_1	586.8	1912	900	0	0	5400	24645	2000	35443.8
F_1L_2	586.8	1912	900	0	0	6201	24645	2000	36244.8
F_1L_3	586.8	1912	900	0	0	21600	24645	2000	51643.8
F_2L_1	516.5	1798	954	1600	700	5400	24645	2000	37613.48
F_2L_2	516.5	1798	954	1600	700	6201	24645	2000	38414.48
F_2L_3	516.5	1798	954	1600	700	21600	24645	2000	53813.48

Table 180. Gross and net returns from the treatments under aerobic and flooded systems

Treatments	Grain yield (kg ha^{-1})	Straw yield (kg ha^{-1})	Returns price/grain Rs. 14 kg^{-1} (b)	Returns price/straw Rs. 3 kg^{-1} (c)	Gross return (Rs.) d=(b+c)	Net return (Rs.) e=(d-a)
			Aerobic rice			
F1L1	5940	6200	83160	18600	101760	66316.2
F1L2	6020	6250	84280	18750	103030	66002.2
F1L3	6180	6400	86520	19200	105720	-823.8
F2L1	6100	6150	85400	18450	103850	66236.52
F2L2	6300	6400	88200	19200	107400	**68202.52**
F2L3	6840	6900	95760	20700	116460	7746.52
			Flooded rice			
F1L1	4820	5190	67480	14460	81940	46496.2
F1L2	5120	5690	71680	15360	87040	50795.2
F1L3	5190	5440	72660	15570	88230	36586.2
F2L1	5210	6440	72940	15630	88570	50956.52
F2L2	5290	5500	74060	15870	89930	**51515.52**
F2L3	5110	4870	71540	15330	86870	33056.52

4.12. Cost of cultivation and net return from aerobic and flooded systems

The data on cost of cultivation including fertilizer inputs, lime, labour charges, and cost for plant protection are presented in table 179. The data showed that, under both systems of rice cultivation, cost of cultivation had increased in treatments where lime was applied as per SMP buffer method. Between these two, the highest increase was recorded in aerobic system since the quantity of lime applied was much higher when compared with that under flooded system. This situation was reflected in the net returns also (table180), where the lowest returns was recorded in lime application as per SMP buffer method under both systems. Under aerobic rice, a negative return was recorded in the treatment combination F_1L_3.

Under both systems, the treatment combination where fertilizers applied as per soil test with lime as per ΔpH (F_2L_2) recorded the highest net returns from the crop.

Discussion

5. Discussion

The results presented in chapter 4 are discussed here under with the support of available literature wherever possible. The data on different soil and plant parameters generated at different growth stages of the crop, the changes from the initial status in the experimental soils and possible chemical transformations under aerobic and flooded environment are discussed in detail.

The soil reaction of the experimental field on aerobic rice was extremely acidic (4.2), and that of flooded rice was very strongly acidic (4.9) at the onset of the experiment. The organic carbon and available phosphorus status of the soil in both the fields were medium. The available potassium status was low. Both the soils were severely deficient in available Ca and Mg. The level of available sulphur was sufficient. The soils were sufficient in all the available micronutrients except boron.

5.1 In situ measurement of soil pH, Electrical conductivity and redox potential

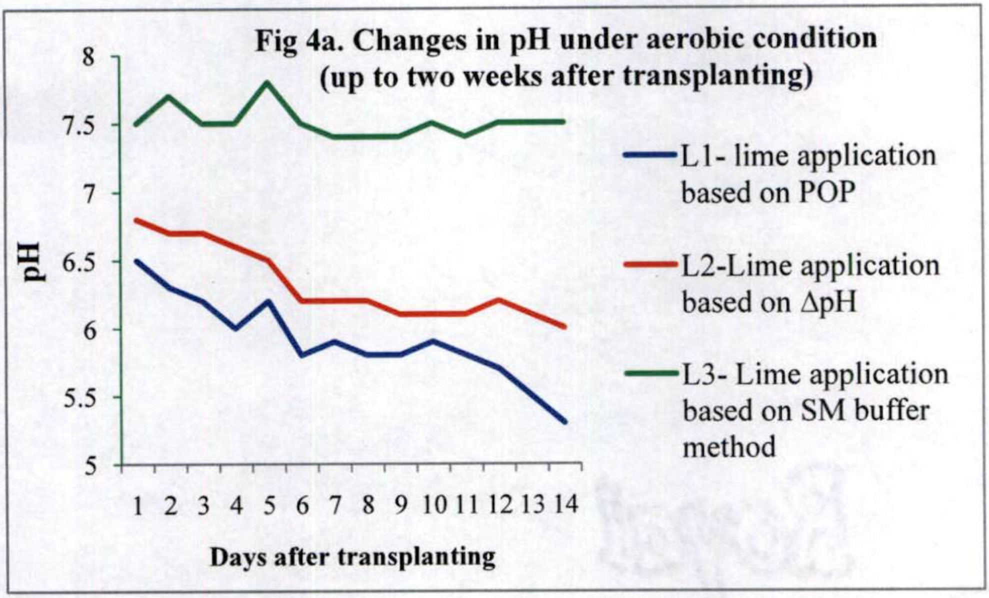
5.1.1. Soil pH

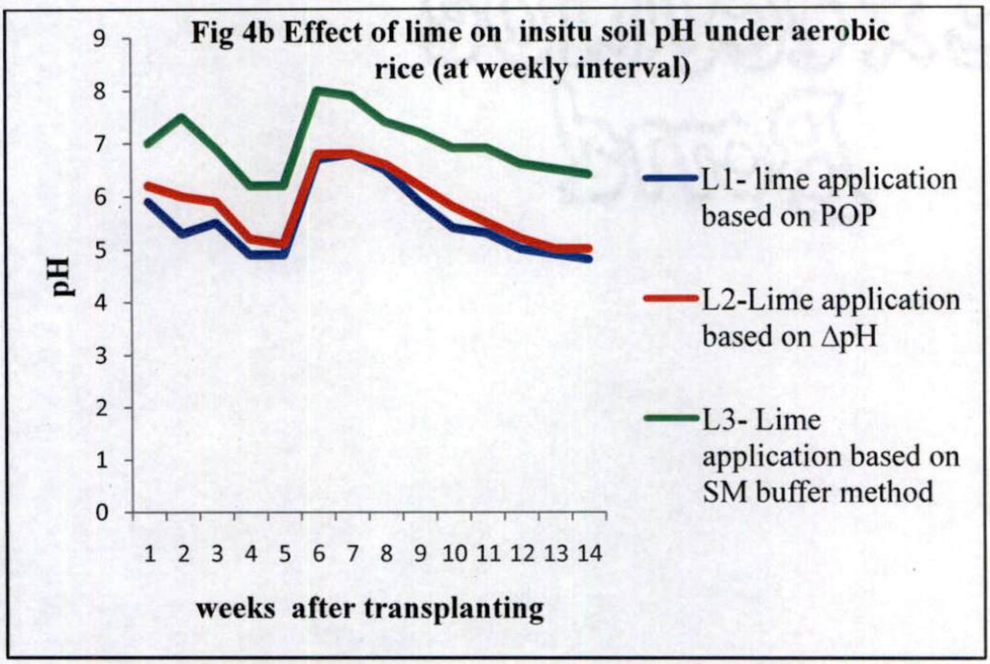
In situ measurement of soil pH was done immediately after transplanting till the harvest of the crop under both systems of rice cultivation. The pH increased immediately after application of lime, which was applied just before transplanting under both systems of rice cultivation. The rate of increase was in proportion to the quantity of lime applied under both systems. However, the rate was observed to be less under flooded system of rice. Soil pH was found to decrease to the initial level in plots of aerobic rice where lime was applied as per POP (L_1), while the pH was stabilized around six under flooded system. The pH attained the highest value of 8 at six weeks after transplanting in aerobic rice when lime was applied as per SMP buffer method, quantity being 8.5 t ha^{-1}. The corresponding pH under flooded system was 6.8 where the quantity of lime applied was 2.4 t ha^{-1} (table 5, fig 4).

5.1.2. Electrical conductivity

Under aerobic system, the EC recorded was in accordance with the quantity of lime applied. The highest EC recorded under the lime treatment as per SMP buffer

Fig 4.Insitu measurement of pH under aerobic and flooded systems





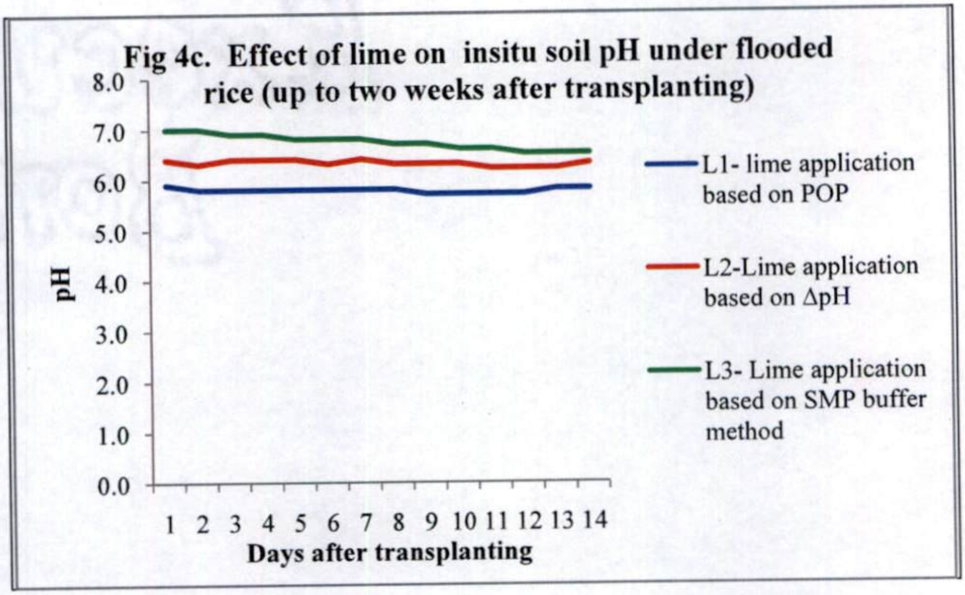


Fig 4c. Effect of lime on insitu soil pH under flooded rice (up to two weeks after transplanting)
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
pH
1 2 3 4 5 6 7 8 9 10 11 12 13 14
Days after transplanting
L1- lime application based on POP
L2-Lime application based on ΔpH
L3- Lime application based on SMP buffer method

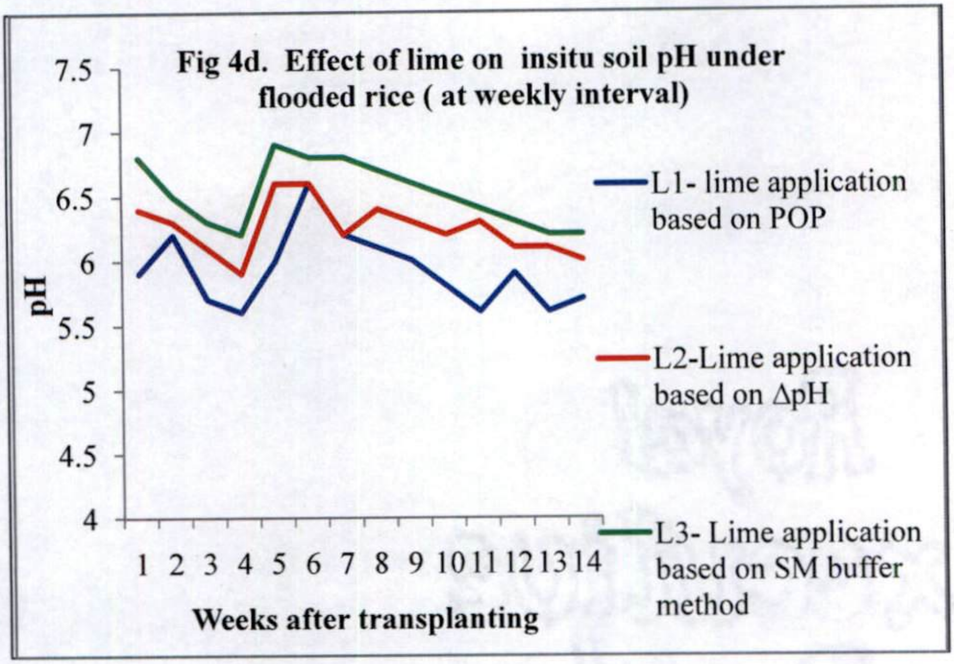
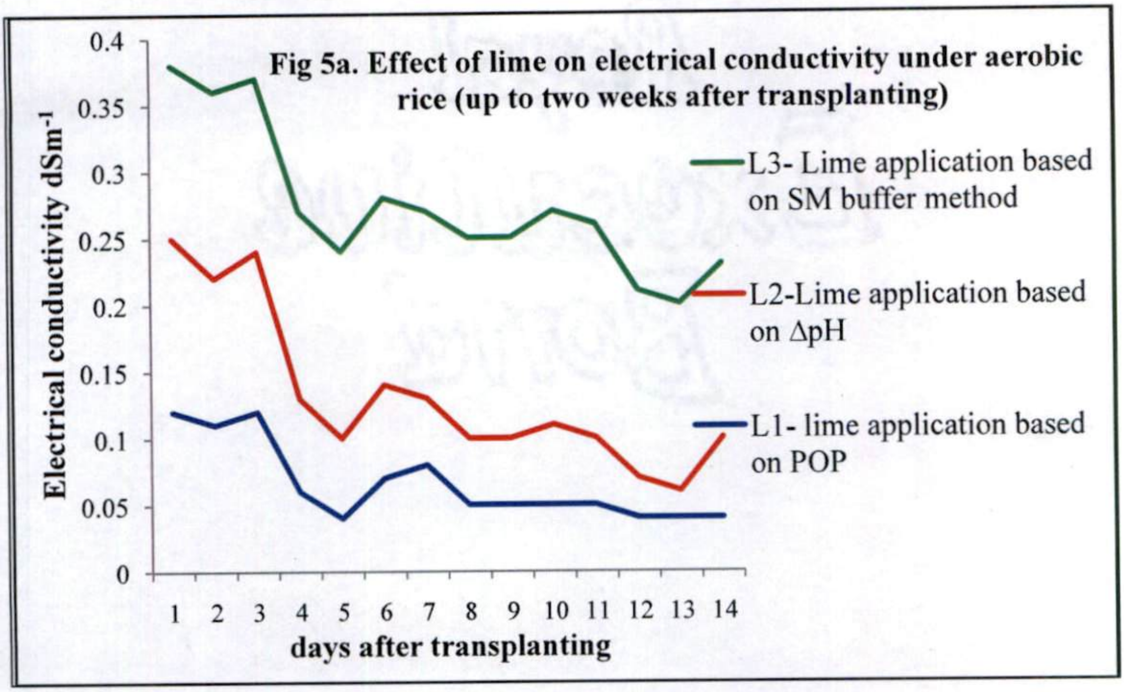
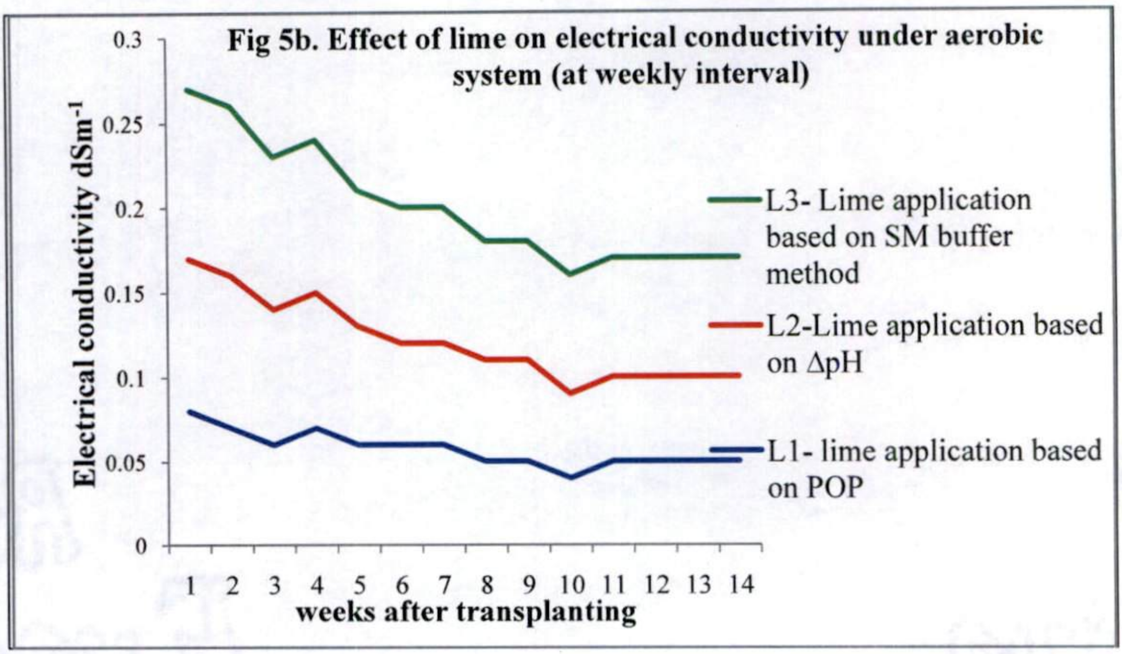


Fig 4d. Effect of lime on insitu soil pH under flooded rice (at weekly interval)
7.5
7
6.5
6
5.5
5
4.5
4
pH
1 2 3 4 5 6 7 8 9 10 11 12 13 14
Weeks after transplanting
L1- lime application based on POP
L2-Lime application based on ΔpH
L3- Lime application based on SM buffer method

Fig 5. Insitu measurement of electrical conductivity under aerobic and flooded systems





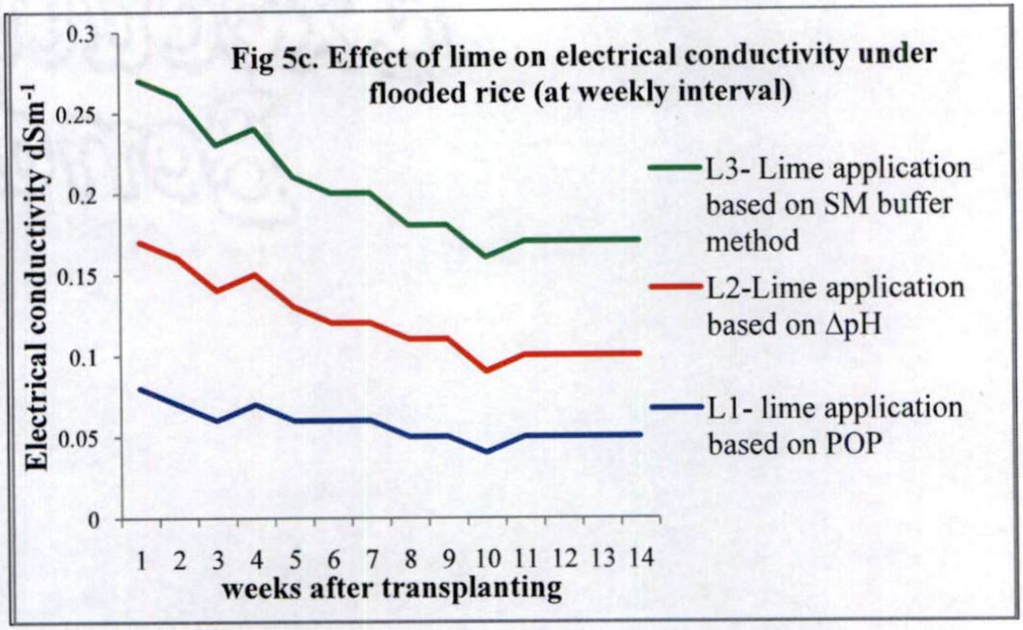


Fig 5c. Effect of lime on electrical conductivity under flooded rice (at weekly interval)
Electrical conductivity dSm-1
0.3
0.25
0.2
0.15
0.1
0.05
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14
weeks after transplanting
L3- Lime application based on SM buffer method
L2-Lime application based on ΔpH
L1- lime application based on POP

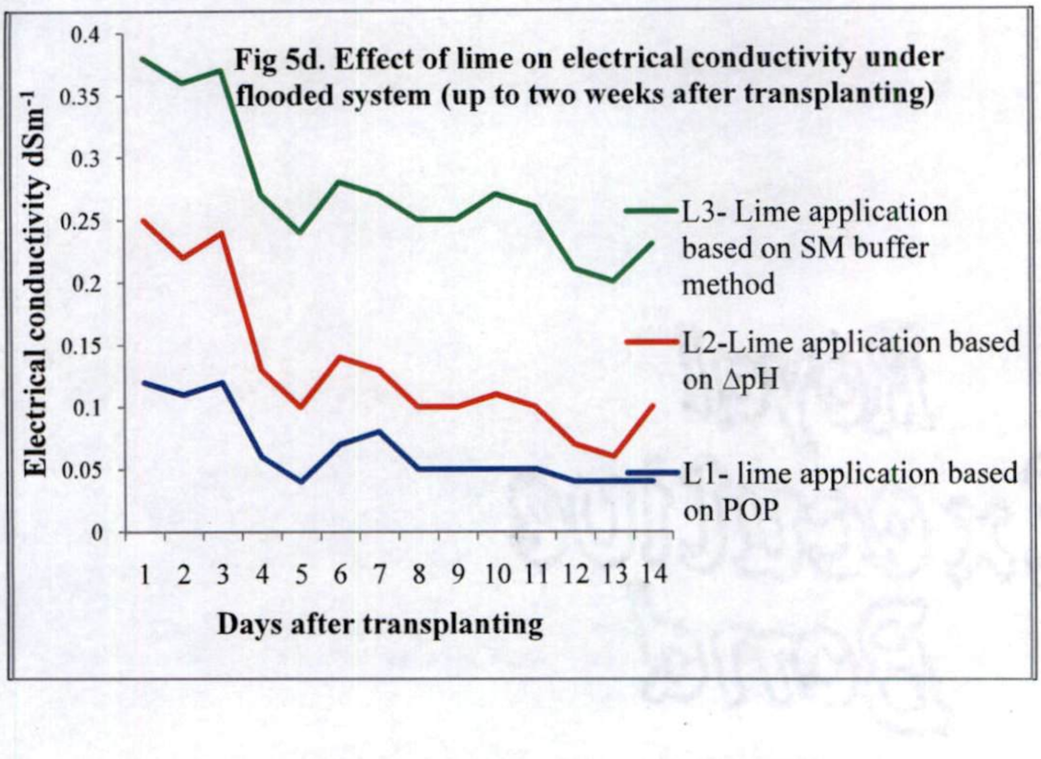
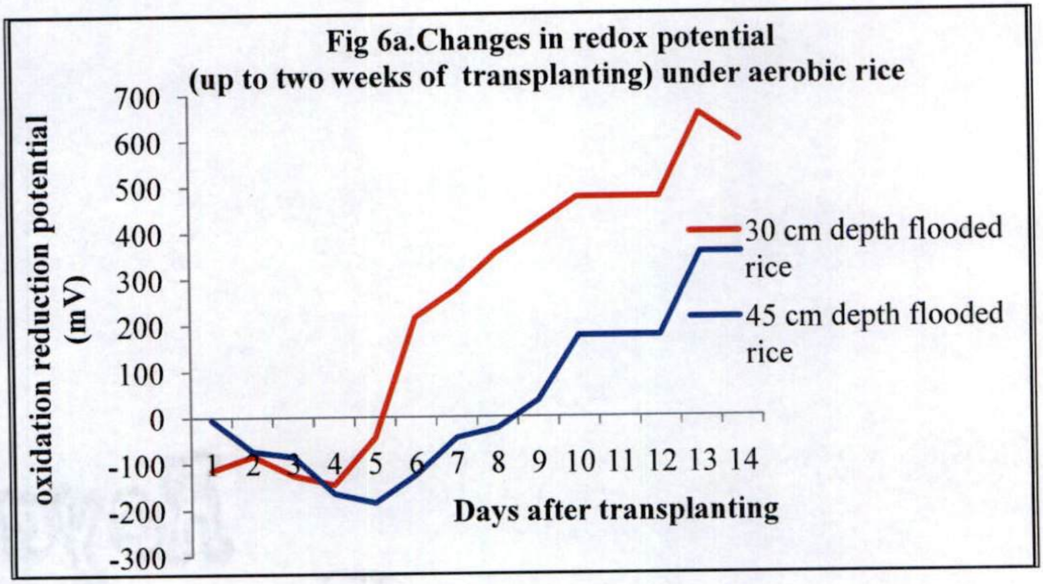
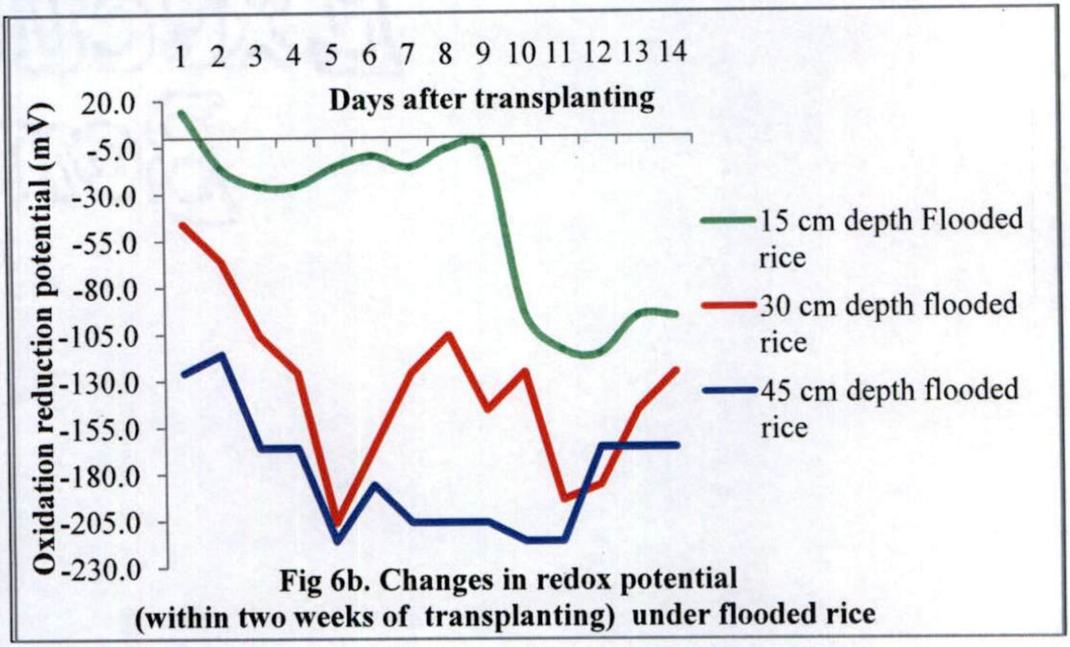


Fig 5d. Effect of lime on electrical conductivity under flooded system (up to two weeks after transplanting)
Electrical conductivity dSm-1
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14
Days after transplanting
L3- Lime application based on SM buffer method
L2-Lime application based on ΔpH
L1- lime application based on POP

Fig 6. Insitu measurement of redox potential under aerobic and flooded systems





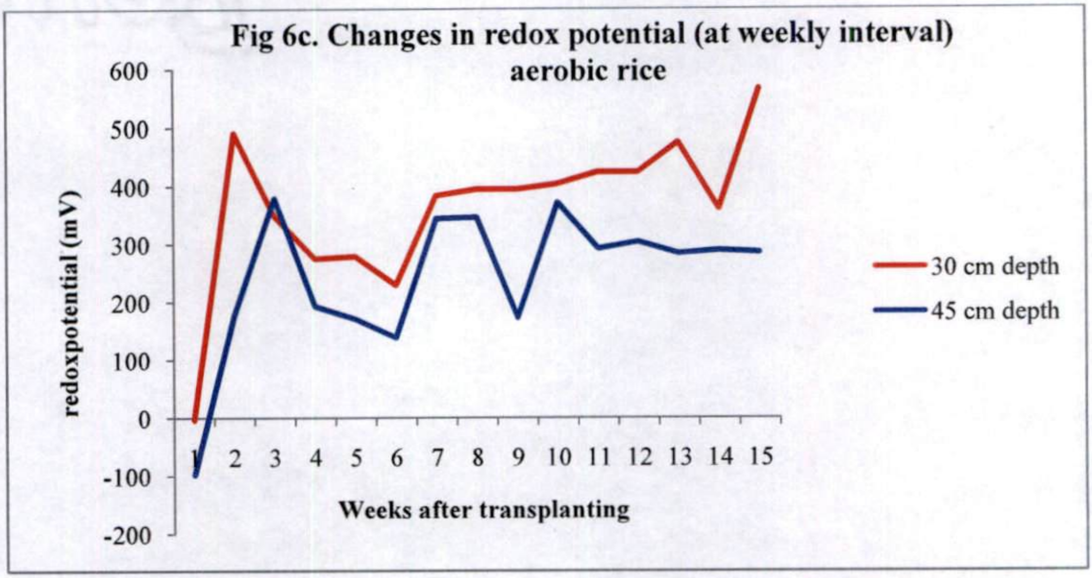


Fig 6c. Changes in redox potential (at weekly interval) aerobic rice
600
500
400
300
200
100
0
-100
-200
redoxpotential (mV)
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Weeks after transplanting
30 cm depth
45 cm depth

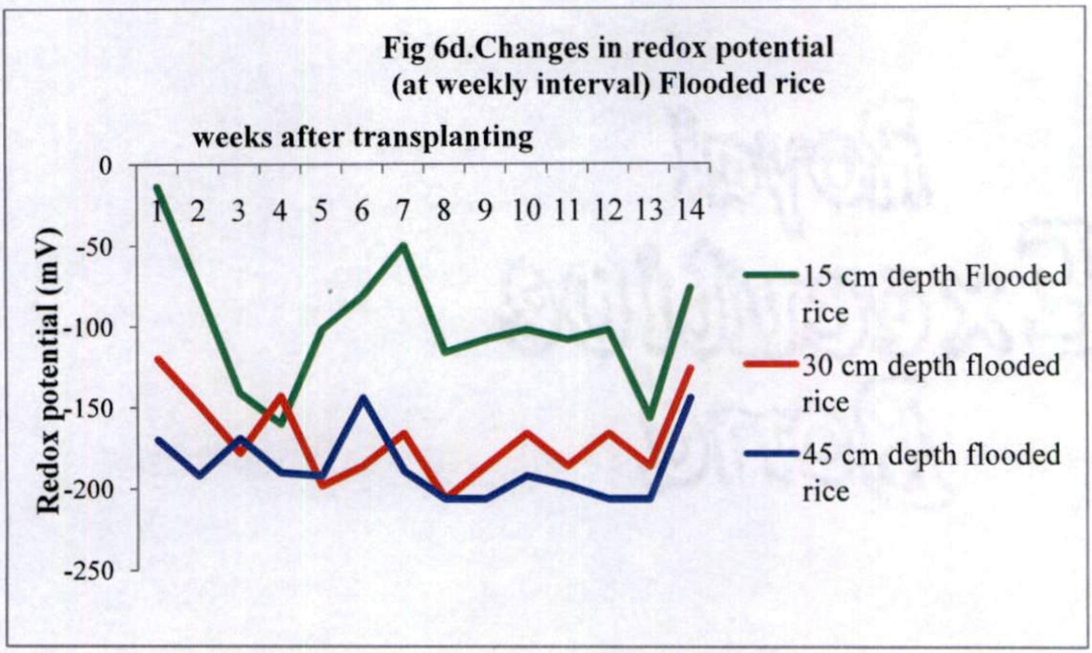


Fig 6d.Changes in redox potential (at weekly interval) Flooded rice
weeks after transplanting
0
-50
-100
-150
-200
-250
Redox potential (mV)
1 2 3 4 5 6 7 8 9 10 11 12 13 14
15 cm depth Flooded rice
30 cm depth flooded rice
45 cm depth flooded rice

method was 0.22 dSm^{-1} from six weeks to nine weeks after transplanting, the quantity of lime applied being the highest (8.5 t ha^{-1}). This naturally must have increased the electrolyte concentration attributing to the increase in EC (table 6, fig 5).

5.1.3 Redox potential

Under aerobic system, the redox potential which was negative at the start due to puddle environment which later transformed to positive values indicating the transformation of anaerobic environment to aerobic environment, which remained throughout the cropping season.

Under flooded system, the redox potential was negative throughout the cropping season which is an indication of maintenance of anaerobic environment and possible reduction of the entire system. There was more reduction in redox with the increase in depth (table 7, fig 6).

5.2. Effect of treatments on soil pH, EC and available nutrient status under aerobic and flooded systems.

The effect of applied lime and fertilizers on physicochemical properties viz. soil pH, EC, organic carbon, and available nutrient status under aerobic and flooded systems are discussed here under.

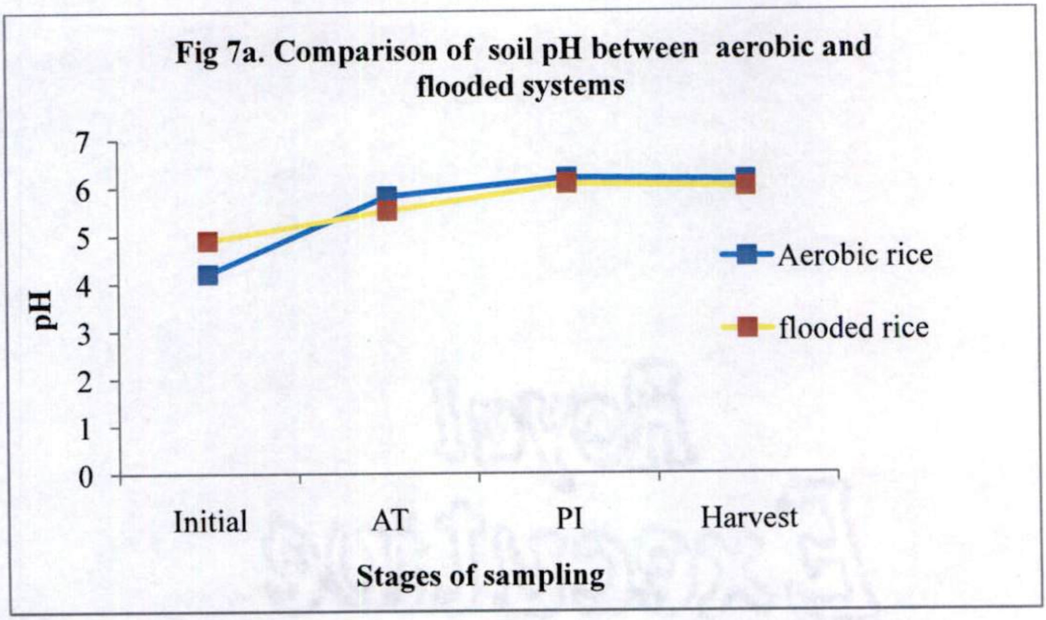
4.2.1. Soil pH

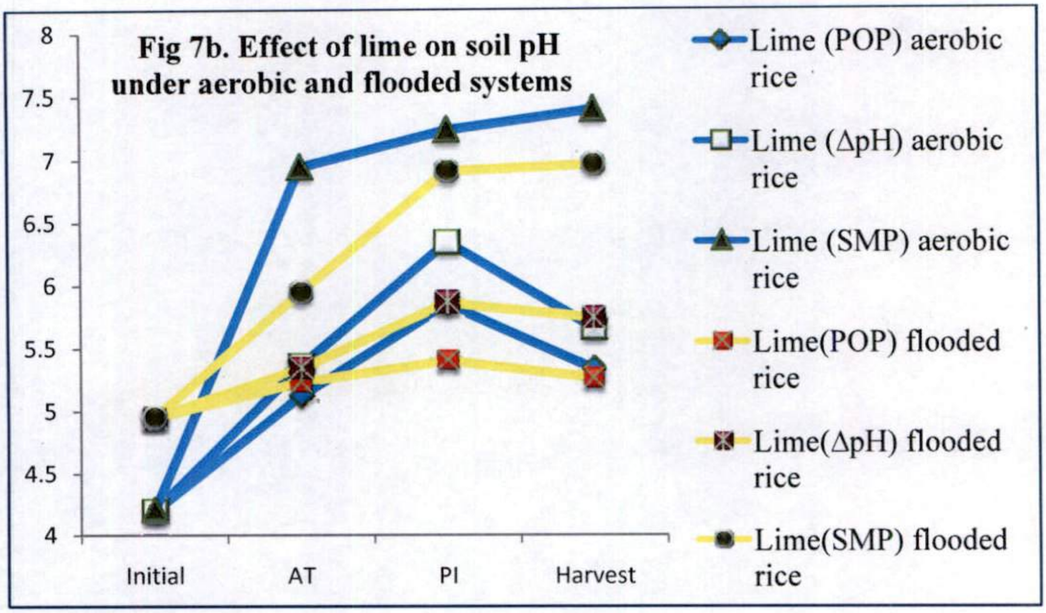
Under aerobic system, the soil pH increased from 4.2 (initial) to 7.4 (at harvest) in the lime treatment as per SMP buffer method (L_3). In lime as per ΔpH (L_2), and POP (L_1) the pH recorded at harvest were 5.7 and 5.3 respectively.

Under flooded system, the soil pH increased from an initial value of 4.9 to 7.0 at harvest in the lime treatment as per SMP buffer method (L_3). The other two lime treatments viz. application as per ΔpH (L_2), and POP (L_1), recorded a soil pH of 5.3 and 5.7 respectively.

Under both the systems, the increase in pH under the treatment where quantity of lime applied based on lime requirement estimated by SMP buffer method was

Fig 7. Changes in soil pH under aerobic and flooded systems





significantly much higher than the increase in pH resulted from the other two treatments viz. lime based on POP and ΔpH (table 8, 9,10 and fig 7).

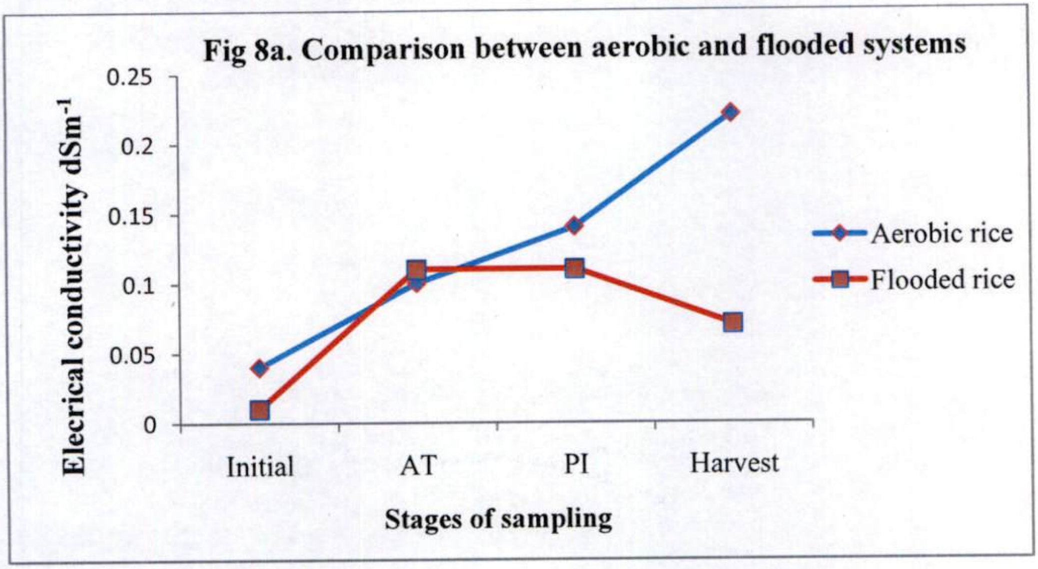
SMP buffer method of lime estimation, estimates the quantity of the lime to neutralize the total acidity, whereas the lime requirement based on ΔpH gives the lime required to neutralize the active acidity. Naturally the lime requirement estimated by SMP buffer method (8.5 $tha^{-1,}$ and 2.4 tonnes ha^{-1} under aerobic and flooded systems respectively) is much higher than the amounts recommended in POP (600 kg ha^{-1}) as well as the amount based on ΔpH (776 kg ha^{-1}, and 689 kg ha^{-1} under aerobic and flooded systems respectively). However, increase in pH was lesser in flooded situation for the same level of lime in comparison with that in aerobic situation. Even though, the treatments were based on the same method of estimation, quantity estimated was higher in aerobic soil since estimation was done on dry basis. This in turn resulted in recording the highest pH at different stages of the crop when compared with the other lime treatments. It can be concluded that irrespective of the method of rice cultivation, effectiveness of liming was superior when estimated by SMP buffer method.

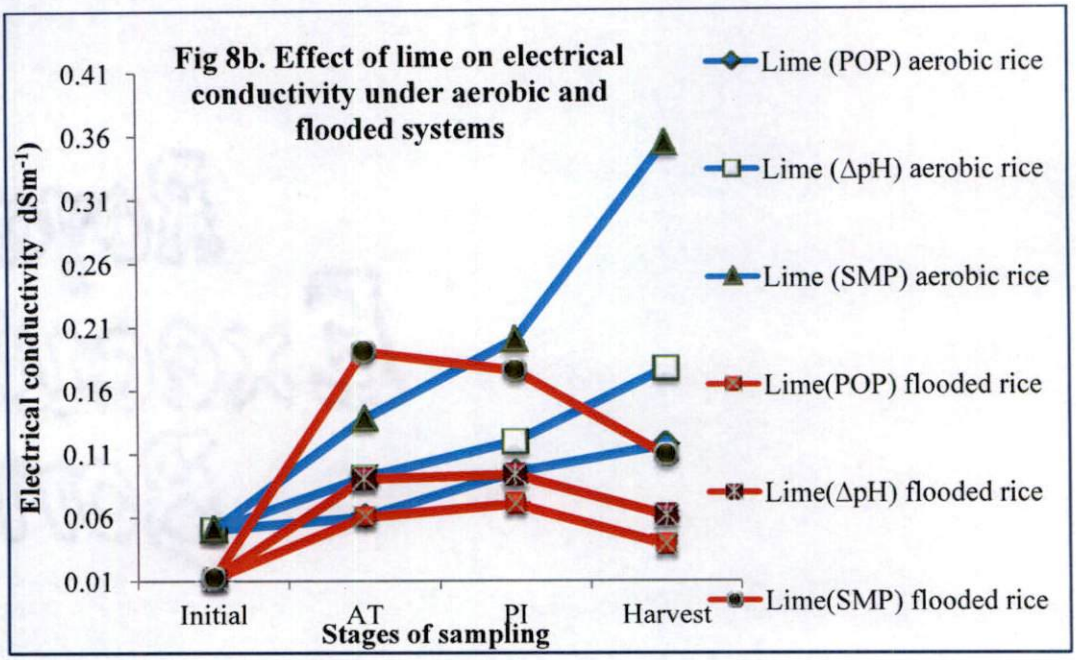
4.2.2. Electrical conductivity

In general, under both the systems, higher EC was recorded under treatment of fertilizers as per soil test (F_2) because of application more quantity of fertilizers in this treatment where $MgSO_4$ and borax were additionally applied when compared with the fertilizer treatment as per POP.

Under both systems, the highest electrical conductivity was recorded in the treatments in which lime applied based on SMP buffer (L_3) method, the effect being significantly higher than that in other lime treatments, because of the increased total electrolyte concentration since the quantity of lime applied was much higher in SMP buffer method (table11 to 13 and fig 8).

Fig 8. Changes in Electrical conductivity under aerobic and flooded systems





Among the interactions, lime as per SMP buffer method with fertilizers as per soil test (F_2L_3) recorded higher EC under both systems because of higher electrolyte concentration due to addition of higher quantity of lime along with $MgSO_4$ and borax.

The lowest EC was recorded under flooded system due to dilution effect under flooding.

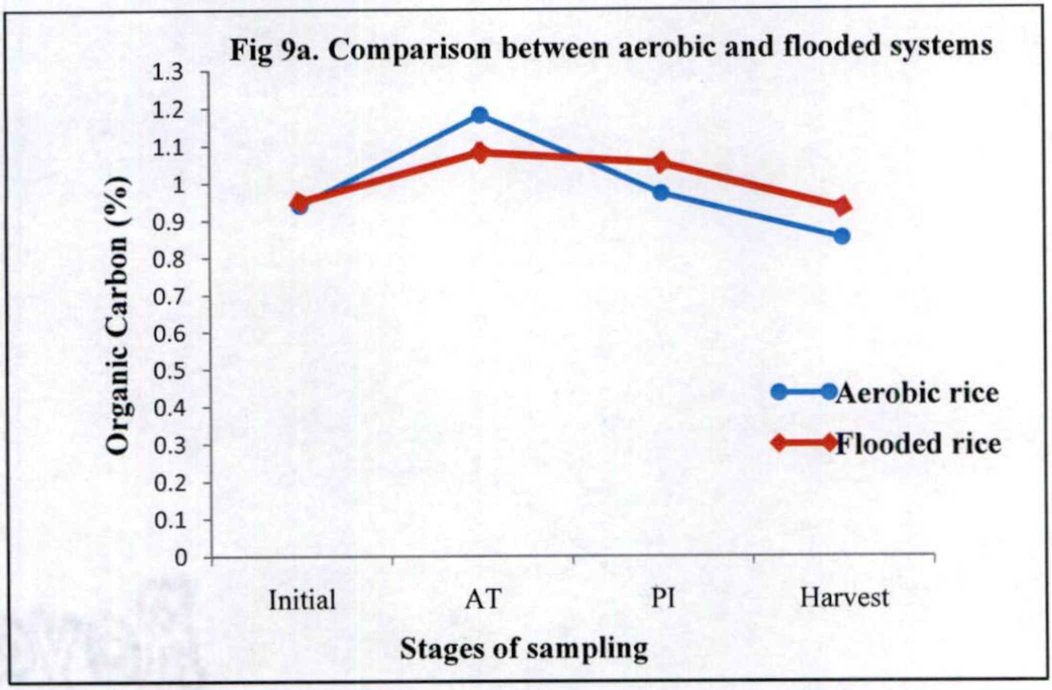
Under flooded system, the EC increased from initial status, remained constant at active tillering and panicle initiation, and then decreased at harvest. The initial increase in EC under submergence and its further decrease was also observed by Ponnamoeruma, (1972) and Narteh and Sahrawat, (1999).

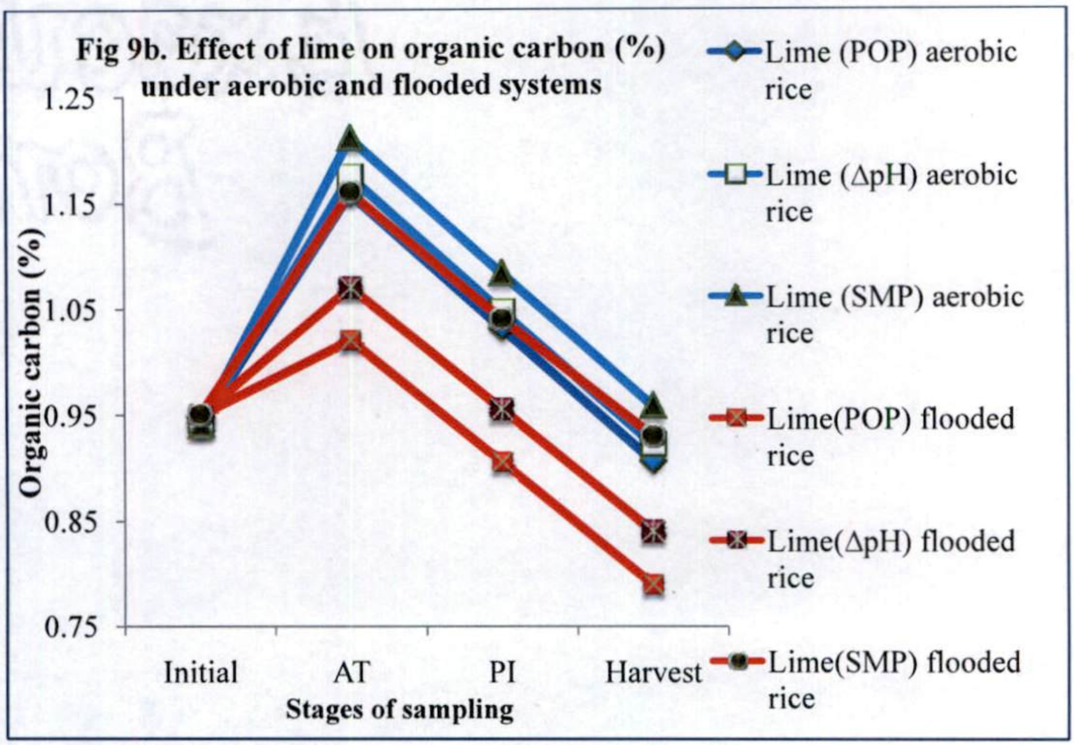
Under flooded condition, especially with fertilizer and liming materials, electrical conductivity must have shot up from the initial value within a period of a week or two and then might have declined and stabilized. The mean value of EC, both at AT and PI is same which is an indication of the above fact. Under aerobic system, the EC showed a steady increase from initial stage to harvest with alternate wetting by irrigation water and drying. This must have resulted in steady dissolution of applied inorganic inputs resulting in increased electrical conductivity. On the other hand, under flooded environment, in stagnant water the lime and fertilizers applied get dissolved at once resulted in the highest EC value (0.19 dSm^{-1}) and then diluted gradually to cause a decrease as time elapsed.

5.2. 3. Organic Carbon

Under both systems, the general increase in organic carbon irrespective of treatment was due to application of organic manure in all treatments @ 5 tonnes ha^{-1}. The highest organic carbon content recorded in treatment where lime based on SMP buffer method (L_3) was due to quicker decomposition of applied undecomposed manure in presence of lime at active tillering. The OC found decreased at PI than that at active tillering due to decomposition and mineralization of applied organic manure under both systems of rice cultivation. The organic carbon content in both systems was found reduced at harvest in comparison with active tillering as well as at panicle

Fig 9. Changes in organic carbon





initiation. However, a more reduction in the organic carbon content was found in aerobic system, than that at initial stage because of complete decomposition of applied organic manure, and consequent loss as CO_2. In case of flooded rice, almost similar organic carbon as that of initial stage was recorded at harvest because of the reduced rate of decomposition of organic matter under flooded environment. The dereased rate of decomposition of organic matter under submergence was reported by Sahrawat (2005; 2012).

Under both systems, the highest organic carbon was recorded in treatment with lime applied based on SMP method (L_3) in comparison with the other two lime treatments at this stage due to quicker decomposition of applied undecomposed manure in presence of more quantity of lime (table 14 to 16 and fig 9).

5.2.4. Available phosphorus

Under both systems, fertilizer application based on POP (F_1) had a significant influence in increasing the available P status of the soil due to increased quantity of P-fertilizer in F_1 (Factomphos @ 225 kg/ha) in comparison with P applied based on soil test (Factomphos @ 211.5 kg/ha). This resulted in higher available P status in F_1 (treatment with POP).

Under aerobic system, application of lime as per ΔpH recorded the highest available P status at active tillering and panicle initiation. Lime as per SMP buffer method recorded the lowest available P due to precipitation/reversion of applied soluble P to tri calcium phosphate as a result of increased Ca due to application of larger quantity of lime. This is evidenced from the fact that there was a reduction in available Ca status from 315.15 mg kg^{-1} at active tillering to 290.81 mg kg^{-1} at panicle initiation, with an increase in Ca bound P from a distribution of 16.3% at active tillering to 18.1% at PI. Further, at harvest, available P increased in this treatment. The precipitated phosphorus as insoluble tri calcium phosphate (with excess quantity of lime – 8.5 t ha^{-1}) might have solubilized as time progresses through

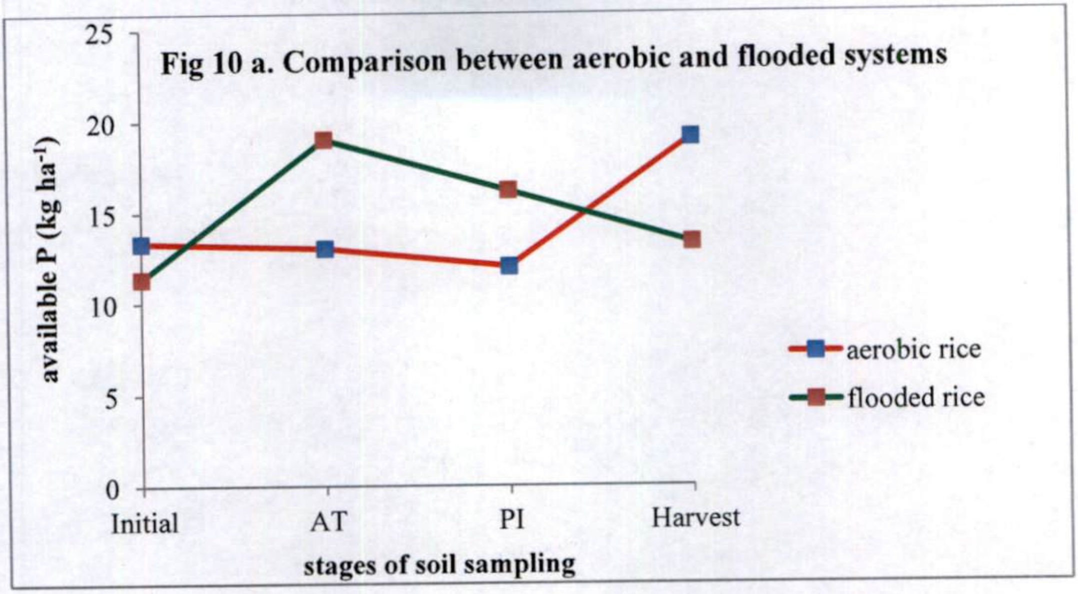


Fig 10 a. Comparison between aerobic and flooded systems
25
20
15
10
5
0
available P (kg ha-1)
Initial
AT
PI
Harvest
stages of soil sampling
aerobic rice
flooded rice

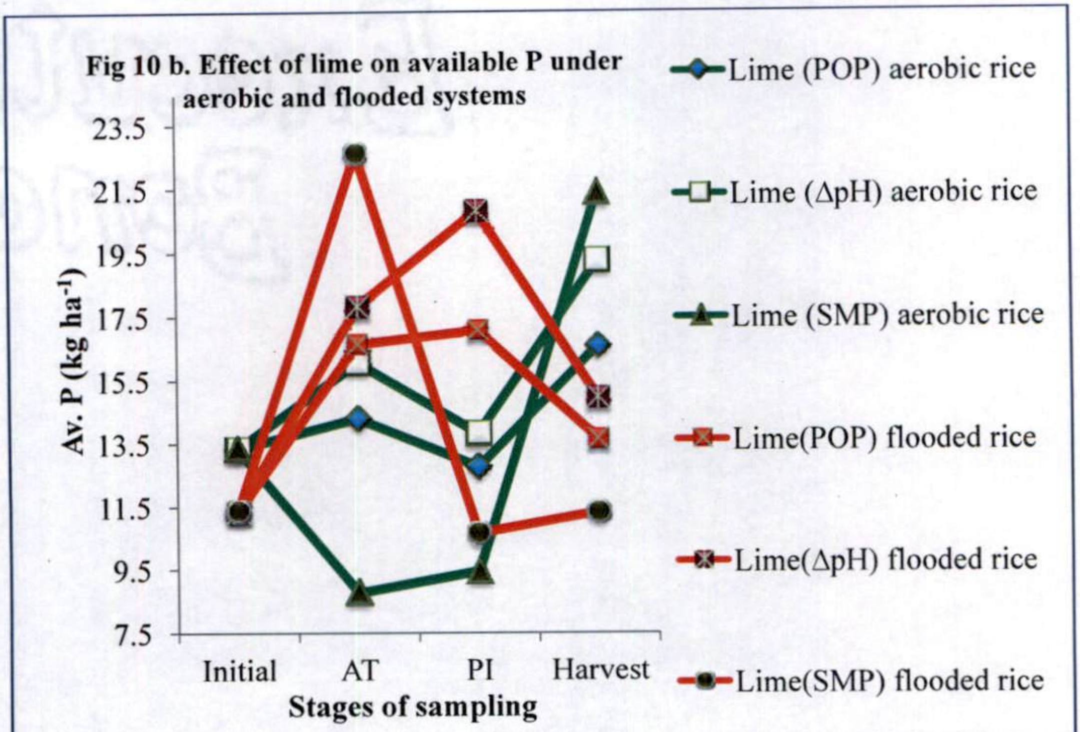


Fig 10 b. Effect of lime on available P under aerobic and flooded systems
23.5
21.5
19.5
17.5
15.5
13.5
11.5
9.5
7.5
Av. P (kg ha-1)
Initial
AT
PI
Harvest
Stages of sampling
Lime (POP) aerobic rice
Lime (ΔpH) aerobic rice
Lime (SMP) aerobic rice
Lime(POP) flooded rice
Lime(ΔpH) flooded rice
Lime(SMP) flooded rice

the total growing season slowly, which in turn resulted in an increase in available P status in lime treatment as per SMP buffer method(table17 to 19 and fig 10).

Under flooded condition, the highest available P was recorded in lime applied treatment as per SMP buffer method at active tillering and panicle initiation. The increased availability of P might be due to increase in pH from 4.9 to 5.9. The quantity of lime was more in lime treatments as per SMP buffer method (2.4 t ha^{-1}), which neutralizes the potential acidity also. At harvest, the available P in this treatment decreased substantially probably because of precipitation as tri calcium phosphate as well as due to P uptake. After prolonged periods of flooding, phosphorus becomes less available, probably due to higher fixation (Patrick and Mahapatra 1968). Fageria *et al.* (2011) also reported that the formation of insoluble tricalcium phosphate is favored at a high pH.

The available P was substantially high under flooded condition at active tillering and panicle initiation due to reduced environment, which resulted in reduction of Fe and Mn, releasing the corresponding bound P to the soil solution. (The increase in P under flooded system is reported by Fageria, *et al.*, 2011). The other mechanisms of phosphorus release in a flooded soil postulated by Patrick and Mahapatra (1968) include release of occluded phosphate by reduction of hydrated ferric oxide coating and displacement of phosphate from ferric and aluminum phosphate by organic amons.

Under aerobic situation, there was a slight increase in available P due to application of fertilizers. The available P content in aerobic rice increased substantially at harvest of the crop in comparison with that at initial, active tillering and panicle initiation, might be the effect of solubilization of reverted insoluble $Ca_3(PO_4)_2$ to mono calcium phosphate which is an after effect of depletion of P in soil solution due to plant uptake.

5.2.5 Available potassium

The available K increased from the initial level at active tillering due to application of lime and fertilizers under both systems of rice cultivation. The increase in available K was in accordance with the initial value. The available K found reduced at harvest from that of initial, active tillering and panicle initiation because of plant uptake under both systems.

Under both systems, the quantity of fertilizer applied as per soil test (F_2) had significantly increased the available K in comparison with the treatment where fertilizer was applied as per POP (F_1) since the quantity of fertilizer applied was more (79.5 kg muriate of potash ha^{-1}) under this treatment.

Higher available K found under aerobic system must be due to increased availability of K under aerobic condition because of reduced rate of leaching losses, together with decrease in competition from Fe and Mn by application of lime (table 20 to 22 and fig 11).

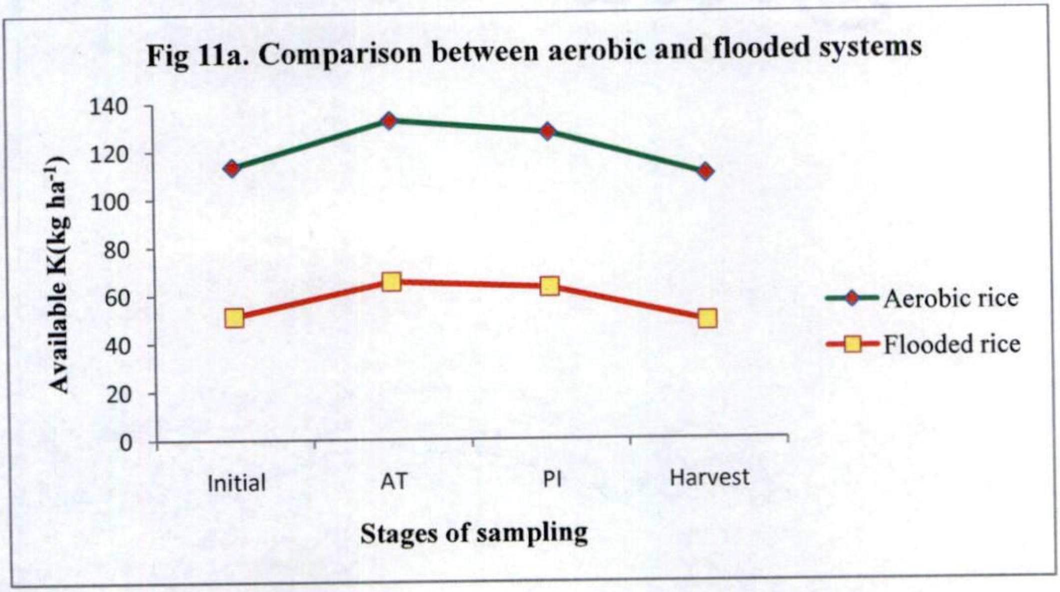
5.2.6. Available calcium

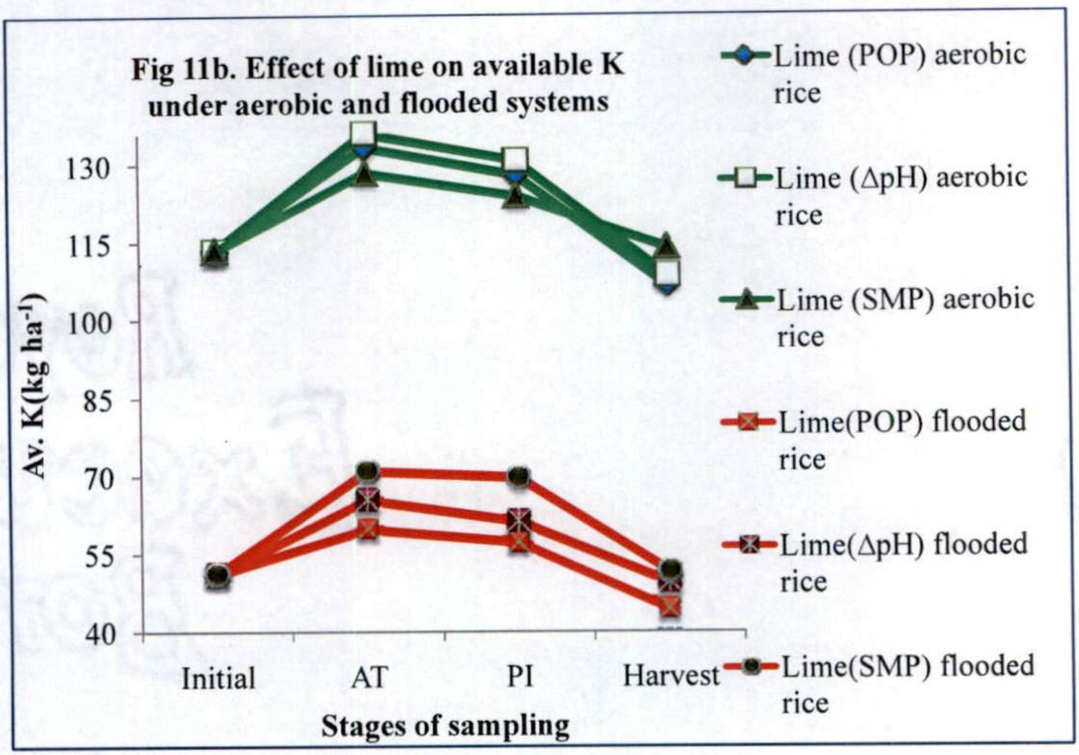
Under both the systems, the available Ca increased due to application of lime. Application of lime as per SMP buffer method (L_3) recorded the highest available Ca than the other two lime treatments. Increase in available Ca in all the treatments was found to be a function of the quantity of lime applied (table 23 to 25 and fig 12).

Flooded system recorded higher available Ca than that under aerobic condition at active tillering. The increase in available Ca was substantially higher under flooded condition due to

1) Solubility of applied lime (as CaO) and its subsequent conversion to $Ca(OH)_2$ might be more under flooded environment.
2) Formation of insoluble calcium phosphate under aerobic environment must have reduced both available Ca and P levels in comparison with flooded situation especially under high dose of lime.

Fig 11. Changes in available potassium





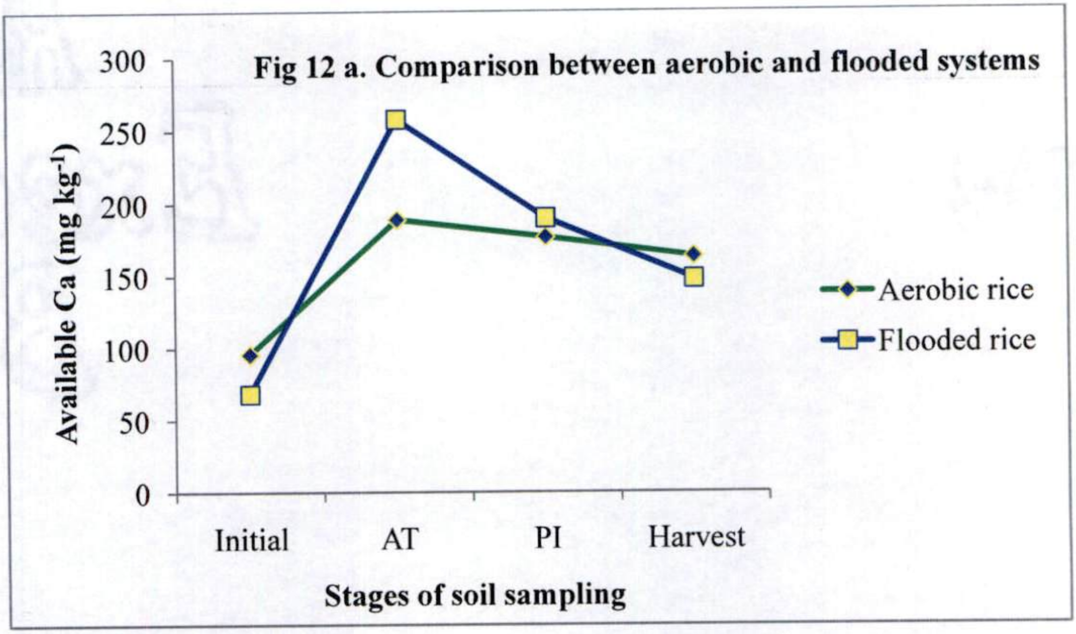


Fig 12 a. Comparison between aerobic and flooded systems
300
250
200
150
100
50
0
Available Ca (mg kg⁻¹)
Initial
AT
PI
Harvest
Stages of soil sampling
Aerobic rice
Flooded rice

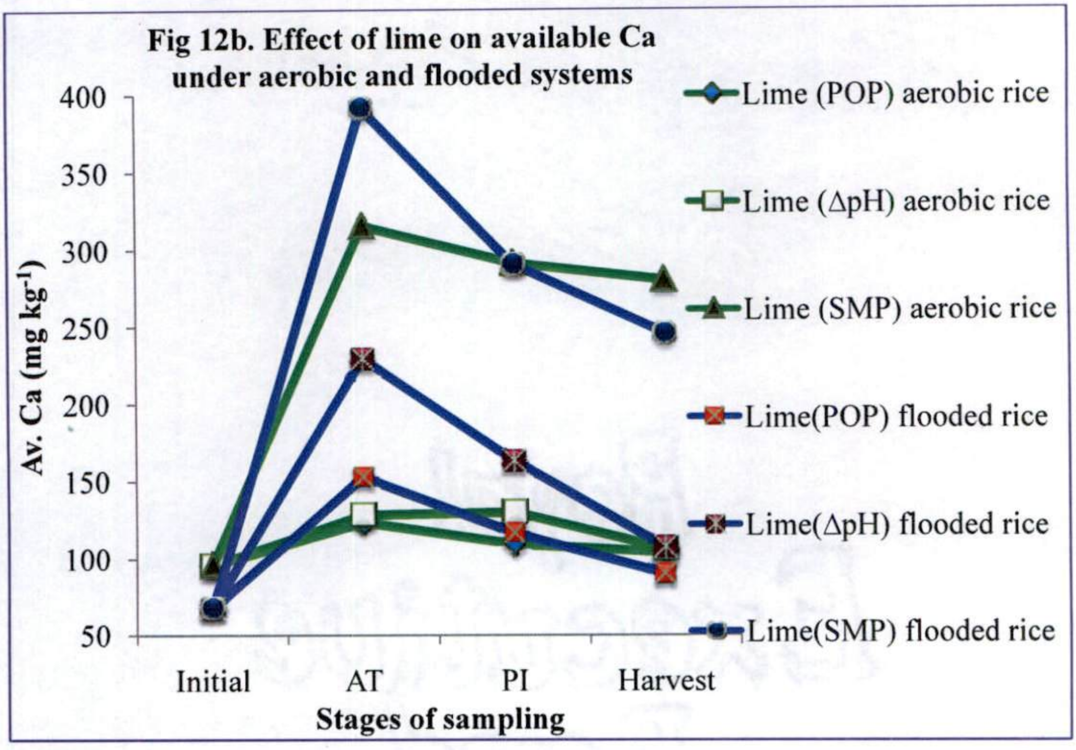


Fig 12b. Effect of lime on available Ca under aerobic and flooded systems
400
350
300
250
200
150
100
50
Av. Ca (mg kg⁻¹)
Initial
AT
PI
Harvest
Stages of sampling
Lime (POP) aerobic rice
Lime (ΔpH) aerobic rice
Lime (SMP) aerobic rice
Lime(POP) flooded rice
Lime(ΔpH) flooded rice
Lime(SMP) flooded rice

However, the available Ca status decreased substantially under flooded system at PI and harvest when compared with that at active tillering, which must be due to precipitation of insoluble calcium phosphate and as calcium borate to a small extent. The absorption by plant must have also decreased the available Ca content.

At harvest, under aerobic system, higher available calcium (163.26 mg kg^{-1}) was observed. This might be due to dissolution of precipitated tri calcium phosphate under in aerobic condition releasing the corresponding Ca and P to the soil solution.

The available Ca decreased at harvest in comparison with that at active tillering and panicle initiation, and became deficient (<300 mg kg^{-1}) under both systems.

5.2.7 Available magnesium

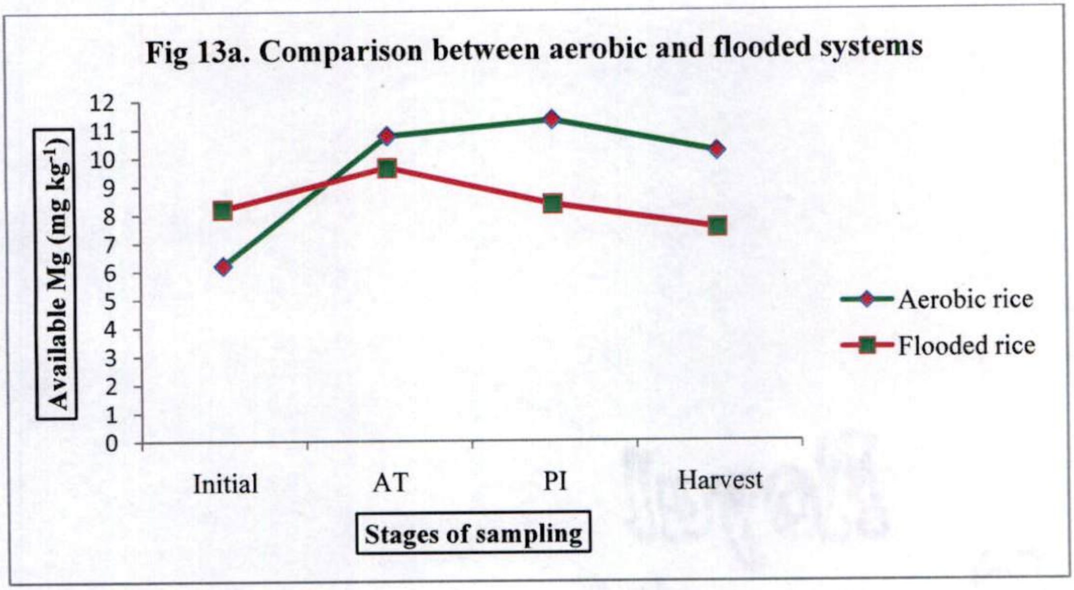
Under both systems, application of fertilizers as per soil test (F_2) had increased the available Mg status of the soil due to application of $MgSO_4$ at 80kg ha^{-1} in this treatment. Fertilizer treatment as per POP was found to decrease the available Mg status by mining of Mg from the native pool in the soil, which itself is severely deficient. The quantity of lime applied as per SMP buffer method (L3) was found to improve the available Mg content in soil compared with other two lime treatments might be due to the effect of pH(table 26 to 28 and fig 13).

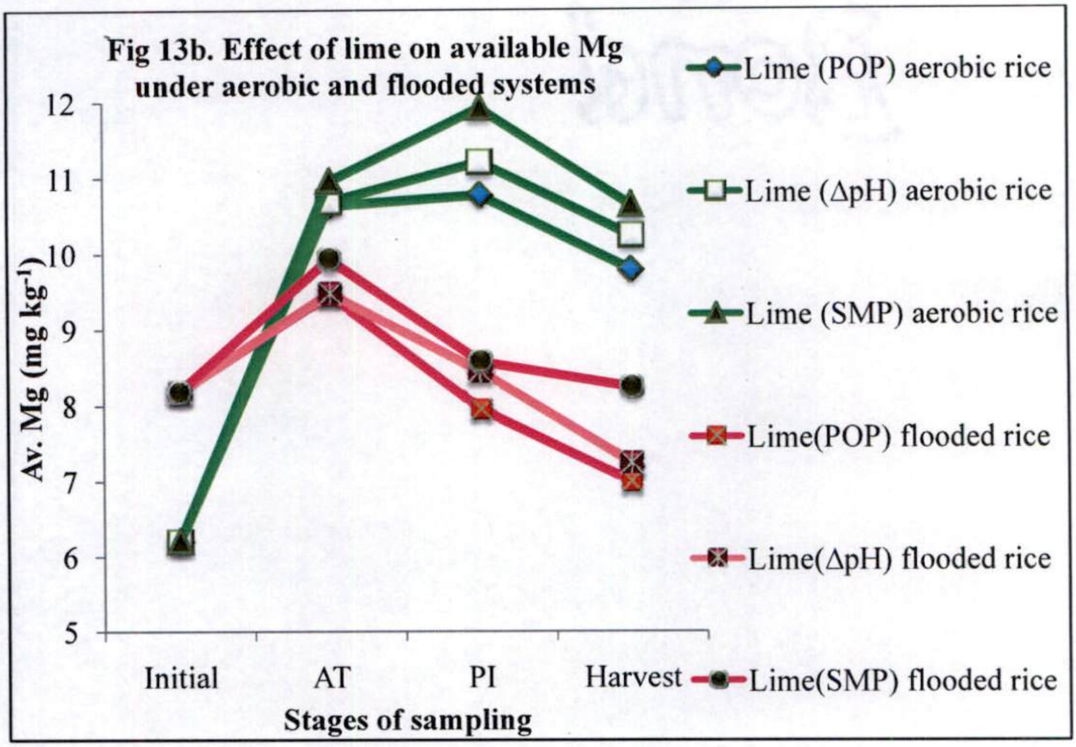
Aerobic system of rice cultivation recorded significantly higher available Mg status in comparison with flooded rice cultivation system. The decrease in available Mg was more in flooded system probably due to leaching of $MgSO_4$ under this environment.

5.2.8 Available sulphur

Under both systems, application of fertilizers as per soil test (F_2) increased the available sulphur status of the soil, since $MgSO_4$ was applied in these treatments at the rate of 80 kg ha^{-1} along with factomphos (20:20:0:15) as a source of N and P. Available S status in fertilizer treatment as per POP (F_1) also increased than that at initial status because of applied factomphos as a source of N and P.

Fig 13. Changes in available magnesium





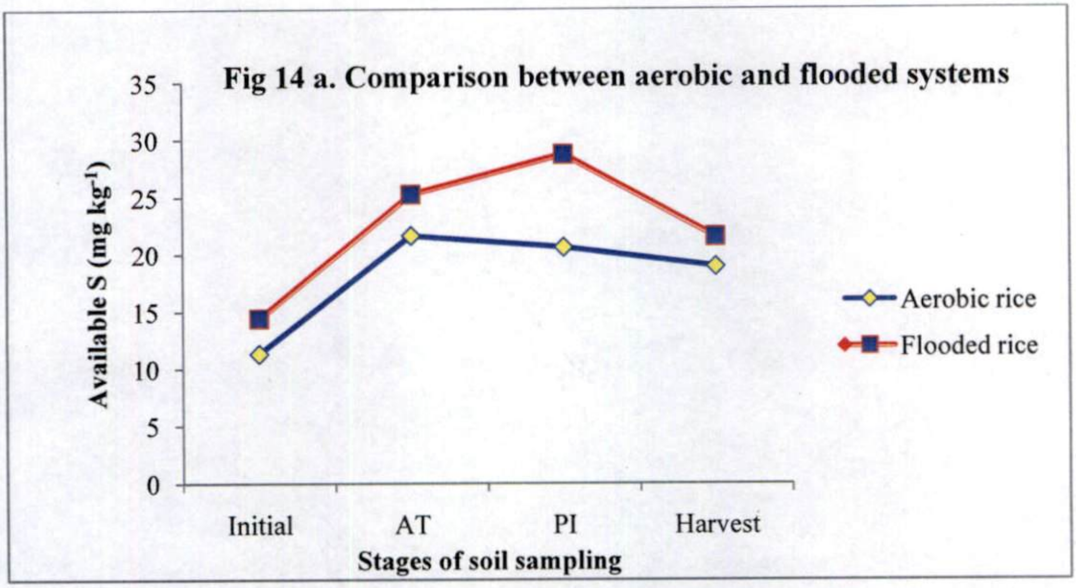


Fig 14 a. Comparison between aerobic and flooded systems
Available S (mg kg-1)
35
30
25
20
15
10
5
0
Initial
AT
PI
Harvest
Stages of soil sampling
Aerobic rice
Flooded rice

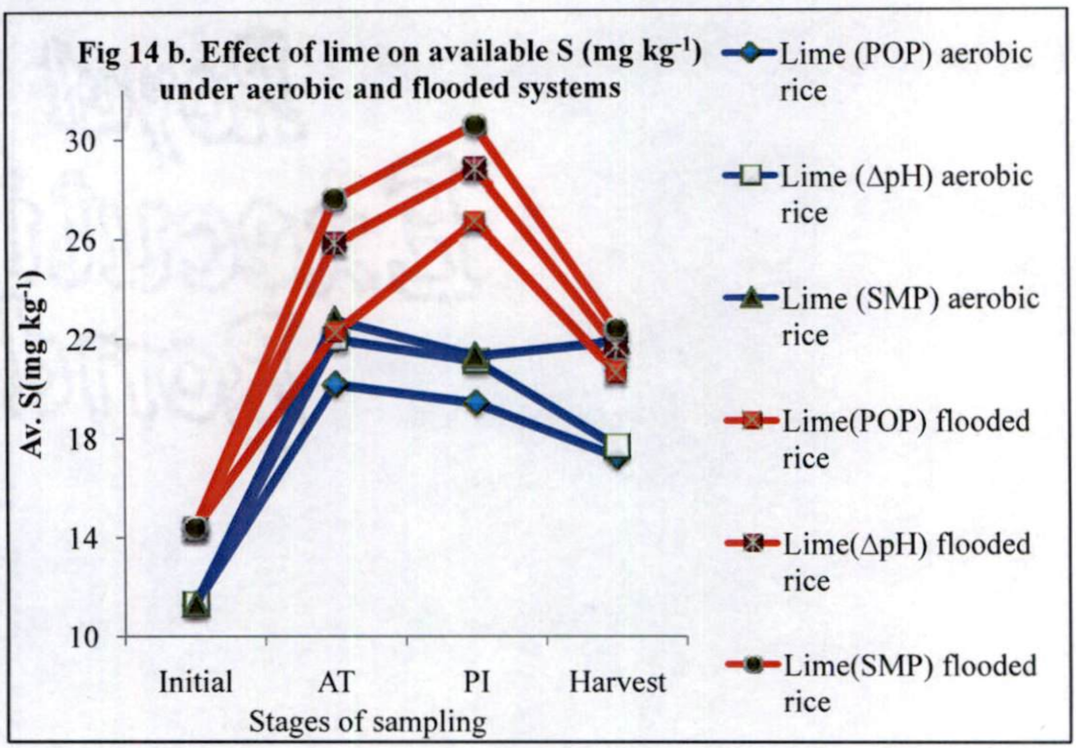


Fig 14 b. Effect of lime on available S (mg kg-1) under aerobic and flooded systems
Av. S(mg kg-1)
30
26
22
18
14
10
Initial
AT
PI
Harvest
Stages of sampling
Lime (POP) aerobic rice
Lime (ΔpH) aerobic rice
Lime (SMP) aerobic rice
Lime(POP) flooded rice
Lime(ΔpH) flooded rice
Lime(SMP) flooded rice

Under both systems, application of lime as per SMP buffer method increased the available sulphur. This might be due to the indirect effect of increased pH on enhanced rate of mineralization of added organic matter, resulting in release of more SO_4-S (table 29 to 31 and fig 14).

Higher available sulphur was recorded in flooded system than that of aerobic system of rice cultivation in all the stages of sampling.

Under both systems, the available sulphur was found decreased at harvest of the crop due plant absorption, in comparison with that at active tillering and panicle initiation, but was increased than that of initial stage because of fertilizer application as well as release of SO_4–S from mineralization of organic matter applied.

5.2.9 Available iron

Under both systems, application of lime was found significant in decreasing the available Fe status of the soil at active tillering. Among the lime doses, application as per SMP buffer method (L_3) decreased the available Fe status of the soil throughout the crop growth (table 32 to 34 and fig 15).

The other two doses of lime also decreased the available Fe under aerobic system during all the stages of sampling.

Under flooded system, the other two doses of lime (as per POP, and ΔpH) might have contributed in precipitation, but at the same time, reduction of Fe^{3+} to Fe^{2+} (soluble forms) might have contributed to increase the concentration since the lime applied in these treatments was not sufficient to neutralize the reserve acidity. Hence the available Fe was found increased under flooded system from the initial status in the treatments where lime application was done based on POP and ΔpH, and it was decreased in the treatments where lime was applied as per SMP buffer method. Thus there was an increase in overall mean of available Fe status of 115.84 mg kg^{-1} from the initial level of 113.74 mg kg^{-1} under flooded system. (The increased availability of Fe under flooded system was reported by Ponnamperuma, 1972). The

Fig 15. Changes in available iron

Fig 15 a. Comparison between aerobic and flooded systems

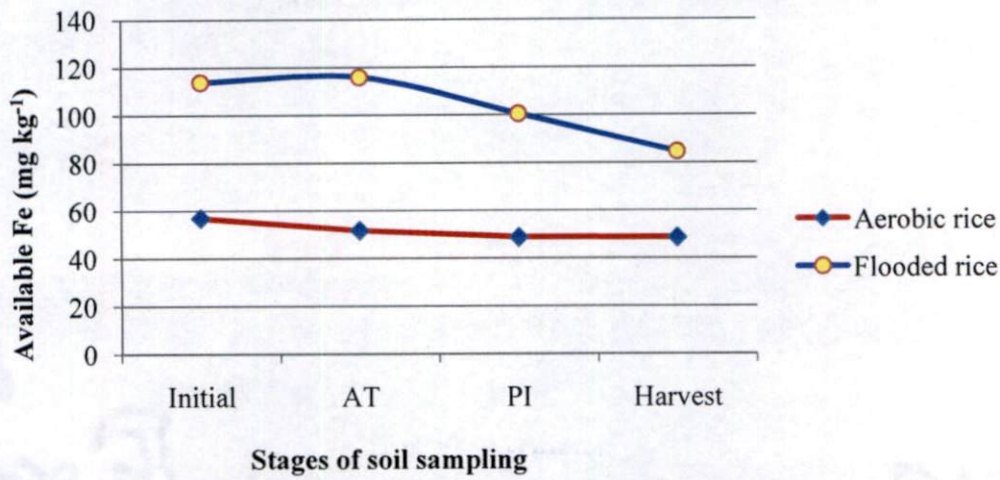
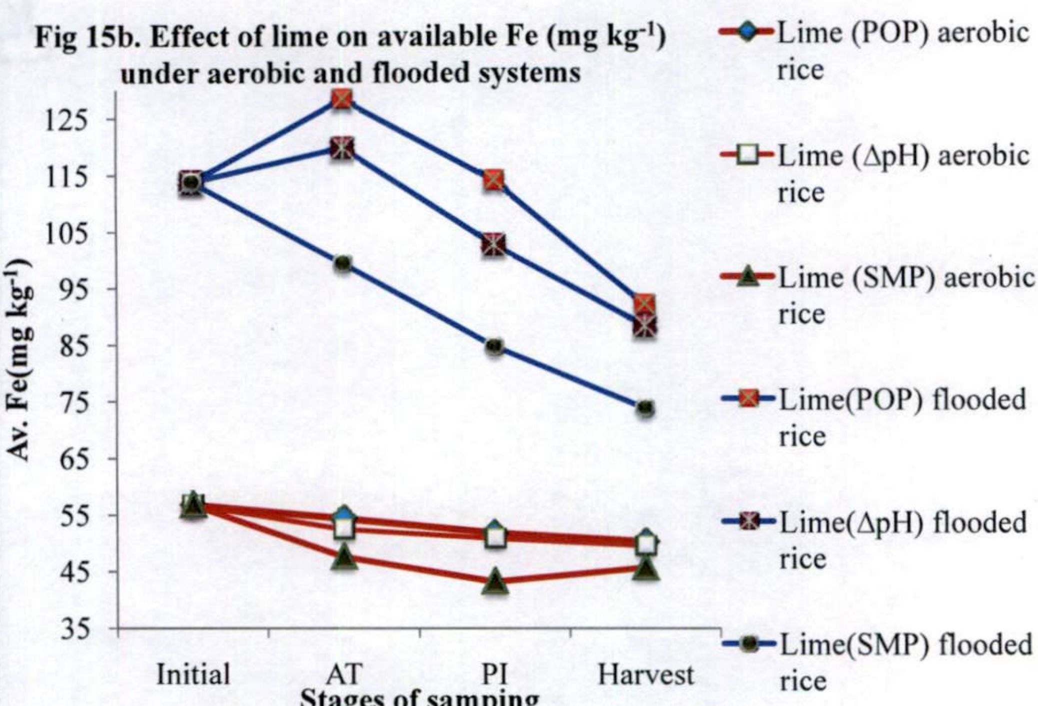


Fig 15b. Effect of lime on available Fe (mg kg^{-1}) under aerobic and flooded systems



available iron was found decreased from the initial level in all the lime treatments under aerobic rice cultivation system.

Fe toxicity is a severe problem for rice cultivation due to high acidity and Fe content in lateritic soils of Kerala. The solubility of Fe increases with flooding due to reduction from ferric to ferrous forms. The higher available Fe content under flooded reduced environment substantiates the above. Application of lime decreased the toxic levels of Fe due to precipitation resulting from increased pH and the most significant effect was recorded in treatments where lime was applied as per SMP buffer method under both systems.

Available Fe found decreased at harvest of the crop in comparison with that at other stages of sampling under flooded system of rice cultivation. However, the available Fe content under aerobic system of rice at harvest of the crop recorded almost same status as that at panicle initiation and found reduced when compared with that at initial and at active tillering.

Application of lime as per SMP buffer method recorded lowest available Fe status in comparison with other lime treatments under both systems of rice cultivation.

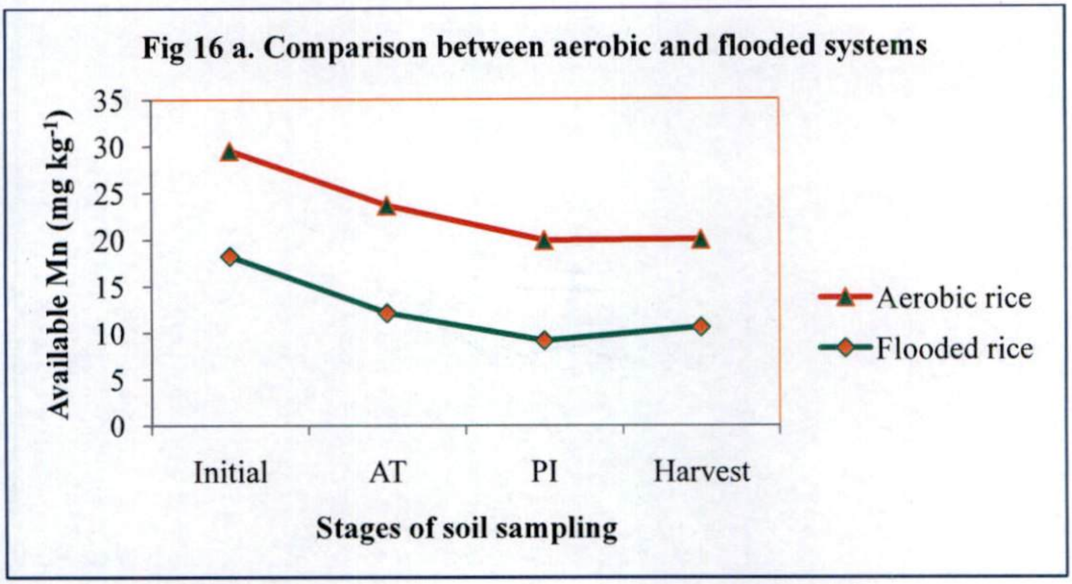
5.2.10 Available manganese

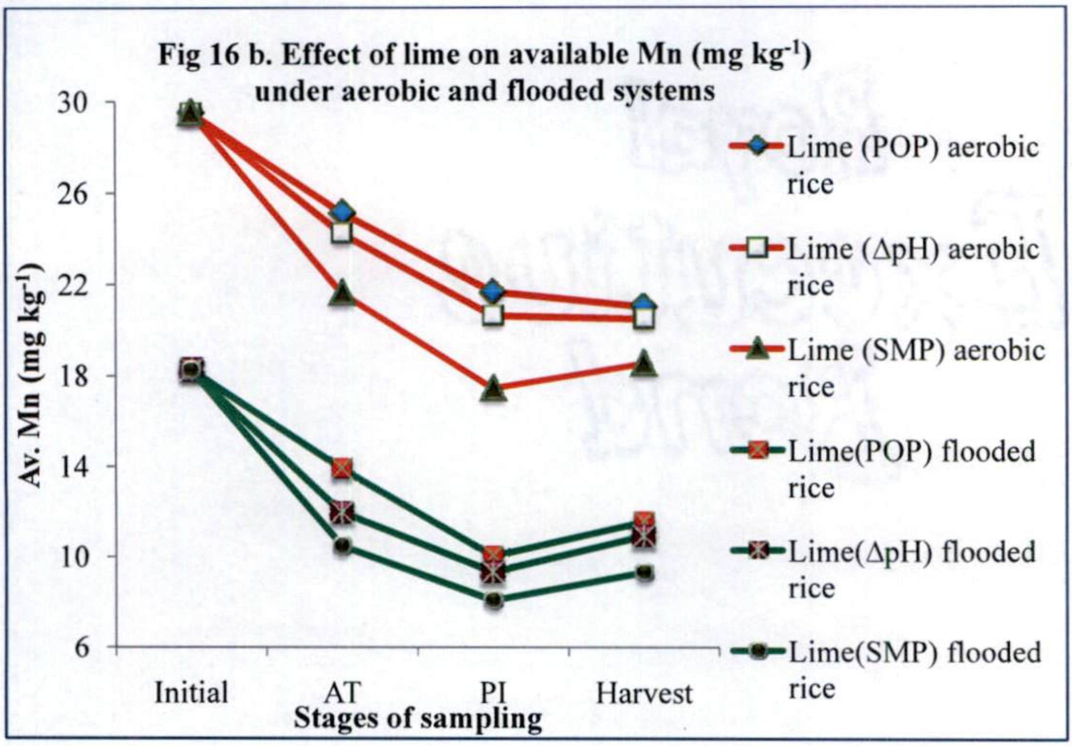
Under both the systems, quantity of lime applied as per lime requirement based on SMP buffer method was found to decrease the available Mn status of the soil significantly, followed by lime application based on ΔpH.

Application of lime decreased the toxic levels of Mn due to precipitation resulting from increased pH. The highest pH was recorded in treatments where lime was applied as per SMP buffer method where the quantity applied was highest (8.5 tonnes ha^{-1} under aerobic and 2.4 tonnes ha^{-1} under flooded system) (table 35 to 37 and fig 16).

In general, under both the systems, the treatments where fertilizers were applied as per soil test (F_2) decreased the available Mn status of the soil in

Fig 16. Changes in available manganese





comparison with the treatment were fertilizers were applied as per POP (F_2). This might be due to balanced absorption of nutrients by the crop. This is evidenced from the Mn content in plant under both systems where the highest Mn content was recorded in the treatment F_2.

Flooded condition recorded lower available Mn than aerobic rice during all the stages of sampling. This might be in accordance with the initial available Mn (recorded 29.52 mg kg^{-1} under aerobic and 18.24 mg kg^{-1} under flooded system respectively). Further, the rapid reduction of manganese under submergence within one to two weeks and further precipitation as well as more absorption of Mn by the crop (table 75) might have caused the reduced levels of available Mn in this system. The higher Mn content in plant was found higher under flooded system during all the stages of sampling.

5.2.11. Available zinc

Under aerobic system, among the lime treatments, quantity of lime applied as per the lime requirement estimated based on SMP buffer method (L_3) recorded the highest available Zn status at all the stages of sampling. This must be the effect of increased pH. However, all the lime treatments decreased available Zn from initial status of 1.70 mg kg^{-1}, and the system became deficient in available Zn (<1 mg kg^{-1}). The reduction in available Zn under aerobic system of rice cultivation might be due to more uptake of Zn by the crop at this stage (table 38 to 40 and fig 17).

. Under flooded system, lime applied treatments recorded the lowest available Zn status at all the stages of sampling. Application of lime decreased the available Zn status of soil with the highest effect in SMP buffer method where the quantity of lime was much higher than the other two lime treatments. Reduction in available Zn might be due to reduced availability of Zn resulted from formation of $Zn(OH)_2$ and $ZnCO_3$ in soil solution.

In general, the available zinc was found decreased at harvest of the crop when compared with that at initial, active tillering and panicle initiation under both systems

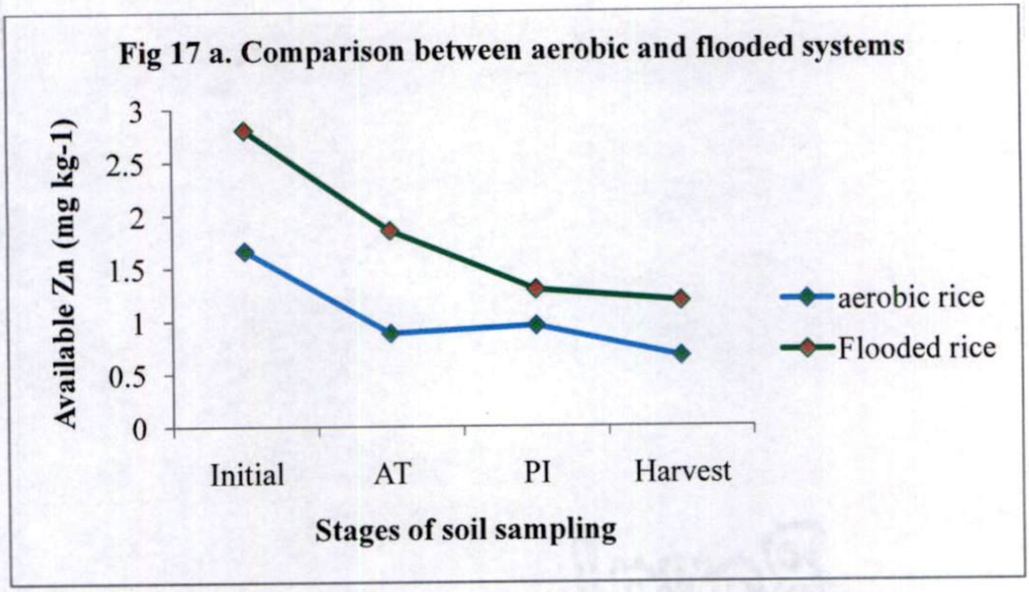


Fig 17 a. Comparison between aerobic and flooded systems
3
2.5
2
1.5
1
0.5
0
Available Zn (mg kg-1)
Initial
AT
PI
Harvest
Stages of soil sampling
aerobic rice
Flooded rice

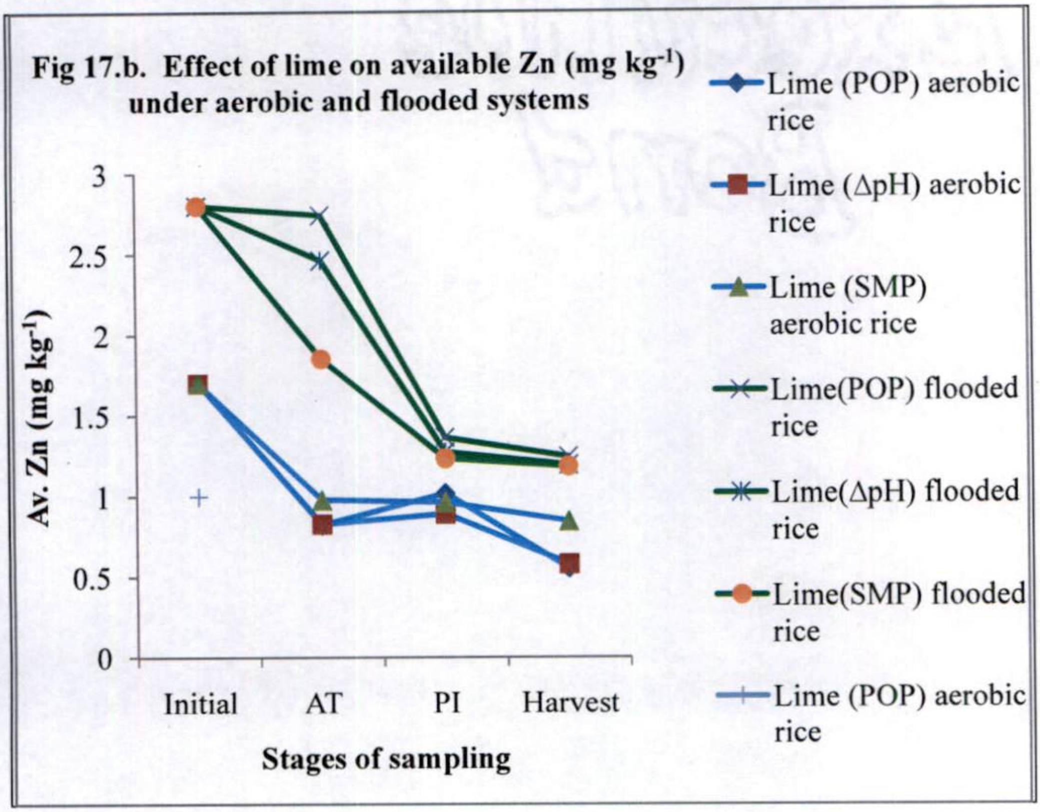


Fig 17.b. Effect of lime on available Zn (mg kg-1) under aerobic and flooded systems
3
2.5
2
1.5
1
0.5
0
Av. Zn (mg kg-1)
Initial
AT
PI
Harvest
Stages of sampling
Lime (POP) aerobic rice
Lime (ΔpH) aerobic rice
Lime (SMP) aerobic rice
Lime(POP) flooded rice
Lime(ΔpH) flooded rice
Lime(SMP) flooded rice
Lime (POP) aerobic rice

of rice cultivation. Under aerobic system, the available Zn was decreased and became deficient (<1mg kg^{-1}) from active tillering till harvest of the crop. Under flooded condition, though the available zinc was decreased, the status was sufficient to meet the requirements for plants.

5.2.12. Available copper

Under aerobic system, quantity of lime applied as per SMP buffer method (L_3) recorded the lowest available Cu at active tillering and panicle initiation. Application of lime decreased the higher levels of Cu due to precipitation resulting from increased pH in treatments where lime was applied as per SMP buffer method (lime applied was highest - 8.5 tha^{-1}). At harvest, this treatment recorded the highest available Cu (table 41 to 43 and fig 18).

In general, flooded system of rice cultivation recorded lower levels of available Cu. The decrease in available Cu status under flooded system was also reported by Fageria *et al.*, (2011). This was in accordance with the initial available Cu status (9.6 mg kg^{-1} under aerobic and 6.1 mg kg^{-1} under flooded system).

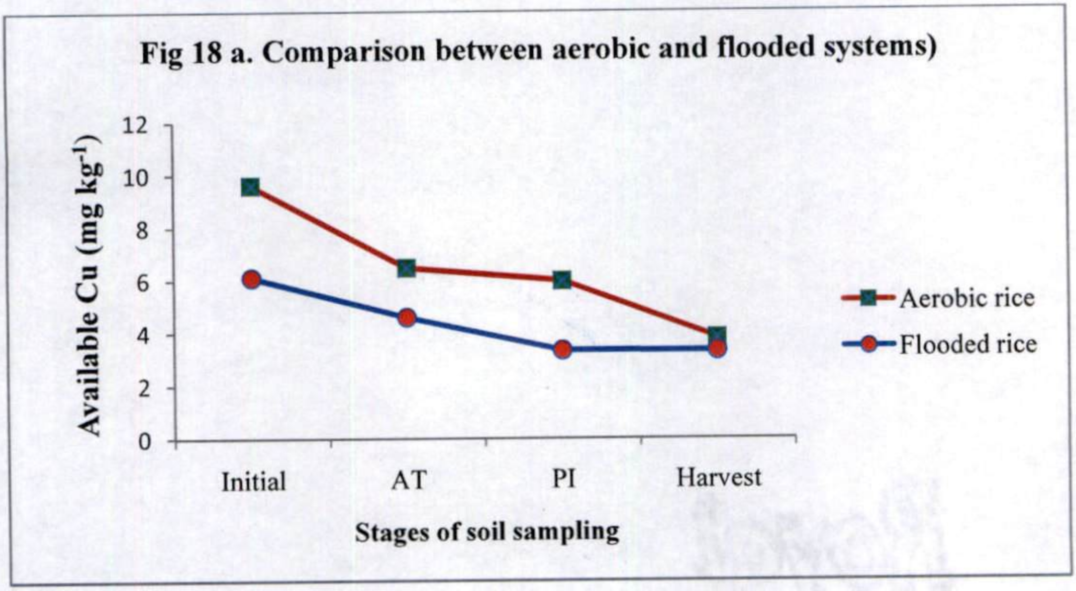
Available copper was found decreased at harvest in comparison with that at initial, active tillering and panicle initiation under aerobic system of rice cultivation. However, the available Cu under flooded system recorded same at panicle initiation and harvest and was lower than that at active tillering.

5.2.13 Available boron

Under both the systems of rice cultivation, the available boron content was significantly higher in the treatments where fertilizers were applied as per soil test (F_2) (table 44 to 46, fig 19 c). Application of borax at the rate of 10 kg ha^{-1} in this treatment resulted in increased available B status.

Under aerobic system, the available boron content found decreased in the treatment with fertilizer application as per POP (F_1) in comparison with the initial available boron in soil. This decrease was due to mining of the native available B because of plant absorption.

Fig 18. Changes in available copper



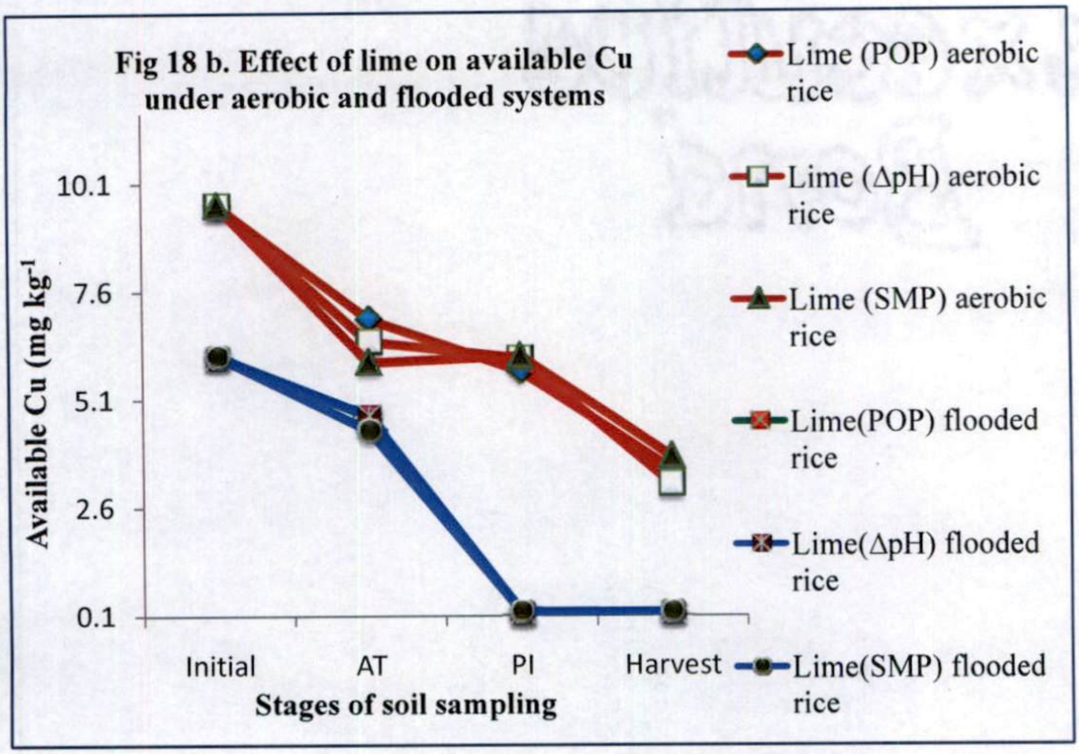
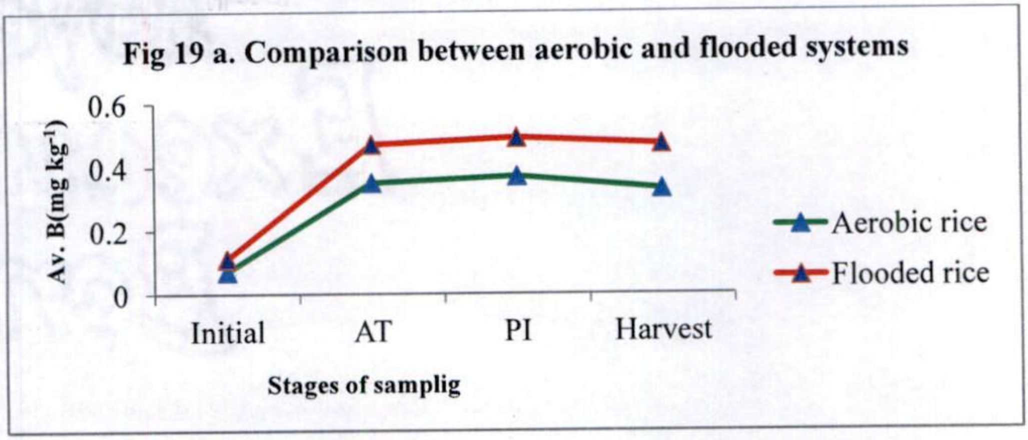
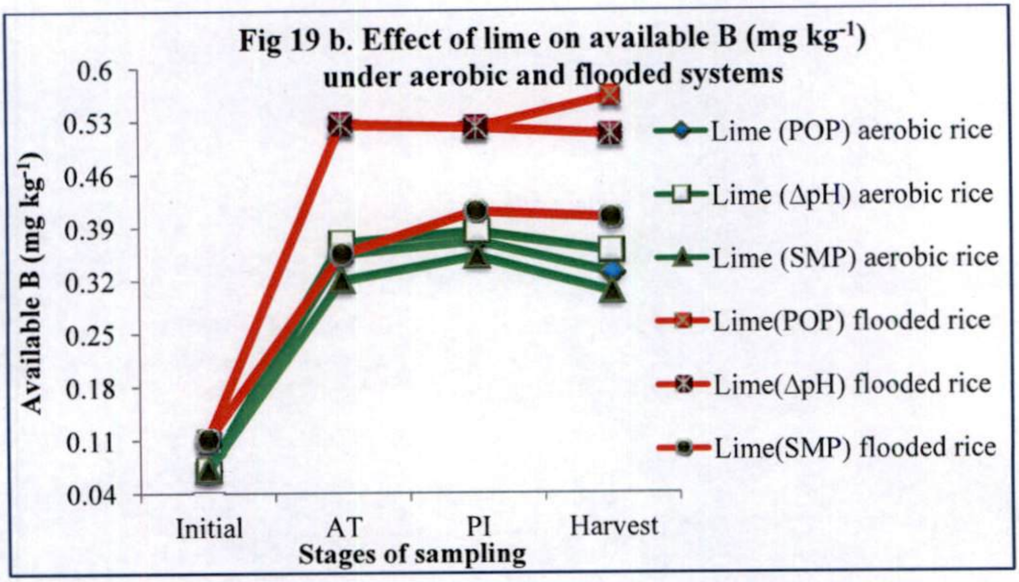
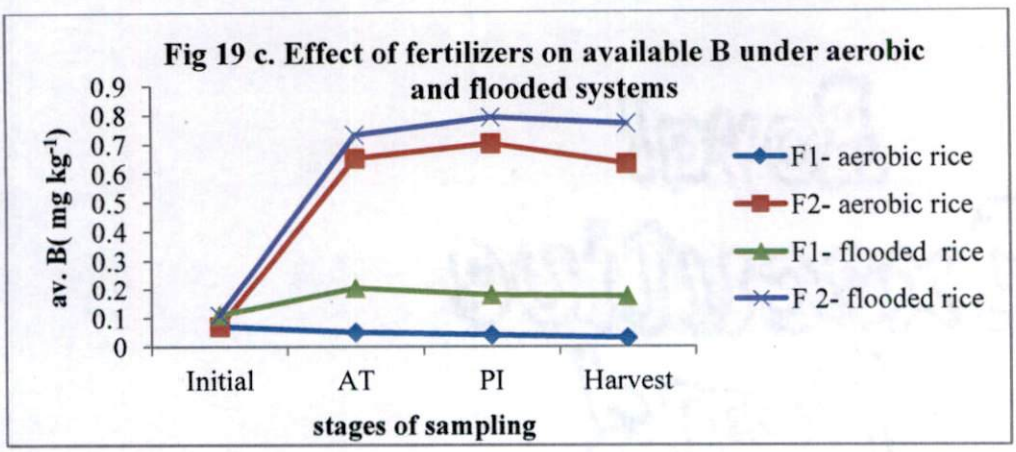


Fig 19. Changes in available boron







Under both the systems, application of lime as per ΔpH (L_2) recorded the highest available boron. This must be the effect of favourable pH. Application of lime as per SMP buffer method (L_3) recorded the lowest available boron content which was higher than the initial status of available boron. The quantity of lime applied in treatments as per SMP buffer method was much higher than that of the other two lime doses, which might have precipitated with the applied boron, resulting in a reduction in available B status of soil (table 44 to 46 and fig 19).

Application of fertilizer as per soil test with application of lime as per ΔpH (F_2L_2) was significantly superior in increasing the available B status (0.69 mg kg^{-1}) of the soil because of the combined effect of increase in pH with applied borax.

The available boron was found significantly higher in flooded rice system, must be due to more solubility of applied borax under flooded environment.

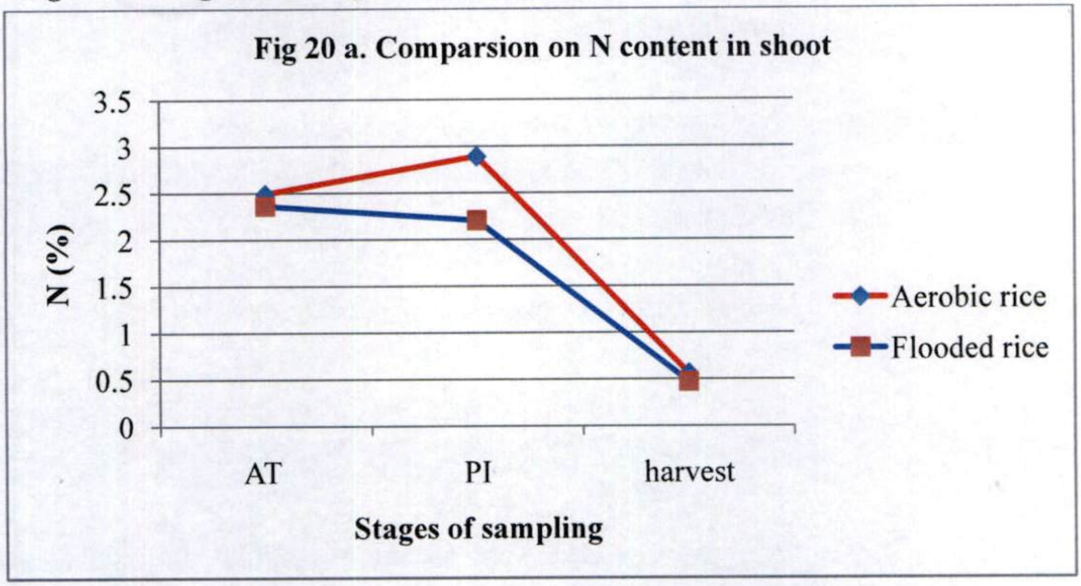
The increase in available B content in fertilizer treatment as per soil test (F_2) at PI was due to the second split of borax under both systems of rice cultivation, and further decrease at harvest was due to plant absorption.

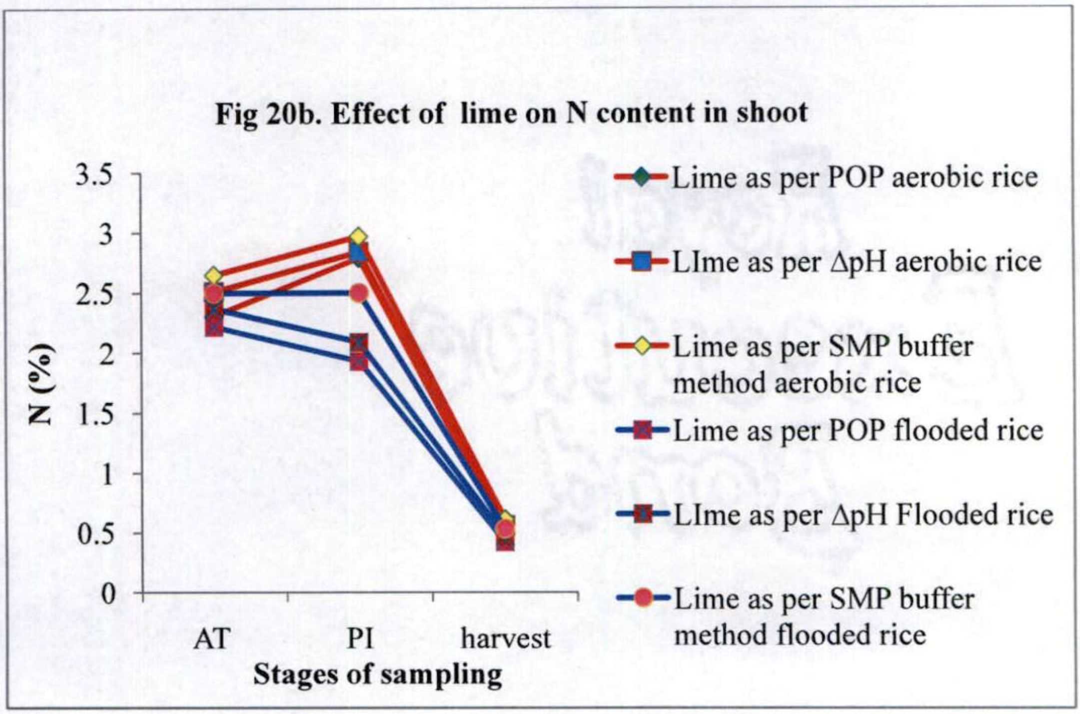
5.3. Effect of fertilizers and lime on nutrient content in plant

5.3.1 Nitrogen

Under both systems of rice cultivation, application of lime as per SMP buffer method (L_3) was found to increase the nitrogen content in shoot upto PI as well as in grain. This was due to quicker decomposition of applied undecomposed manure in presence of lime, resulting in mineralization of nitrogen. (Table 47 to 50 and fig 20) However, the rate of mineralization was less under flooded condition indicated by the lesser organic carbon status and lesser N content in plant. Application of fertilizers as per soil test (F_2) was found to increase the N in plant even though higher amount of nitrogen was applied in treatment with POP. This might be due to balanced rate of nutrient application which might have enhanced the uptake, especially that of nitrogen and magnesium in this treatment.

Fig 20. Changes in nitrogen content in plant





Rice cultivation under aerobic condition recorded higher nitrogen content in plant at panicle initiation and at harvest, than that in anaerobic condition, probably due to enhanced mineralization under aerobic environment. There was no significant difference between aerobic and flooded systems of rice cultivation in improving nitrogen content in grain.

The nitrogen content in straw was found decreased at harvest than that at previous stages of sampling under both systems of rice cultivation, probably because of lesser absorption at later stages as well as due to dilution effect.

Highest nitrogen content in grain was recorded in treatments where lime was applied as per SMP buffer method under both systems of rice cultivation.

5.3.2. Phosphorus

Under aerobic system, the highest P in plant was recorded in lime treatment as per SMP buffer method at active tillering. This must be due to more absorption of available P under favourable pH condition. This absorption in addition to precipitation of P as insoluble calcium phosphate must have reduced the available P status in soil at this stage. At panicle initiation, application of lime as per SMP buffer method recorded lowest P content in plant. This is because of decreased P availability in soil due to the precipitation of applied P as insoluble Ca phosphate. Further at harvest in treatment of lime as per SMP buffer method recorded the highest P content in straw due to increase in pH to near neutrality, which must have resulted in solubilisation of this insoluble calcium phosphate to mono calcium phosphate, which is evident from the increased available P status at this stage.

Under flooded system, amount of lime as per ΔpH (L_2) recorded the highest phosphorus content in plant due to favourable pH. Uptake of P was reduced in treatment L_3 due to reduced availability of P by precipitation/reversion of applied soluble P.

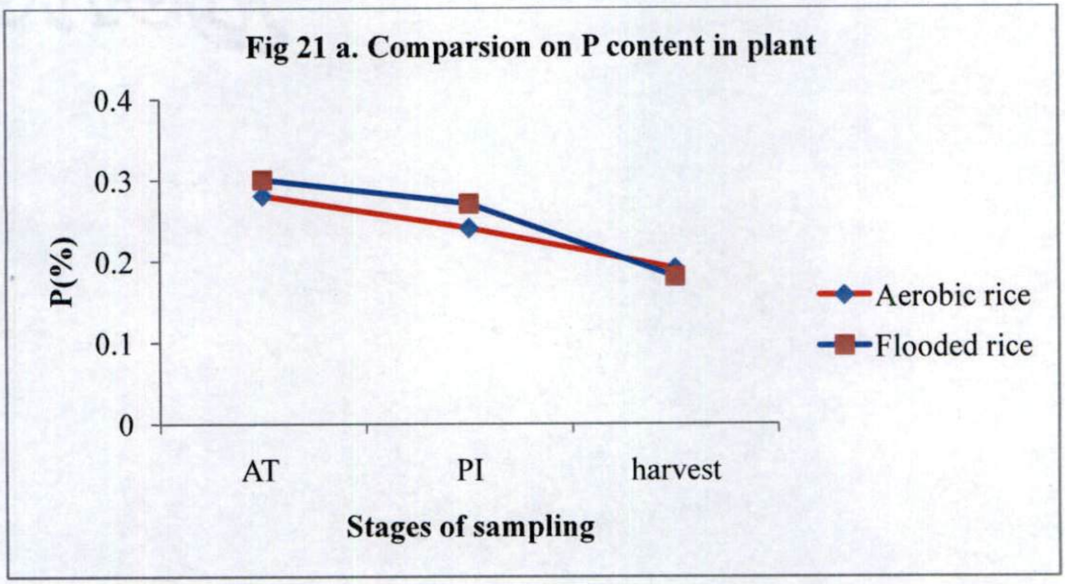


Fig 21 a. Comparsion on P content in plant
0.4
0.3
0.2
0.1
0
P(%)
AT
PI
harvest
Stages of sampling
Aerobic rice
Flooded rice

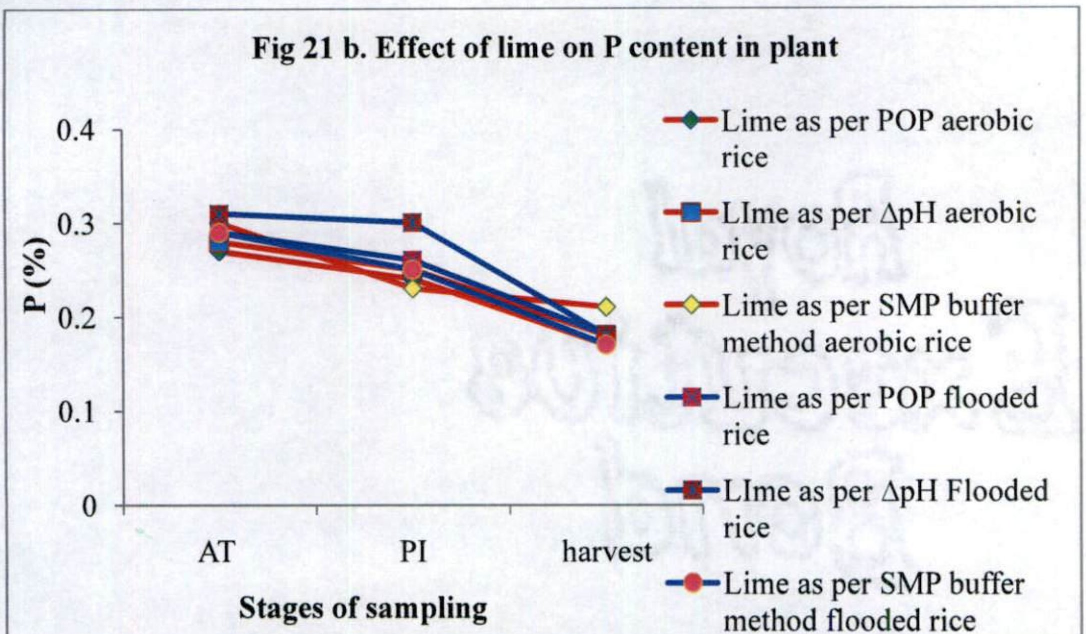


Fig 21 b. Effect of lime on P content in plant
0.4
0.3
0.2
0.1
0
P (%)
AT
PI
harvest
Stages of sampling
Lime as per POP aerobic rice
LIme as per ΔpH aerobic rice
Lime as per SMP buffer method aerobic rice
Lime as per POP flooded rice
LIme as per ΔpH Flooded rice
Lime as per SMP buffer method flooded rice

Significantly higher P content in plant was recorded in flooded rice than that of aerobic rice at active tillering and panicle initiation. This might be due to presence of substantially high available P under flooded condition. The reduction of Fe and Mn under submergence might have resulted in releasing the corresponding bound P to the soil solution (table 51 to 54 and fig 21).

5.3.3 Potassium

Under both systems, application of lime based on SMP buffer method (L_3) was found to increase the potassium content in plant during all the stages of sampling. Application of lime as per SMP buffer method must have decreased the competition from available Fe and Mn by precipitation under acidic lateritic environment, thereby increasing the uptake of K (table 55 to 58 and fig 22).

Application of fertilizers as per soil test (F2) recorded significantly higher potassium content in plant (2.16 %) in comparison with fertilizer applied as per POP (2.13%) because of application of more amount of potash fertilizer in treatments of fertilizers as per soil test.

Higher K content in plant was recorded in aerobic system. This was due to the presence of more available K under aerobic environment, since leaching of K is less under aerobic condition. Under flooded system, excess absorption of Fe by rice a retard the absorption of K in acid soils (Chang, 1971).

5.3.4 Calcium

Under both systems, lime applied based on SMP buffer method (L_3) increased the calcium content in plant. The highest amount of lime was applied in treatment as per SMP buffer method (8.5 t ha^{-1} lime in aerobic and 2.5 t ha^{-1} lime in anaerobic), resulted in highest uptake of Ca (table 59 to 62 and fig 23). The quantity of fertilizers applied as per soil test (F_2) recorded the highest calcium content, might be due to balanced rate of cation absorption.

Flooded system of rice cultivation recorded higher calcium content in plant than that of aerobic system. This might be due to the solubilisation of applied lime (as

Fig 22. Changes in potassium content in plant

Fig 22 a. Comparsion on K content in plant

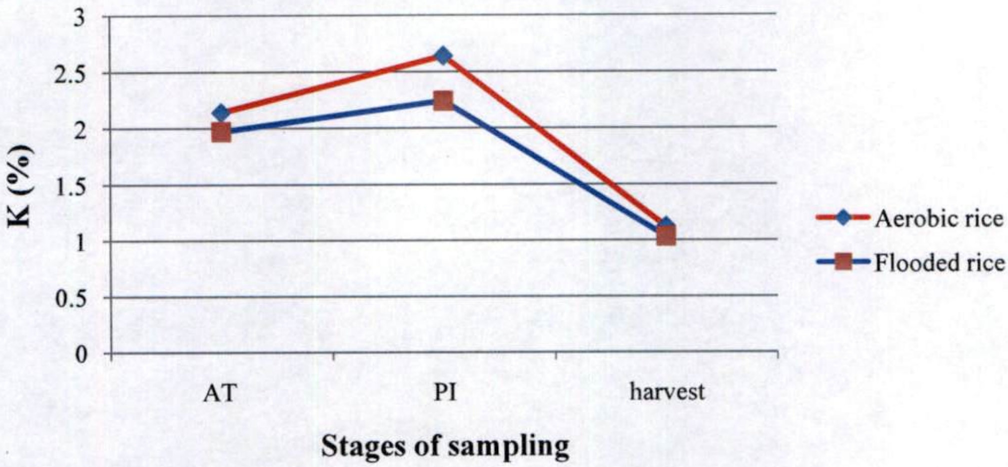


Fig 22 b. Effect of lime on K content in plant

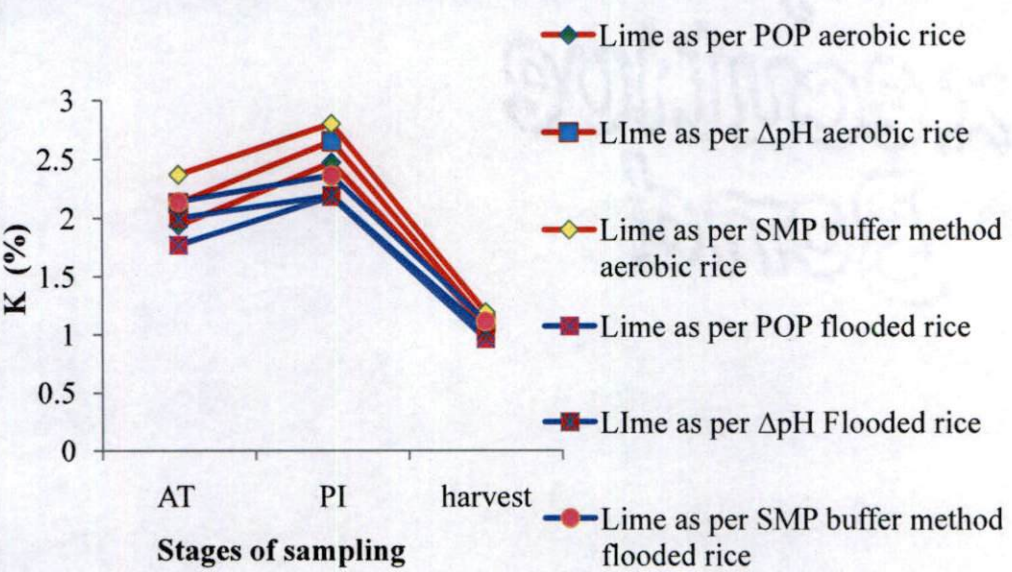
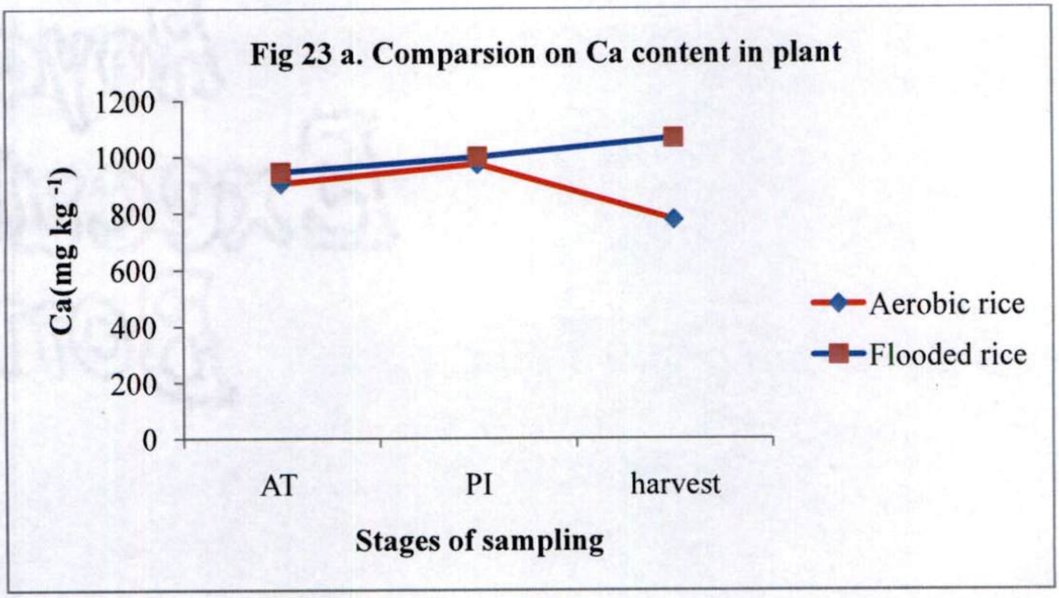
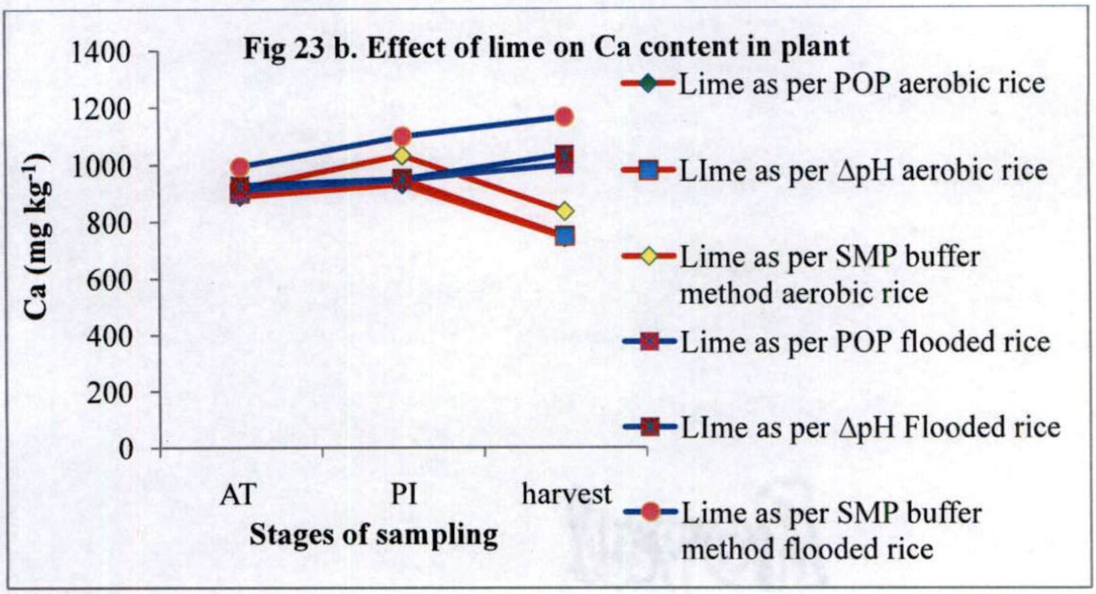


Fig 23. Changes in calcium content in plant





CaO) and its conversion to $Ca(OH)_2$. This resulted in improvement in available Ca status and hence more absorption.

Among the interactions, fertilizer as per soil test with lime as per SMP buffer method (F_2L_3) recorded the highest calcium content in plant at this stage due to increased available calcium status in soil and due to balanced rate of cation uptake.

5.3.5 Magnesium

Under both systems, quantity of lime applied as per SMP buffer (L_3) recorded the highest magnesium content in plant. Application of more quantity of lime as per SMP buffer method (8.50 t ha^{-1}) must have decreased the competition from available Fe and Mn due to precipitation under acidic lateritic environment, thereby increasing the absorption of Mg (table 63 to 66 and fig 24). The quantity of fertilizers applied as per soil test (F_2) recorded the highest magnesium content in plant in comparison with fertilizer applied as per POP because of application of $MgSO_4$ @ 80 kg ha^{-1} as soluble source of Mg in this treatment.

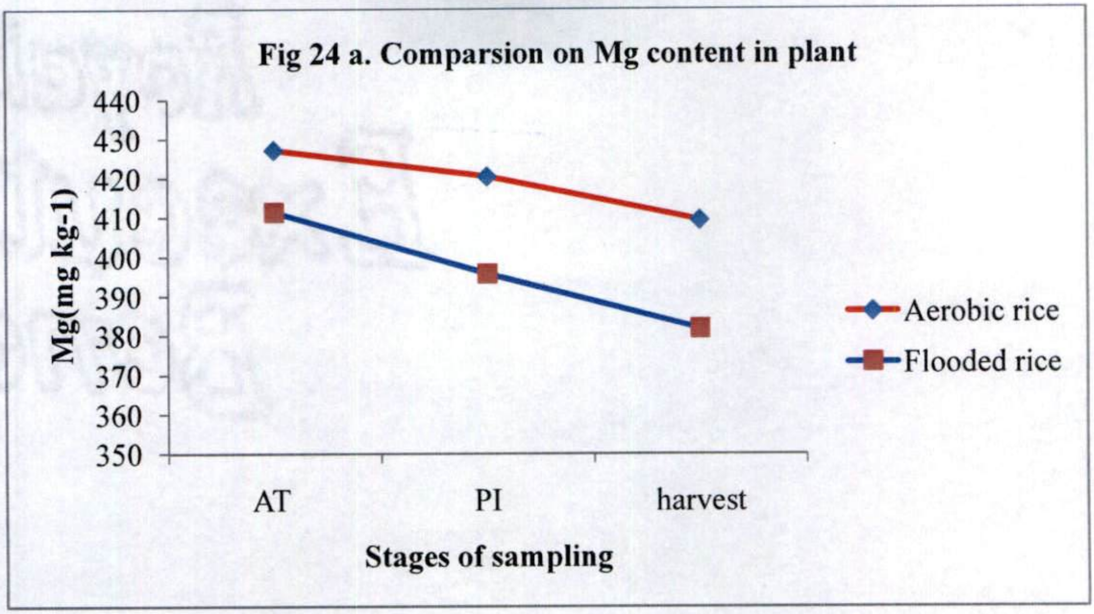
The content of Mg in plant was more under aerobic situation because of less leaching of applied soluble Mg source ($MgSO_4$) from the soil under aerobic situation which resulted in more amount of available Mg in aerobic soil and hence more absorption.

5.3.6 Sulphur

Under both systems, lime applied as per SMP buffer method (L_3) recorded significantly highest sulphur content in plant. This was due to the increased available sulphur in L_3. Enhanced rate of mineralization of added organic matter as well as the indirect effect of increased pH, resulted in more absorption also (table 67 to 70 and fig 25).

The quantity of fertilizers applied as per soil test (F_2) recorded higher sulphur content in plant. This treatment increased the available sulphur status of the soil due to application of $MgSO_4$ at 80 kg ha^{-1}.

Fig 24. Changes in magnesium content in plant



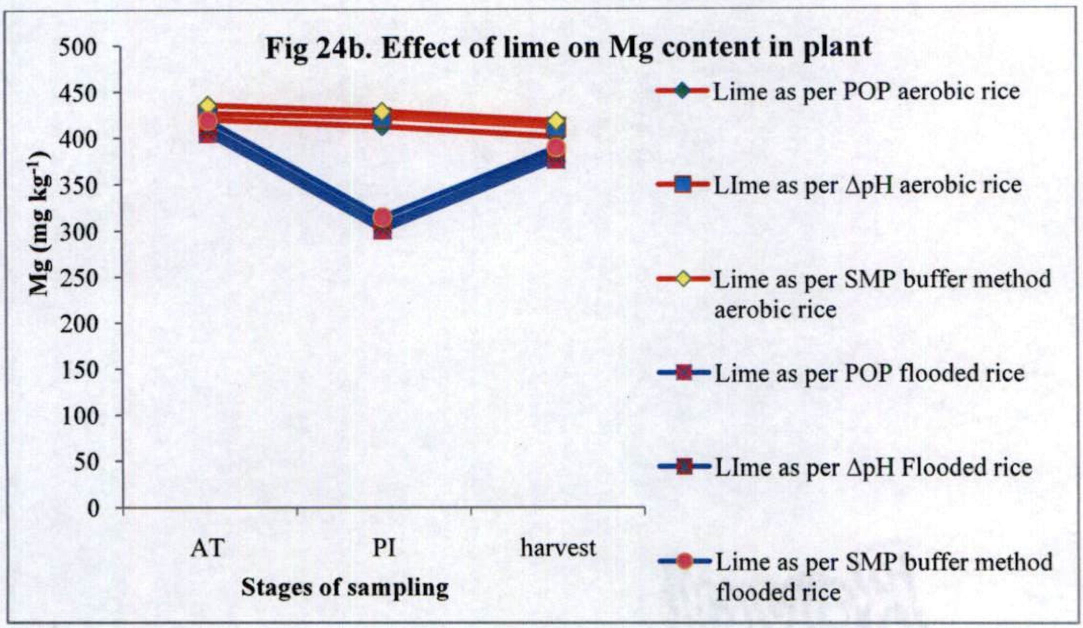
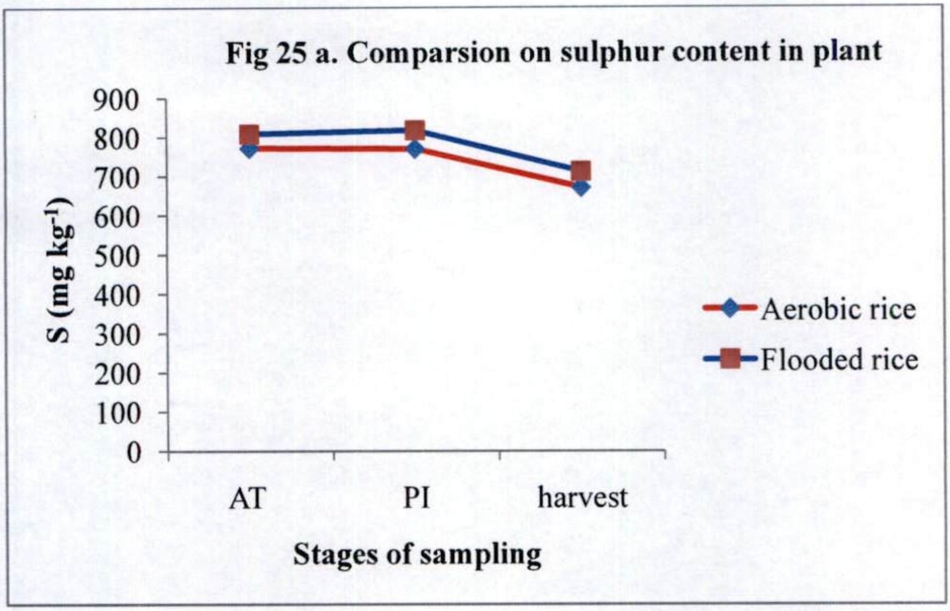
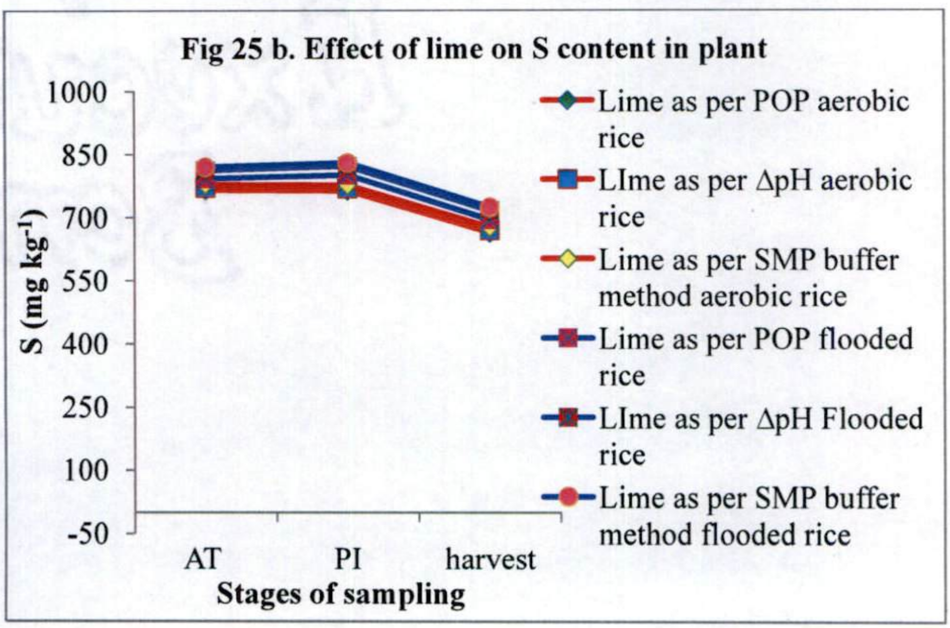


Fig 25. Changes in sulphur content in plant





Higher sulphur content in plant was recorded in flooded system in comparison with aerobic system. The increase in sulphur content in plant under flooded situation was due to more solubility of applied $MgSO_4$.

5.3.7. Iron

Under both systems, lime applied as per SMP buffer method (L_3) recorded significantly the lowest Fe content in plant. Application of lime decreased the Fe toxicity due the antagonistic interaction of applied lime with Fe. The lowest Fe was recorded in treatments where lime was applied as per SMP buffer method (L_3) (table 71 to 74 and fig 26).

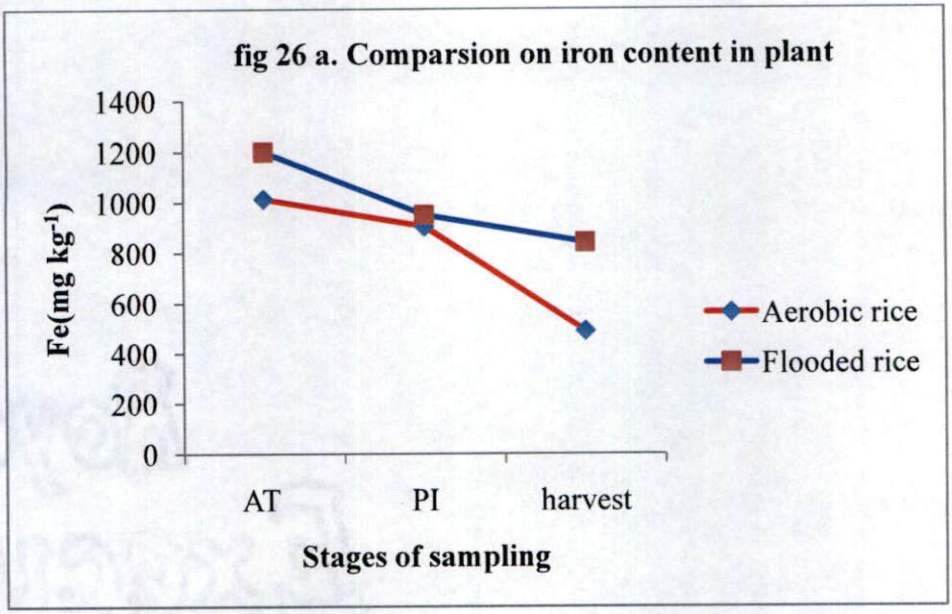
Cultivation of rice under flooded condition was significant in increasing Fe (1183.33 mg kg^{-1}) than that under aerobic system.(The increased concentration Fe in plant tissues under flooded system was also reported by Fan *et al.*, (2012). The solubility of Fe increases with flooding due to reduction from ferric to ferrous form. Hence available Fe content was higher under flooded reduced environment. This higher available Fe resulted in higher Fe content in plant under flooded condition. Fan *et al.* (2012) also reported that the Fe concentration and Fe content in rice were decreased under aerobic cultivation than that of flooded cultivation.

5.3.8 Manganese

Under both systems, lime applied as per SMP buffer method (L_3) recorded significantly the lowest Mn content in plant. Application of lime decreased the Mn toxicity due to precipitation of Mn as its oxides/hydrous oxides. This precipitation was most significant in L_3, and hence less uptake by the plant in this treatment (table 75 to 78 and fig 27).

Cultivation of rice under flooded condition recorded higher Mn (253 mg kg^{-1}) than that under aerobic system. Jugsujinda and Patrick (1977) observed that Mn

Fig 26. Changes in iron content in plant



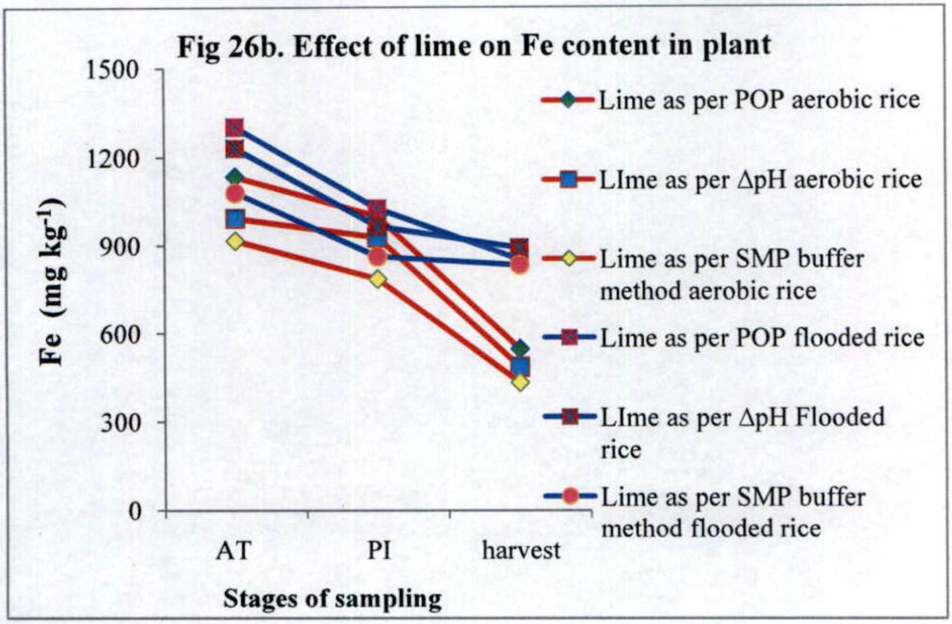
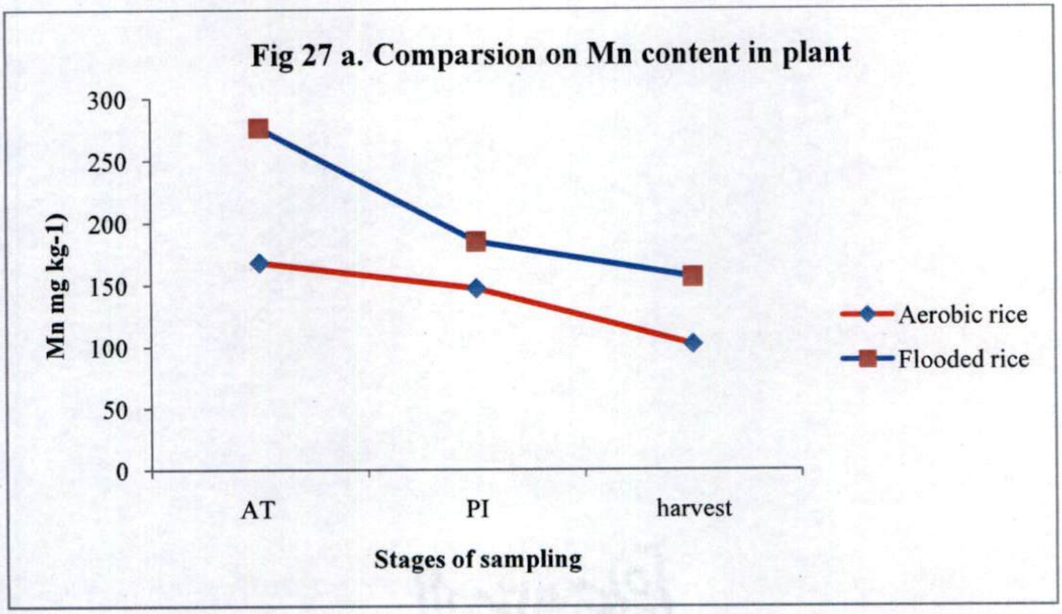
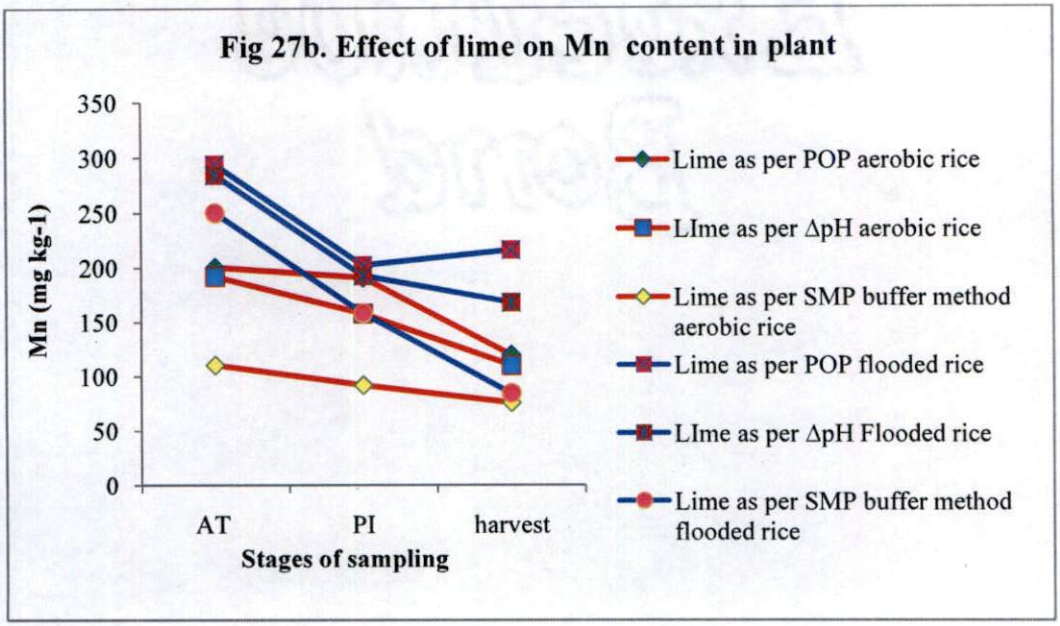


Fig 27. Changes in manganese content in plant





uptake by rice was higher under anaerobic conditions than under aerobic conditions. The Mn uptake by rice increased with increasing Mn^{2+} activity in soil solution in controlled redox suspensions (Schwab and Lindsay, 1983).

Aerobic system decreased the toxic levels of available Mn due to precipitation resulting from increased pH.

In general, the Mn content in straw was the highest in treatments where lowest quantity of lime was applied (L_3), and was the lowest in the treatment where lime was applied based on SMP buffer method (highest quantity of lime). The content of Mn in plant was found reduced at harvest in comparison with that at active tillering and panicle initiation under both systems of rice.

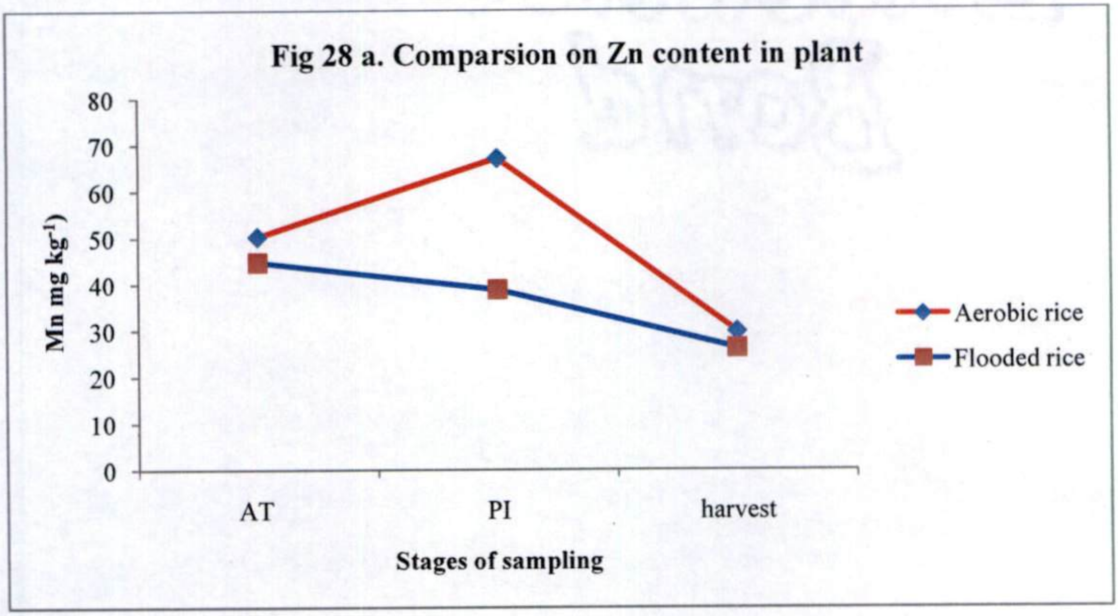
5.3.9 Zinc

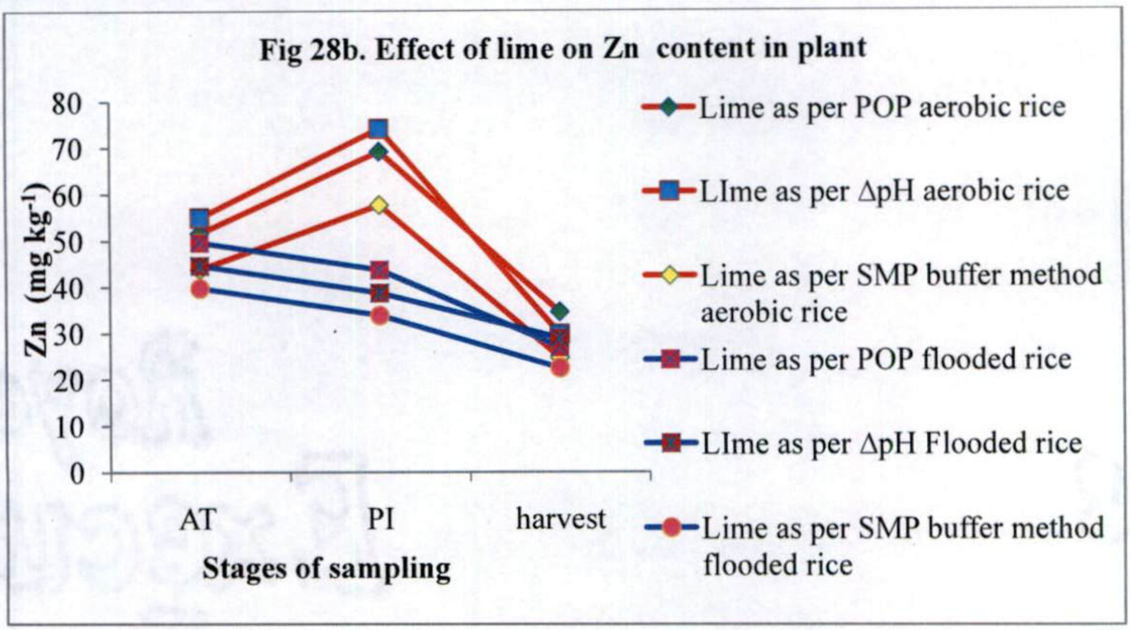
Under aerobic system, quantity of lime applied as per ΔpH (L_2) recorded higher zinc content in plant. Application of lime as per SMP buffer method (L_3) recorded the lowest zinc content in plant. Competitive absorption of other cations like K, Ca and Mg might have reduced Zn absorption in treatment with lime as per SMP buffer method.

Under flooded system, lime applied as per POP (L_1) significantly increased the zinc content in plant because of favourable pH for Zn absorption. Application of lime as per SMP buffer method (L_3) has decreased the Zn because of decreased availability of Zn resulted from formation of $Zn(OH)_2$ and $ZnCO_3$ in soil solution.

The aerobic system of rice cultivation was found significantly higher in improving zinc content in plant, because of decrease in completion from toxic levels of Fe and Mn, which in turn resulted in more Zn uptake. Zn content in plant under flooded system of rice cultivation was lower (38.70 mg kg^{-1}) because of reduced availability of Zn resulted from formation of $Zn(OH)_2$ and $ZnCO_3$ in soil solution under flooded condition (table 79 to 82 and fig 28).

Fig 28. Changes in zinc content in plant





5.3.10 Copper

Under aerobic system, at active tillering, lime as per SMP buffer method recorded the highest copper content in plant due to release of Cu from organic matter (rate of decomposition was higher in this treatment).

Under flooded system, at active tillering, lime applied as per SMP buffer method (L_3) recorded significantly the lowest Cu content in plant due to precipitation under high pH (table 83 to 86 and fig 29).

Aerobic system recorded significantly the lowest copper content in plant than that in flooded system. The applied quantity of lime under aerobic condition must have precipitated the available Cu, resulting in decrease in available Cu.

5.3.11 Boron

Under both systems, fertilizers applied as per soil test (F_2) recorded higher boron content in plant than that in fertilizer as per POP (F_1) during all the stages of sampling due to increased absorption from applied borax.

Under aerobic system, lime applied treatment as per ΔpH (L_2) recorded the highest boron content in plant because of increased absorption under favourable pH. Application of lime as per SMP buffer method (L_3) recorded the lowest B content in plant due to reduced absorption of boron. The reduction in absorption must be due to decreased availability of available B due to precipitation as calcium borate, in presence of huge quantity of lime (table 87 to 90 and fig 30).

Under flooded system, the quantity of lime applied as per SMP buffer method (L_3) recorded the highest boron content in plant because of favourable pH for uptake.

Flooded system recorded higher boron content in plant in comparison with that in aerobic rice due to higher solubility of applied borax under flooded condition during all the stages of sampling.

Fig 29. Changes in boron content in plant

Fig 29 a. Comparsion on B content in plant

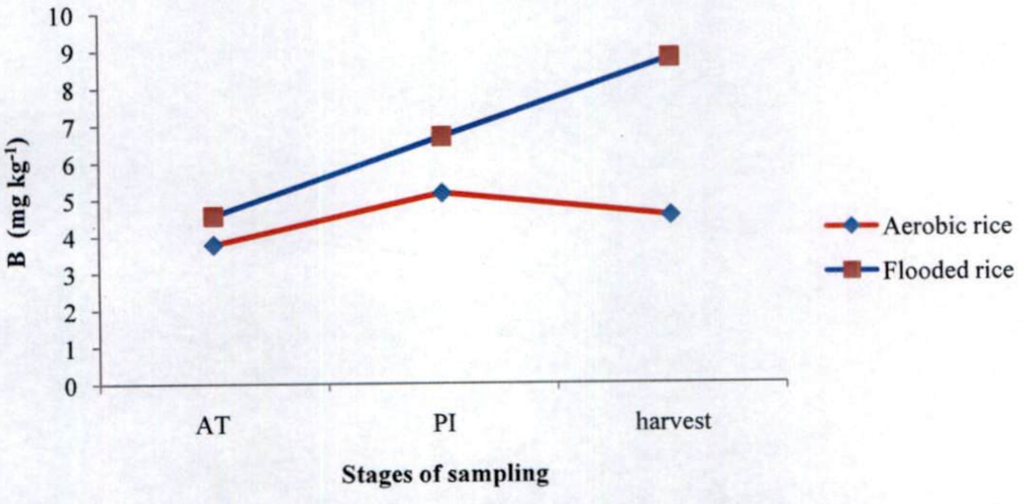
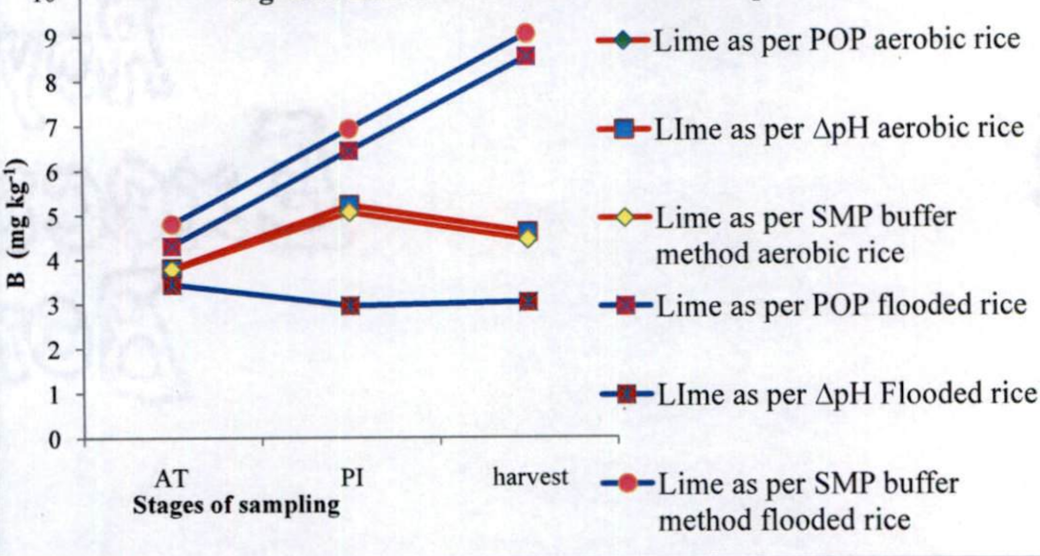


Fig 29b. Effect of lime on B content in plant



5.4. Dynamics of phosphorus under aerobic and flooded system of rice cultivation

5.4.1 Aerobic system

Under aerobic system, the major fraction of P was Fe-P which had contributed to available pool through Ca-P as indicated by its decrease in percentage contribution from 52.1 at initial stage to 42.8 % (Fig. 30) at harvest of the crop. The applied P might have precipitated as tri calcium phosphate [$Ca_3(PO_4)_2$], which is insoluble. The negative correlation of available P with Ca-P at active tillering and panicle initiation, as well as the direct effect of Ca-P (very high and negative) at active tillering and panicle initiation substantiates this precipitation of Ca-P as insoluble form (table 91 to 107).

At the same time, the Fe-P was found significantly and positively correlated with available P at active tillering and panicle initiation indicating that this fraction was the major one which contributed to available pool. But as the time proceeded, the contribution of Fe-P to available P might have decreased and the precipitated tri calcium phosphate had contributed to available pool by reverting to mono calcium phosphate which is the major fraction at near neutral pH contributing to available P.

Hence it can be concluded that under aerobic condition, the major fractions controlling the availability of phosphorus are Fe-P and Ca-P, through each other dictated by the change in pH.

5.4.2. Flooded system

The major fractions which contributed to available P in soil under flooded condition were Fe-P (the distribution was decreased from 57.5 % at initial stage to 54.9 % at harvest), Al-P (decreased to 9.5 % at harvest from 12.5 % at initial level) and sesquioxide occluded P (distribution decreased from 21.8 % at initial stage to 18.1 % at harvest). The decrease in the distribution of above mentioned fractions were counterpoised by the corresponding increased percentage distribution of Ca bound P from an initial status 5.7 % to 12.5 % at harvest of the crop.

At active tillering, the Ca-P had contributed directly to available P as indicated by the correlation coefficients and direct effects of partial coefficients of Ca-P on available P (table 285). The occluded P fraction was negatively correlated with available P, at the same time; its indirect effect through Ca-P was positive and very high indicating the conversion of occluded P to Ca-P which is available for plant uptake (table 286). As the time elapsed, the other fractions (Fe-P and Al-P) must have solubilized by reduction due to submergence as well as increase in pH due to applied lime, might have contributed to available pool as indicated by the correlation coefficients. The data on the direct effects of Fe-P & Al-P were very high and negative, and that through Ca-P was very high and positive; indicated that these fraction might have released P through Ca-P (as mono calcium phosphate). The direct effect of occluded P was very high and positive indicating that the native occluded P might have solubilized under anaerobic environment in presence of lime, which might have contributed directly to the available pool.

At panicle initiation, Ca-P was found negatively correlated with available P indicating the precipitation of Ca-P as tri calcium phosphate, and hence contribution to available pool was still through Al-P and Fe-P.

The high positive direct effect of Ca-P at harvest suggests that, Ca-P is contributing to available pool. But, low available P content at this stage is an indirect indication of very low rate of transformation of tri calcium phosphate $Ca_3(PO_4)_2$ to mono calcium phosphate [Ca $(H_2\ PO_4)_2$] which is slowly contributing to the available pool. The availability of P from Fe-P is more initially when compared with that in aerobic condition was due to reduction of Fe^{3+} to Fe^{2+} and subsequent solubilisation of P. This solubilized Fe-P gets precipitated gradually to Ca-P (tri calcium phosphate $Ca_3(PO_4)_2$) in both systems as governed by the change in pH. However the transformation of tri calcium phosphate to mono calcium phosphate was less under flooded environment (this conversion was reported by Patrick and Mahapatra, 1968).

Fig 30. Percentage distribution of P fractions under aerobic and flooded systems

Fig 30a. Initial distribution of P fractions under aerobic system

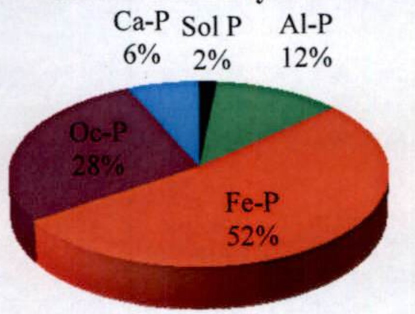


Fig 30 b. Effect of lime on percentage distribution of P fractions under aerobic system at different stages of sampling

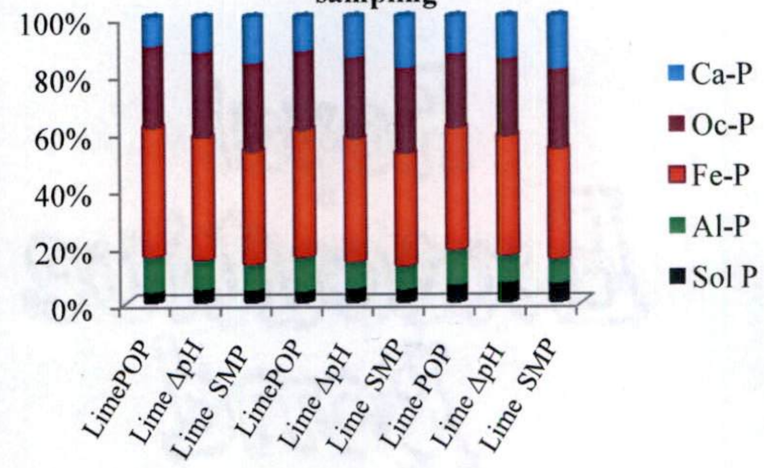


Fig 30 c. Initial distribution of P fractions under flooded system

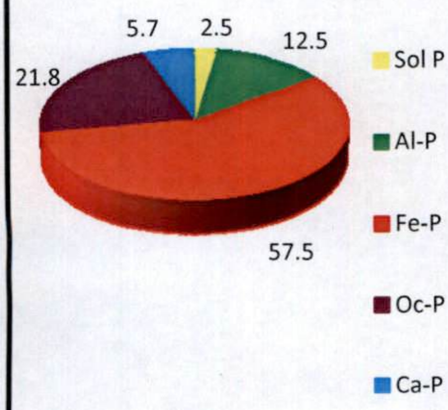
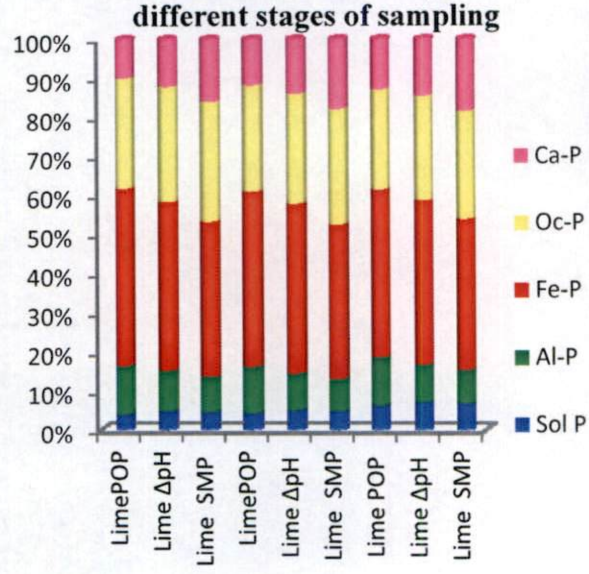


Fig 30 d. Effect of lime on percentage distribution of P fractions under flooded system at different stages of sampling



It can be concluded that under flooded system of rice cultivation, the major fractions contributing to available pool are Al-P, Fe-P, and occluded P, but through Ca-P.

5.5. Dynamics of Fe under aerobic and flooded systems of rice cultivation

5.5.1 Aerobic system

The major fractions contributing to available Fe pool were, OM bound Fe, water soluble + exchangeable Fe, and MnO occluded, as indicated by the variation in percentage distribution of these fractions at different stages of sampling as well as the correlation coefficients (table 108 to 126).

The available Fe was significantly and positively correlated with water soluble + exchangeable Fe, MnO occluded Fe and Amorphous FeO occluded Fe.

As indicated by the path coefficients, water soluble + exchangeable Fe fraction directly contributed to available Fe and hence to plant Fe content at all stages. The OM-Fe contributed to available Fe through water soluble + exchangeable Fe. The MnO occluded Fe contributed to available Fe directly as well as indirectly through water soluble + exchangeable Fe.

The amorphous FeO occluded Fe restricted Fe availability at harvest (direct effect was very high and negative); at the same time it was slowly contributing to available pool through water soluble + exchangeable fraction. Thus all the fractions of Fe contributed to available pool by transformation to water soluble + exchangeable form.

5.5.2. Flooded system

The major fractions contributing to available Fe under flooded system of rice cultivation at all the stages of sampling were water soluble + exchangeable, MnO occluded Fe, and Am FeO occluded fraction. The distribution of water soluble + exchangeable fraction was found increased under flooded system of rice cultivation when compared to that of aerobic system.

The distribution of water soluble + exchangeable fraction was found increased from 1.23 % at AT to 1.30 % at PI and it further decreased gradually to 0.92% at harvest of the crop. This fraction was found significantly and positively correlated with available Fe at all the stages. Thus the water soluble + exchangeable Fe was directly contributing to the available pool.

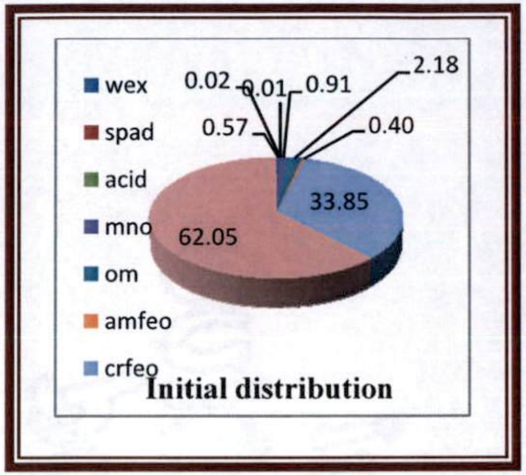
The negative but significant correlation of amorphous Fe Oxide fraction with available Fe and plant Fe content at AT and PI; and its increased per cent distribution from initial value of 1.06 % to 2.88 % at harvest suggest that application of lime precipitated the soluble Fe as amorphous Fe Oxide occluded Fe. The fact that the direct effect of this fraction and its indirect effect through water soluble + exchangeable fraction were with opposite signs (when one became negative the other was positive) indicated that when Fe got occluded in amorphous iron oxides due to increase in pH the concentration of Fe^{2+} in soil solution got decreased and vice versa.

Though MnO-Fe has shown significant positive correlation with available Fe and plant Fe content, its direct effect on Fe availability and plant Fe content was found negative and very high; its indirect effect through water soluble + exchangeable Fe suggest that MnO-Fe had influenced the availability of Fe and its uptake by the plant mainly through water soluble + exchangeable fraction because of reduced atmosphere depending on the pH.

It can be concluded that the availability of Fe and its absorption by the crop was influenced mainly by the concentration of water soluble + exchangeable Fe fraction which was either dissolved from or precipitated to amorphous Fe Oxide occluded Fe and MnO-Fe fractions. The concentration of Fe^{2+} increased due to reduction under anaerobic environment. Then with increased pH due to lime application, the AmFeO-Fe and MnO-Fe were precipitated, which resulted in a decreased per cent distribution of water soluble + exchangeable Fe at harvest.

Fig 31. Distribution of Fe fractions under aerobic system

Fig 31a. Percentage distribution of Fe fractions under aerobic system - Effect of lime as per POP



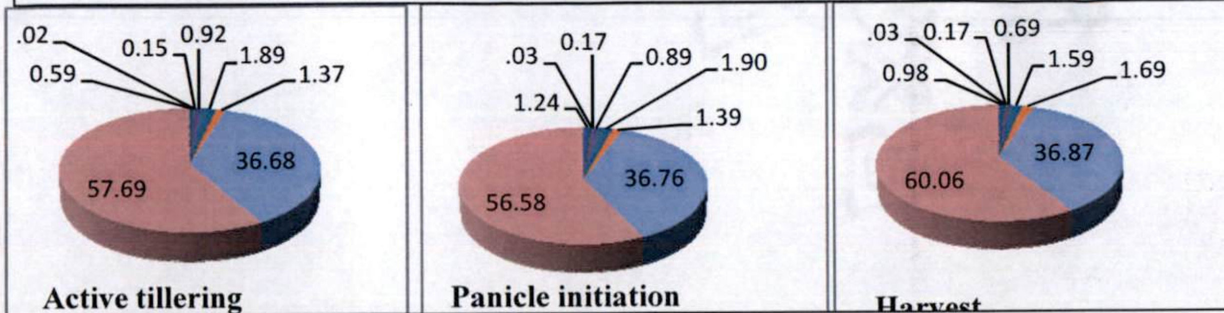


Fig31b. Percentage distribution of Fe fractions under aerobic system - Effect of lime as per ΔpH

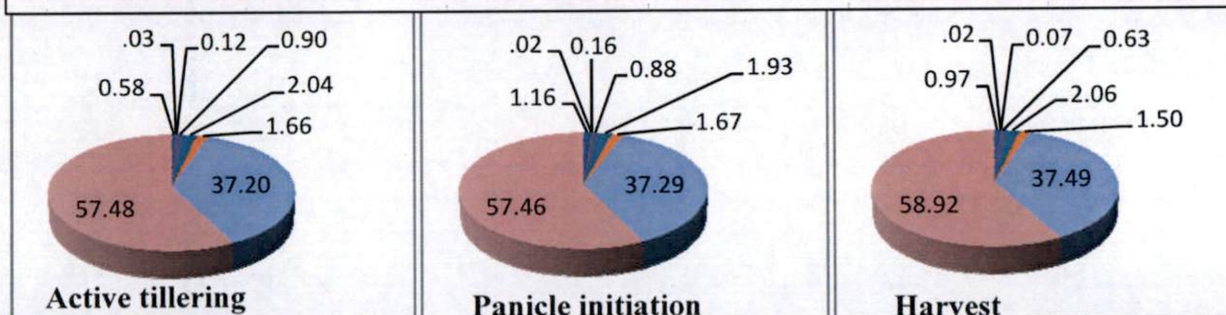


Fig31c. Percentage distribution of Fe fractions under aerobic system - Effect of lime as per SMP buffer method

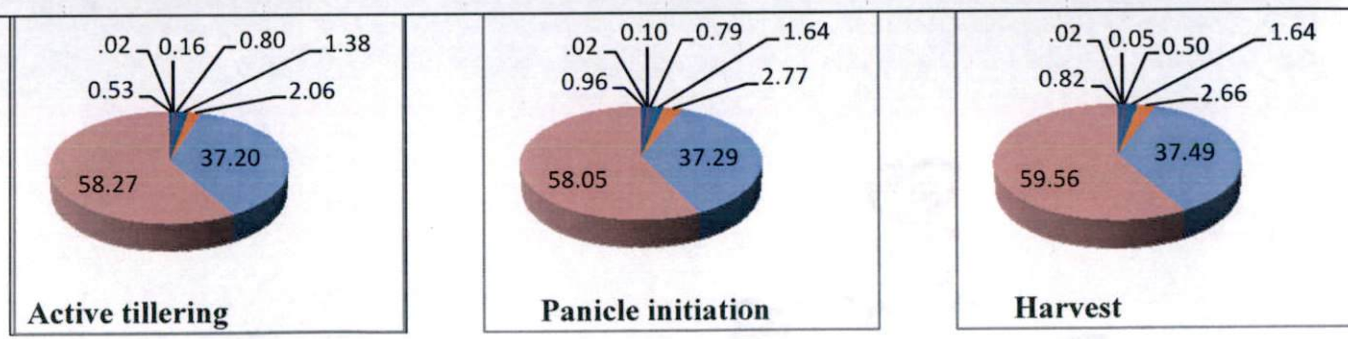
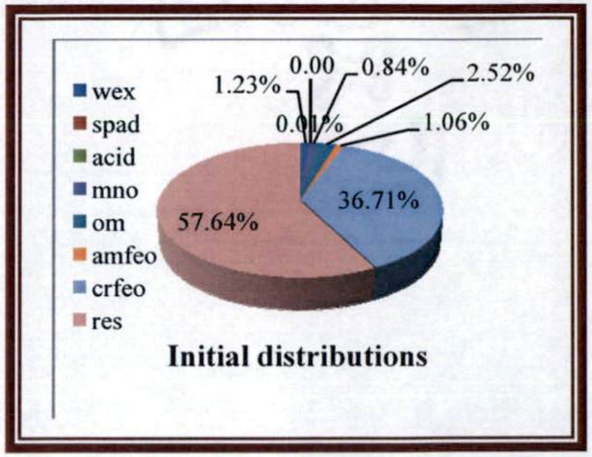


Fig 32. Distribution of Fe fractions under flooded systems

Fig 32a. Percentage distribution of Fe fractions under flooded systems - Effect of lime as per POP



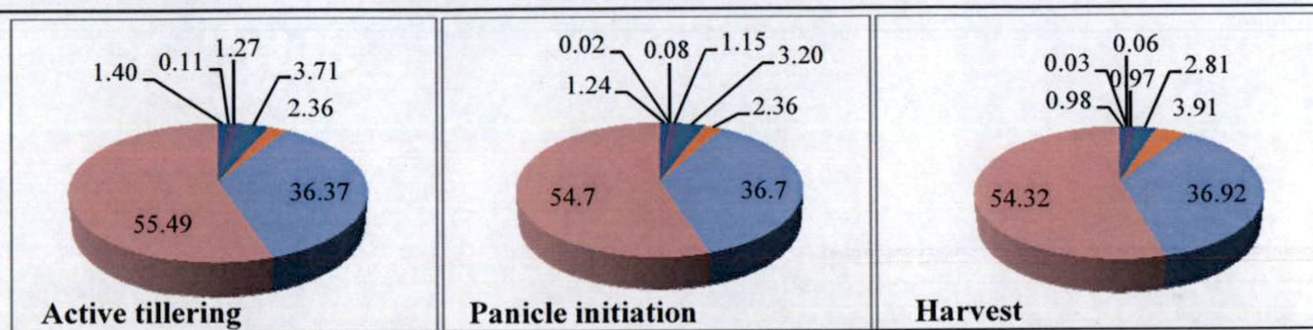


Fig 32b. distribution of Fe fractions under flooded system - Effect of lime as per ΔpH

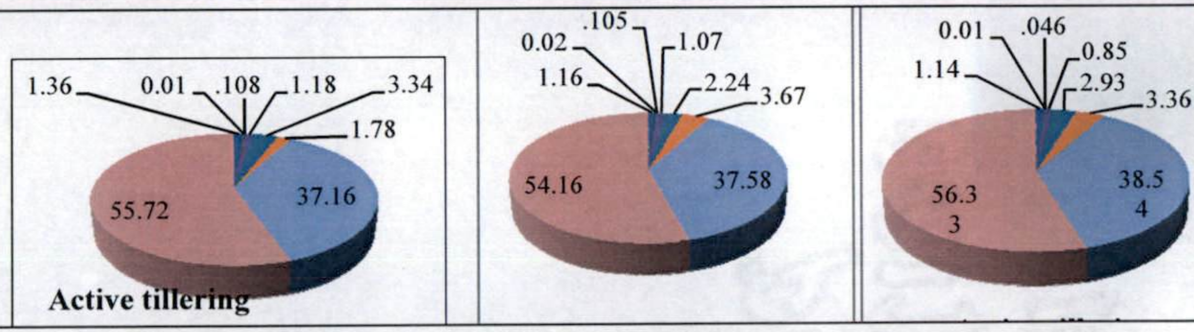
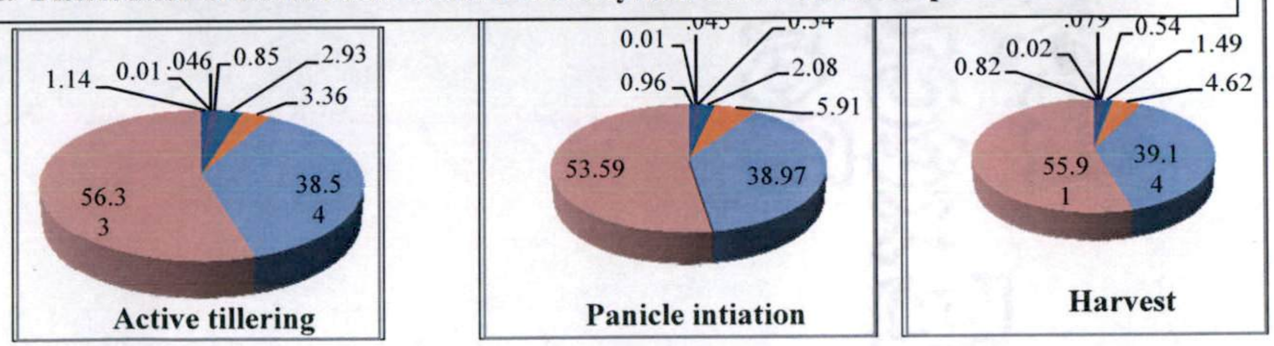


Fig 32c. Distribution of Fe fractions under flooded system Effect of lime as per SMP buffer



5.6. The Dynamics of Zn under aerobic and flooded systems of rice cultivation

5.6.1. Aerobic system

The dominant fraction was 'residual' under aerobic environment. The major fractions contributing to available Zn were water soluble + exchangeable, organic matter occluded, specifically adsorbed and amorphous FeO occluded ones (table from 127 to 145).

The organic matter bound Zn was positively and significantly correlated with available Zn as well as with plant Zn at active tillering. The partial coefficients of organic matter bound Zn indicated that this fraction was contributing to available pool indirectly through water soluble + exchangeable pool (moderate and positive) at this stage. This can be substantiated by the decrease in percentage distribution of organic matter bound Zn from 6.42 % (initial stage) to 4.68 % at active tillering and the corresponding increase in water soluble + exchangeable fraction which was not detected at initial stage, but found increased to 0.21% at active tillering.

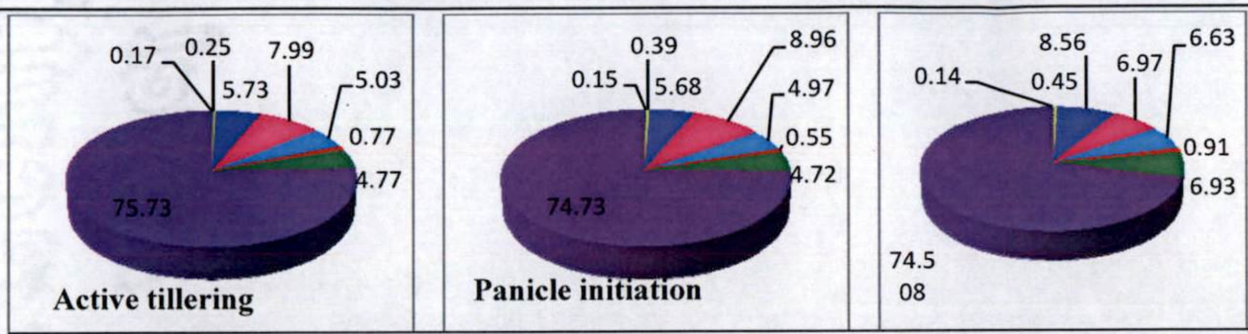
As the time proceeded, the AmFeO - Zn fraction was started contributing to available pool, indicated by the correlation coefficients, as well as the path coefficient (high and positive) of this fraction to available Zn through water soluble + exchangeable Zn at PI. The direct effect of MnO-Zn was found positive and very high at this stage, suggesting the direct contribution of this fraction to Zn availability due to dissolution during alternate wetting and drying. The MnO-Zn decreased from 12.55 % at initial level to 8.53 % at PI.

The fraction, MnO-Zn got transformed into OM-Zn which was contributing to the available pool and hence to the plant Zn content.

Under aerobic condition, the major fractions contributing to available Zn and plant Zn are organic matter occluded Zn, AmFeO-Zn, and MnO-Zn either directly or through OM-Zn. The major contribution of OM-Zn to available Zn was through water soluble + exchangeable pool, when it was transformed to the latter.

Fig 33. Distribution of Zn fractions under aerobic system

Fig 33a. Distribution of Zn fractions under aerobic system - Effect of lime as per POP



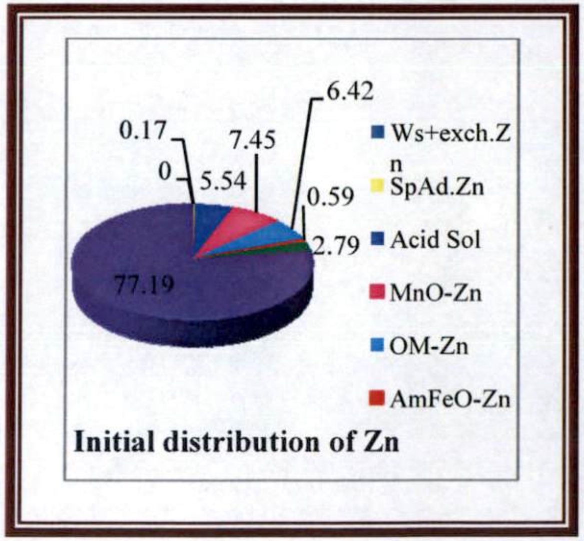


Fig 33b. Distribution of Zn fractions under aerobic system - Effect of lime as per ΔpH

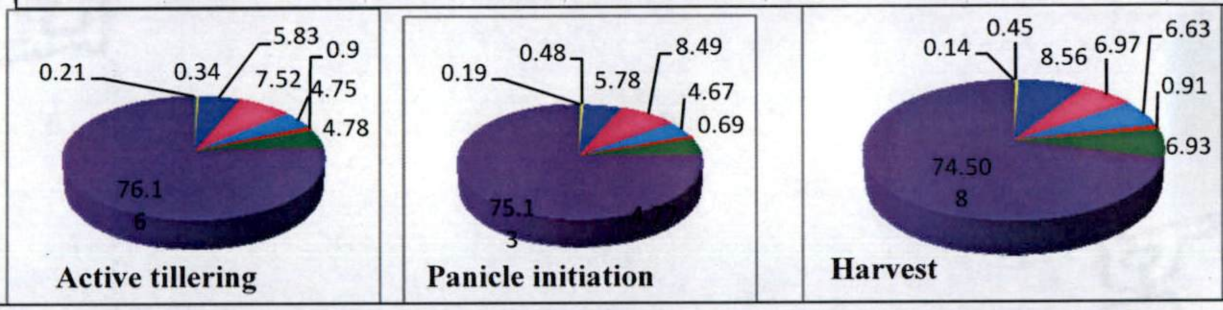
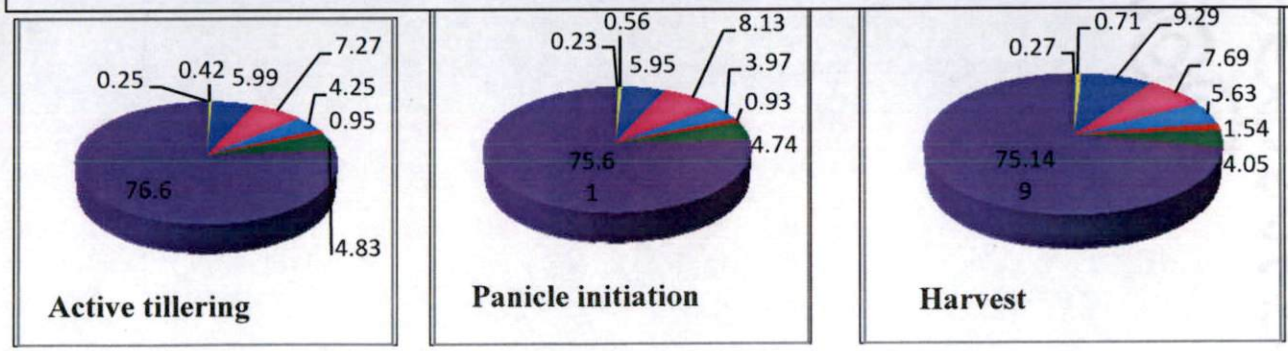


Fig 33c. Distribution of Zn fractions under aerobic system - Effect of lime as per SMP buffer method



The major fractions which contributed to available pool under flooded system of rice were MnO-Zn, OM-Zn and AmFeO-Zn.

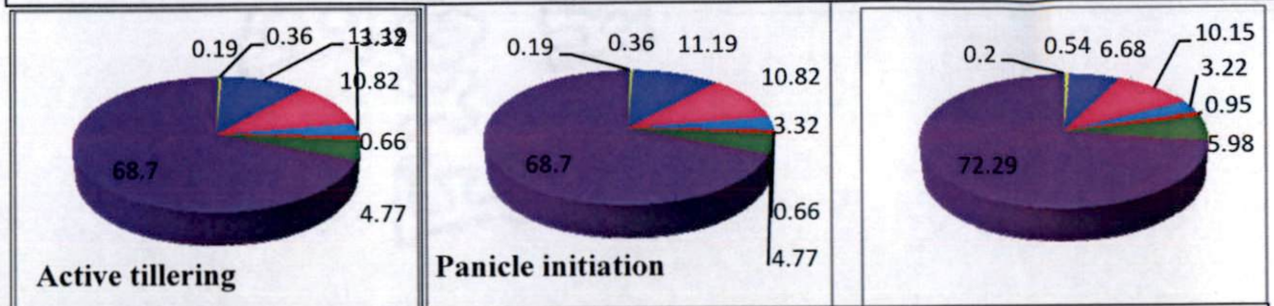
A decrease in distribution of OM-Zn was observed from 5.75 % (at initial) to 2.79 % (at harvest). The MnO-Zn decreased from 12.14 % at initial to 10.76 % at harvest. A substantial increase in AmFeO-Zn was observed at active tillering (10.63 %) from 6.86 % at initial level. The above facts indicated that Zn^{2+} ions were coming to the soil solution from OM-Zn and MnO-Zn under reduced atmosphere which might have later got occluded during the precipitation of amorphous iron oxides as a result of liming.

The direct effect of the OM-Zn was high and positive indicating its contribution to Zn availability at active tillering. The AmFeO-Zn restricted the availability of Zn at panicle initiation, which was indicated by the direct partial coefficients at panicle initiation, as well as its indirect effect (low and negative) through water soluble + exchangeable pool. MnO-Zn also decreased the water soluble + exchangeable fraction.

The major difference between aerobic and flooded systems was; OM-Zn is directly contributing under flooded system while its effect was indirect through water soluble + exchangeable under aerobic environment. This might be due to difference in formation of complexes of Zn with organic matter. Under reduced atmosphere, in flooded system these complexes definitely were directly soluble while Zn might be bound to organic matter either through sorption or ion exchange under aerobic environment.

Fig 34. Distribution of Zn fractions under flooded system

Fig 34a. Distribution of Zn fractions under flooded system - Effect of lime as per POP



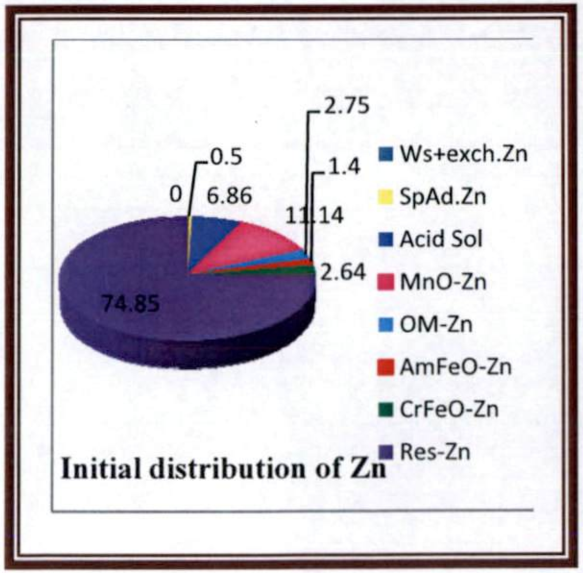


Fig 34b. Distribution of Zn fractions under flooded system - Effect of lime as per ΔpH

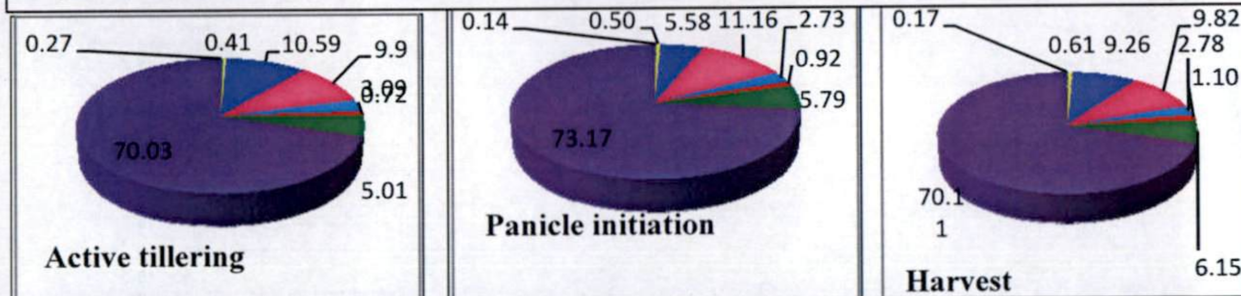
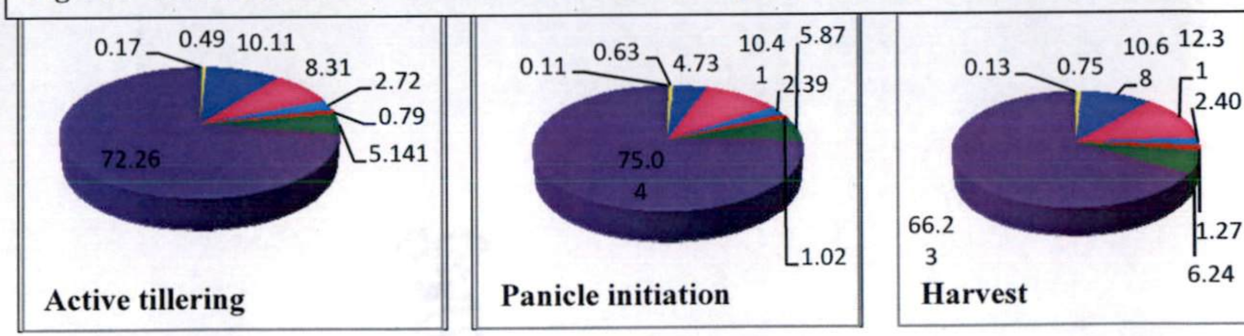


Fig 34c. Distribution of Zn fractions under flooded system - Effect of lime as per SMP buffer



5.7 Dynamics of boron under aerobic system and flooded systems

5.7.1. Aerobic system

The major fraction of boron contributing to available pool under aerobic system of rice cultivation was readily soluble B (percentage distribution was found increased from 0.08 at initial level to 0.36 % at harvest). Specifically adsorbed boron was found decreased from 0.24 % at initial level to 0.15 % at harvest. The oxide bound B and organic matter bound boron has shown an increasing trend in distribution from 5.26 % to 7.84 % and from 2.87 % to 3.98 % respectively at harvest. A corresponding decrease in residual fraction from 91.55 % at initial level to 87.67% at harvest was observed probably due to solubilization (table 146 to 164).

The significant and positive correlations of readily soluble B as well as their direct effect on available B at all the stages of sampling suggests that this fraction is the major one, contributing to available B pool and further for absorption by the crop. The increased distribution of this fraction must be the effect of applied boron.

Specifically adsorbed B was significantly and positively correlated with available B. But, its direct effect was not much significant and indirect effect through RS-B was very high and positive. This indicated that the contribution of this fraction to available pool through readily soluble B was due to release from adsorbed sites.

Fig 35. Distribution of B fractions at different stages

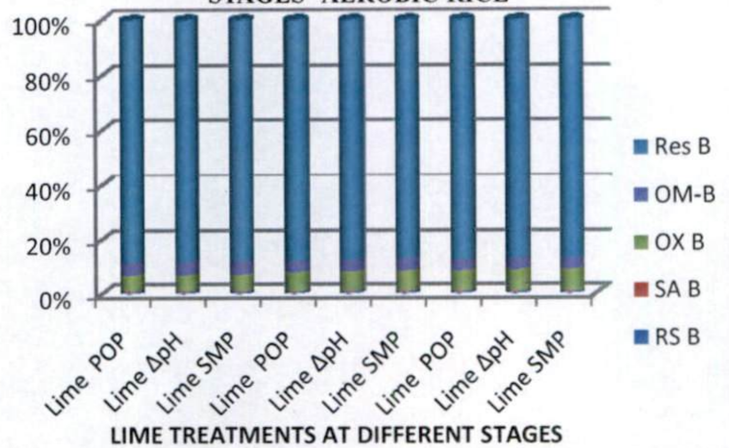


FIG 35 A. PERCENTAGE DISTRIBUTIONS OF B FRACTIONS - EFFECT OF LIME AT DIFFERENT STAGES- AEROBIC RICE

Initial distribution of boron under aerobic system

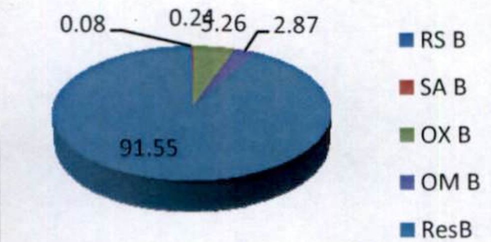
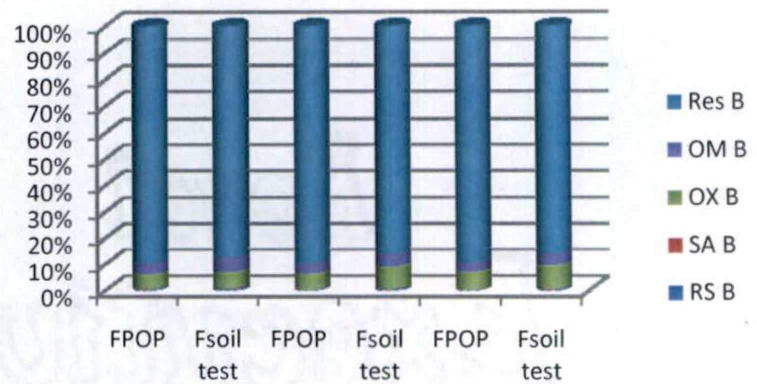


Fig 35b. Effect of applied fertilizers on distribution of B fractions aerobic rice



The percentage distribution oxide bound B was increased from 6.07% at initial level to 9.66% at harvest. The increased pH due to applied lime must have precipitated the Fe-oxides. A portion of the readily soluble B probably had precipitated along with this oxides resulted in an increase in oxide bound boron. Thus it was clear that the oxide bound boron became available when it is solubilized and at higher pH under aerobic environment, B co precipitated with the oxides of Fe and Mn.

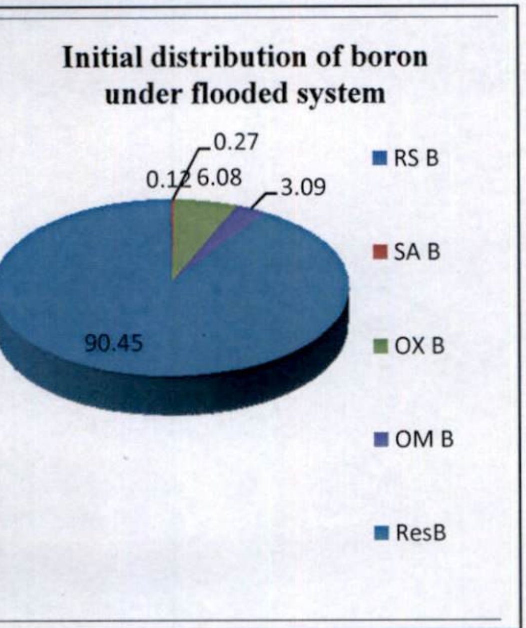
5.7.2. Flooded system

The major fractions contributing to available boron under flooded system of rice cultivation were RS-B, SA-B, OX-B, and residual B.

The distribution of RS-B was found increased due to application of borax (similar observation was also reported by Santhosh, 2013). The increased percentage distribution of RS-B under flooded condition (even after application of equal quantity of boron fertilizer under both systems) was due to increased solubility of applied boron under flooded condition. The significant and positive correlations of RS-B with available boron, as well as its very high direct effect on available boron suggest that, this particular fraction is the major one contributing to available boron.

The distribution of SA-B was found decreased from initial to harvest. The SA-B was positively and significantly correlated with available boron. The direct effect of SA-B was found negative. But, its indirect effect through RS.B (very high and positive) indicated that the specifically adsorbed fraction was also contributing to available B, by releasing boron from specifically absorbed sites to water soluble forms.

The oxide bound boron was found increased from 6.08% at initial to 9.68% at harvest. This suggests that a portion of the applied boron might have precipitated with applied lime and became unavailable for plant absorption. The direct effect of this


Initial distribution of boron under flooded system
0.27
0.12
6.08
3.09
90.45
RS B
SA B
OX B
OM B
ResB

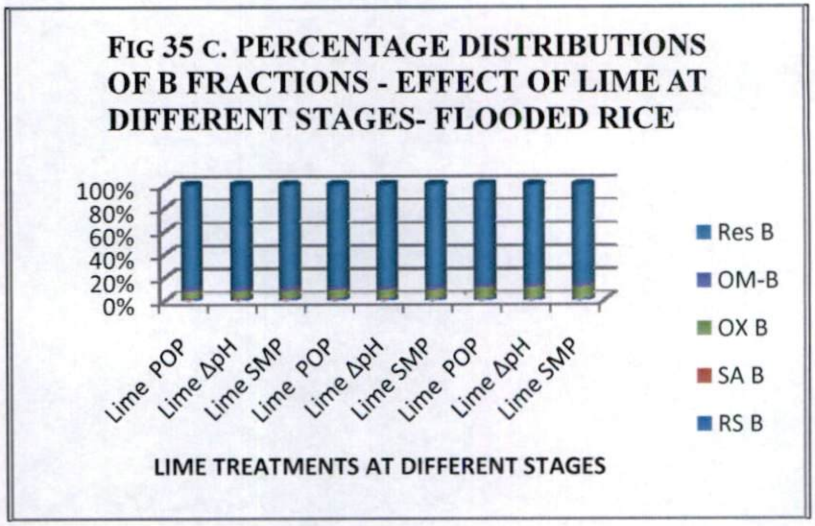


FIG 35 C. PERCENTAGE DISTRIBUTIONS OF B FRACTIONS - EFFECT OF LIME AT DIFFERENT STAGES- FLOODED RICE
100%
80%
60%
40%
20%
0%
Lime POP
Lime ΔpH
Lime SMP
Lime POP
Lime ΔpH
Lime SMP
Lime POP
Lime ΔpH
Lime SMP
LIME TREATMENTS AT DIFFERENT STAGES
Res B
OM-B
OX B
SA B
RS B

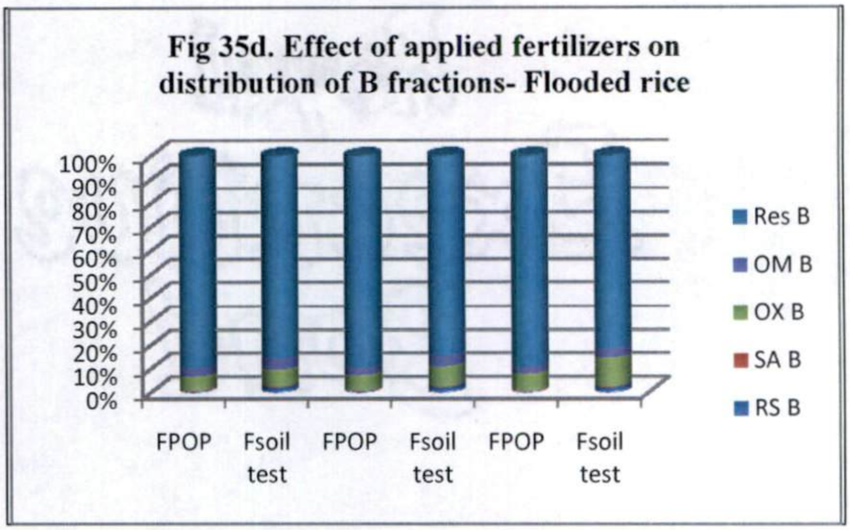


Fig 35d. Effect of applied fertilizers on distribution of B fractions- Flooded rice
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
FPOP
Fsoil test
FPOP
Fsoil test
FPOP
Fsoil test
Res B
OM B
OX B
SA B
RS B

fraction to boron availability was not much significant, but its indirect effect through RS-B was very high and negative, also dictates the above mentioned fact.

The residual boron has also contributed to available boron through RS-B as indicated by its high and positive indirect effect through RS-B at all the stages of sampling.

Hence under both systems, applied boron has contributed directly to available boron through readily soluble B. A portion of the applied B was precipitated as oxide bound boron (by applied lime). The specifically adsorbed boron has contributed to available boron indirectly through RS-B. The residual fraction also showed a decrease in percentage distribution through its contribution to available pool, indirectly through readily soluble Boron.

It is also clear that there is not much difference in the dynamics of boron between the two systems except more solubility under flooded condition.

5.8. Nutrient dynamics and transformation under aerobic and flooded systems of rice cultivation

The pH of the soils both under aerobic and flooded environment increased from initial status, 4.2 to 6.13 and 4.9 to 5.99 respectively. The rate of increase in pH was in proportion with the quantity of lime added. The increase in pH in lime applied treatments as per SMP buffer method (to neutralize the potential acidity) was much higher than the other two lime treatments. The rate of increase in pH was more under aerobic system due to more quantity of lime applied.

The highest electrical conductivity recorded during all the stages of sampling was under aerobic system of rice cultivation. This was due to the increased total electrolyte concentration resulting from the applied fertilizers and lime. The quantity of lime applied was highest in aerobic rice under SMP buffer method, which recorded the highest EC.

The highest organic carbon content was recorded in aerobic rice cultivation at active tillering and panicle initiation even though same quantity of organic manure was added under both systems (5 t ha^{-1}). This was due to the quicker decomposition of applied manure in presence of lime. Further, at harvest, flooded condition recorded highest organic carbon. The enhanced rate of decomposition of organic manure and release of CO_2 must have depleted the organic carbon status quickly under aerobic system. Under flooded anaerobic environment, the decomposition and release of CO_2 was at a slower rate. Further, the rate of decomposition of organic manure was found highest in lime applied treatments as per SMP buffer method, under both systems of rice cultivation. The enhanced rate of decomposition and release of nitrogen from aerobic system resulted in more N content in plant.

The available P status was found highest under flooded system of rice cultivation except at harvest. The increased solubility of Fe and Mn under submergence, released the corresponding bound P to the soil solution. This resulted in highest available P under flooded system at active tillering and at panicle initiation. Corresponding increase in P content in plant was also observed. But at harvest, the applied P precipitated as insoluble calcium phosphate lead to decreased P availability. The correlation coefficients of fractions with available P and partial coefficients indicating the direct and indirect effects also points towards this fact.

Under aerobic condition, the available P recorded at active tillering and panicle initiation was lower than that of the initial status. The applied lime as per SMP buffer method @ 8.5 t ha^{-1} might have precipitated the available P as insoluble calcium phosphate, resulting in overall reduction in P availability. The negative correlation of available P with Ca-P at active tillering and panicle initiation, as well as the direct effect of Ca-P (very high and negative) at active tillering and panicle initiation substantiates this precipitation of Ca-P as insoluble form. But at harvest, the precipitated insoluble calcium phosphate might have solubilised under favourable pH to mono calcium phosphate, so as to increase the available P status which is not happening under flooded environment.

Under both the systems, the increase in available K was in accordance with the initial value. The rate of increase of available K was with respect to the quantity of fertilizer added. The available K was found reduced at harvest from that of initial, active tillering and panicle initiation because of plant uptake under both systems. Lime applied treatments as per SMP buffer method recorded highest available K status due to decreased competition from Fe and Mn which might have precipitated at enhanced pH. The available K status was highest under aerobic condition throughout the crop growth because of reduced rate of leaching under this environment. Highest K content in plant was also recorded under aerobic rice system.

The highest available Ca at active tillering and panicle initiation was recorded in flooded system of rice cultivation. This was due to applied lime which became available by solubilization. At harvest, the available Ca became precipitated as insoluble calcium phosphate which decreased the availability of both Ca and P under flooded condition. This was evidenced from the data of correlation and path analysis. The transformation of insoluble calcium phosphate to mono calcium phosphate occurred only under aerobic condition.

Under aerobic condition, the available Ca was increased, but the rate of increase was less when compared with that of flooded condition, because of the precipitation of applied lime (especially in treatment as per SMP buffer method) with applied P as insoluble Ca·phosphate. Further, at harvest this precipitated calcium phosphate must have solubilized to mono calcium phosphate, which resulted in increase of available Ca and available P at this stage.

The highest Ca content in plant was recorded under flooded system throughout the crop growth even though applied lime was more under aerobic condition. This was because of the better solubility of applied lime under flooded system by the conversion of applied lime as CaO to $Ca(OH)_2$. This might also have contributed to decreased available Ca status in soil under flooded condition.

The available Mg status did not differ much between aerobic and flooded system of rice. But comparatively higher available Mg was recorded under aerobic system because of reduced rate of leaching losses. Higher available Mg was recorded in the fertilizer treatment as per soil test under both systems due to application of $MgSO_4$. This was reflected in Mg content in plant also.

The available sulphur status recorded was the highest under flooded condition during all the stages of sampling. The increased solubility of applied factomphos and $MgSO_4$ resulted in increased the available sulphur status under this system. Application of lime as per SMP buffer method increased the available S status under both systems of rice cultivation because of the indirect effect of applied lime on organic manure decomposition and mineralization of sulphur. This was reflected in sulphur content in plant also.

Under flooded environment, the status of available Fe was higher because of the reduction of Fe^{3+} to Fe^{2+}. The available Fe status was found decreased under aerobic condition due to oxidation of Fe^{2+} to insoluble Fe^{3+}. However under both systems of rice cultivation, the available Fe status was decreased with increase in dose of lime because of precipitation of oxides and hydroxides of iron at near neutral pH. The decrease in water soluble + exchangeable Fe together with increase in AmFeO-Fe also points to the precipitation of Fe. Highest Fe content in plant was recorded under flooded system of rice cultivation.

The available Mn status under flooded environment recorded lower, when compared to that under aerobic condition. This could be in connection with the initial status, which was less under flooded system. Further, the increased availability of Mn due to reduction under submergence resulted in more absorption by the plant depleting its level in soil.

The availability of Cu was found lower under flooded condition, than that of aerobic environment at active tillering and at panicle initiation, due to precipitation of

Cu at increased pH under flooded system. However, the available Cu status was almost similar at harvest under both systems of rice cultivation.

The highest available Zn recorded at all the stages of sampling was under flooded system of rice cultivation. The quantity of Zn present was sufficient under flooded system. The lowest available Zn was recorded under aerobic condition. This could be in relation with the initial status of available Zn in both the systems. The increased absorption of Zn by the crop under aerobic condition also resulted in recording lower available Zn in this system. Precipitation of cations such as Fe^{3+} and Mn^{4+} under aerobic system, due to increased pH, lead to decreased competition for absorption of Zn. The available Zn decreased under aerobic condition and became deficient from active tillering till harvest of the crop.

The available boron status and boron content in plant was high under flooded condition because of the enhanced solubility of applied borax (soluble source of boron) and its absorption. This is evidenced from the correlation of available B as well as boron content in plant with fractions of B. The Path coefficients indicating the direct effect of readily soluble B on available B also pointed towards this fact. The boron was found decreased as the dose of lime increased. Lime applied as per SMP buffer method decreased the available boron due to precipitation of B with lime at higher pH. The boron content in plant increased in treatments where fertilizers added based on soil test under both systems of rice cultivation, due to applied boron.

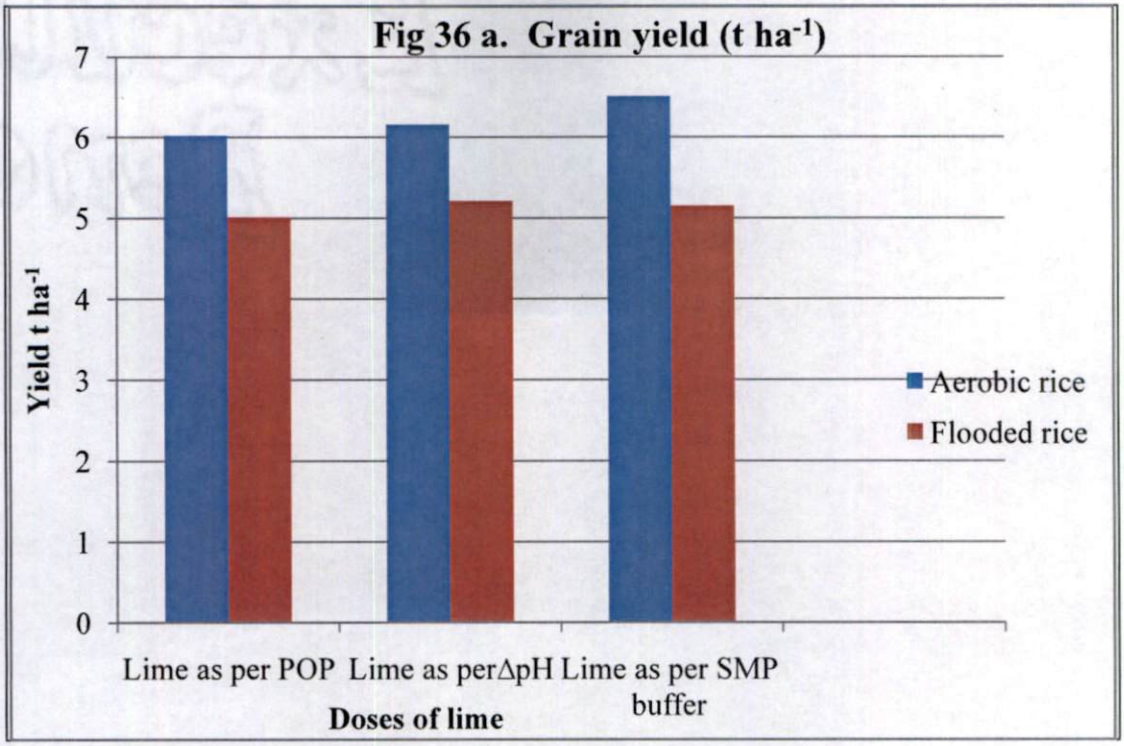
5.9. Yield, yield attributes and physiological parameters under aerobic and flooded systems

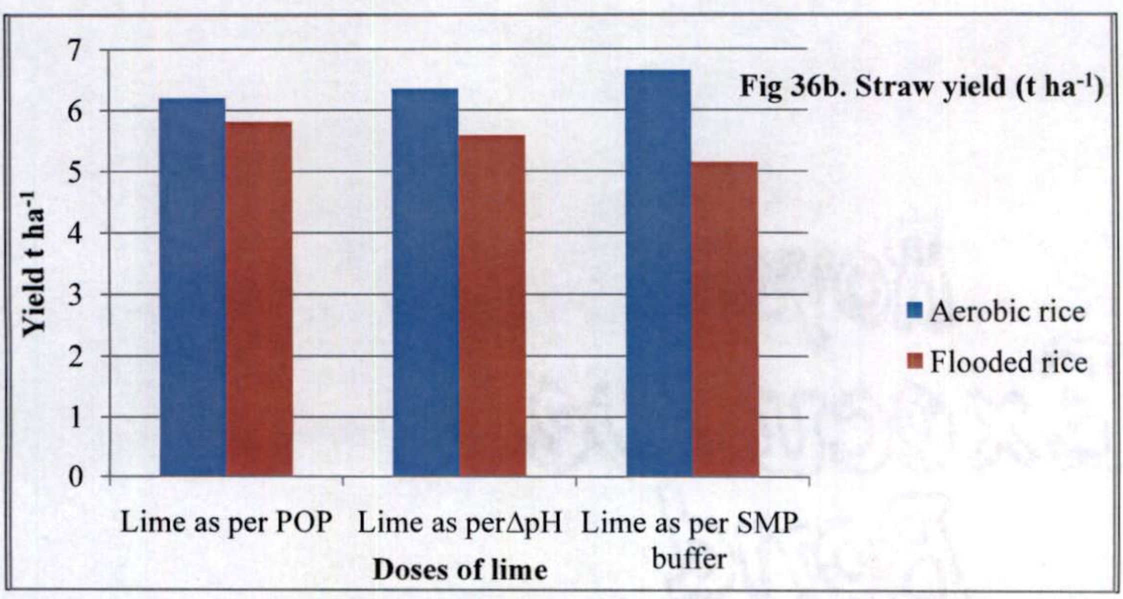
The number of tillers per hill was significantly higher under aerobic system both at AT and at PI stages than that under flooded system (table 166 and 167). The fertilizer treatment as per soil test (F_2) did increase the number of tillers under aerobic system whereas the fertilizer treatments where not at all significantly influencing the number of tillers in flooded system. Application of lime did not have any significant effect on number of tillers under aerobic system while lime applied as per SMP buffer method recorded significantly the lowest number of tillers at active tillering under flooded system. At panicle initiation the treatment with lime applied as per ΔpH and that with lime as per SMP buffer method were on par and recorded higher number of tillers than that in lime applied as per POP. It was also observed that there was a decline in the number of tillers at PI in comparison with that at active tillering under flooded environment. In iron rich lateritic soils, to accommodate high iron concentration unproductive tillers are usually produced at active growth stage which usually becomes dead at the beginning of the productive stage. This mechanism of tiller decline was observed to contain higher concentration of Fe. Such a decline was not observed in the case of aerobic rice. Thus the number of tillers was highest under aerobic condition with application as per soil test along with lime as per ΔpH.

The number of panicles per hill was almost double under aerobic system in comparison with that under flooded system (table 168). The number of grains per panicle was significantly higher under aerobic system than that under flooded system. The treatment with lime as per SMP buffer method recorded significantly higher number of grains per panicle under both systems. Application of fertilizers as per soil test was effective in increasing the number of grains per panicle under aerobic rice while the fertilizers were not found to have any influence on number of grains under flooded environment(table 169).

There was no significant difference between thousand grain weight recorded under flooded and aerobic systems (table 170). Fertilizers as per soil test as well as lime as per SMP buffer method did increase the thousand grain weight significantly under aerobic rice. Under flooded system the fertilizer treatments did not differ significantly while lime as per SMP buffer method recorded the lowest thousand grain weight. The data on grain yield clearly indicate that aerobic system recorded significantly higher yield (6.23 t ha^{-1}) than that under flooded system (5.12 t ha^{-1}).

Fig 36. Effect of lime on yield under aerobic and flooded systems of rice





The fertilizer treatment as per soil test was significantly superior in increasing the grain yield than that with fertilizers as per POP under aerobic environment whereas these treatments did not differ significantly under flooded system (table 171). Under both the systems, the treatments with application of lime as per ΔpH and as per SMP buffer were on par. The treatment with lime as per POP recorded the lowest yield.

Aerobic system of rice recorded significantly higher straw yield than that under flooded system. The fertilizer treatments did not differ significantly with respect to straw yield under both systems. The treatments with lime as per ΔpH and as per SMP buffer method were on par in aerobic rice while in flooded rice the straw yield did not significantly differ in any of the three lime treatments (table 172).

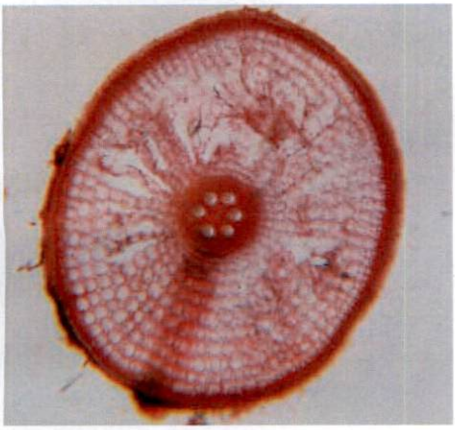
In brief aerobic system with fertilizers as per soil test along with lime as per pH recorded significantly higher number of tillers per hill, number of panicle per hill and number of grains per panicle which naturally contributed in recording significantly higher yield.

The data on fresh root CEC, apparent free space and the anatomical difference with respect to aerenchyma development together indicated that the significantly higher root CEC under aerobic environment could be attribute to more negative sites on the roots under aerobic environment (table 173 and 174). Under flooded system the ferrous ion (Fe^{2+}) which is soluble, got mobilized towards the root surface where it was oxidized in presence of oxygen from the aerenchymatic tissues and got deposited as a coating thereby physically blocking the ion absorption. Under aerobic environment the iron was already in the oxidized insoluble form and hence its mobility towards the roots was restricted there by opening more sites for ion exchange. A slightly higher apparent free space under aerobic environment also supports this argument. There was no significant difference in chlorophyll content between both the systems (table 176, 177 and 178).

The data on shoot and root mass as well as root length and root volume at active tillering stage indicated that aerobic environment enhanced root and shoot growth when compared to flooded system. This might have contributed to more uptake of nutrients and to yield under aerobic system.

The total water requirement of the crop showed almost 57% reduction under aerobic system than that under flooded system. Under both systems, the treatment combination where fertilizers applied as per soil test with lime as per ΔpH (F_2L_2) recorded the highest net returns from the crop.

Plate 12. Rice root under aerobic system without well developed aerenchyma



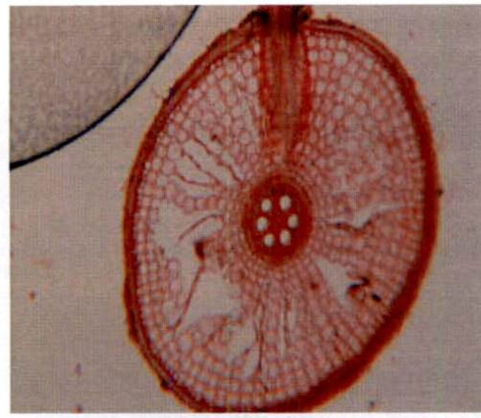
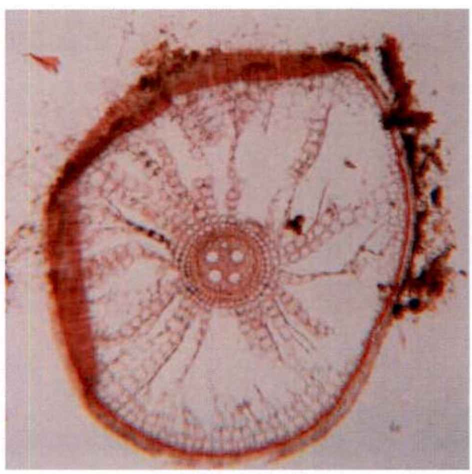


Plate 13. Rice root under flooded system with well developed aerenchyma



Summary

6. Summary

Field experiments on aerobic and flooded systems of rice were conducted in second crop season with the objectives to study the nutrient dynamics and transformations in these systems. These experiments were conducted in second crop season with rice (variety Jyothi), in farmer's field, at Nellikkattiri, Thirumittakode panchayat, Palakkad district. The soil was lateritic in origin. The treatments with two doses of fertilizers (as per Package of Practices Recommendations, KAU and based on soil test) and three doses of lime (as per POP, as per ΔpH and as per SMP buffer method) were imposed in plots of $20m^2$ area in Randomized Block Design with four replications. Under flooded condition, two field experiments were conducted to standardize the method of sampling and analysis for soil test based application of lime and fertilizers. One was based on sampling and soil testing on wet basis keeping the anaerobic environment unchanged, while the other was based on routine sampling and analysis after air drying. Better correlations with respect to available nutrients and plant nutrient contents were obtained for wet analysis based recommendation and hence the data from this experiment was considered for comparison of the nutrient dynamics with that of the experiment on aerobic rice where soil analysis was done after air drying. In situ measurement of pH, electrical conductivity and redox potential was done under both systems of rice cultivation. Redox potential was measured from three different depths under flooded system (15, 30 and 45 cm) and from two different depths under aerobic system (30 and 45 cm). The soil and plant samples were collected at three stages *viz.* at active tillering, panicle initiation and at harvest of the crop. The soil samples collected were analysed for pH, EC, OC available nutrients (P, K, Ca, Mg, S, Fe, Cu, Mn Zn and B), and were also assayed to estimate fractions of soil phosphorus, iron, zinc and boron. The plant samples were analysed for N, P, K, Ca, Mg, S, Fe, Mn, Zn, Cu and B. At harvest straw and grain samples were analysed separately. The salient results of the study are summarised below.

- The pH of the soil of the experimental field on aerobic rice was 4.2 (extremely acidic), and that of flooded rice was 4.9 (very strongly acidic). The organic carbon and available phosphorus status of the soil in both the fields were medium. The available potassium status was low. Both the soils were severely deficient in available Ca and Mg. The level of available sulphur was sufficient. The soils were sufficient in all the available micronutrients except boron.
- The pH increased immediately after application of lime, which was applied just before transplanting under both systems of rice. The rate of increase was in proportion to the quantity of lime applied under both systems. However, the rate of increase in pH was observed to be less under flooded system of rice.
- Soil pH was found to decrease to the initial level in plots of aerobic rice where lime was applied as per POP (L_1), while the pH was stabilized around six under flooded system
- Electrical conductivity increased immediately after application of lime, under both systems. The rate of increase was in proportion to the quantity of lime applied under both the systems. However, the rate of increase was observed to be less under flooded system of rice.
- Under flooded system, the redox potential showed a decreasing trend immediately after transplanting. The redox potential became more negative (around -200mV) as the depth of sampling increased. The lowest redox values were recorded in this system at 45 cm depth.
- Under aerobic system, the data showed that redox potential increased immediately after transplanting and became positive (around +400mV) within one week after transplanting and remained positive throughout the duration of the crop.

- The organic carbon status of the soils under both systems, increased in all the treatment combinations because of application of cow dung at the rate of 5t ha^{-1}.
- At active tillering, highest organic carbon status was recorded in treatment with lime applied based on SMP method of estimation under both systems. The organic carbon content in aerobic rice was significantly higher than that in flooded system of rice at active tillering.
- Highest organic carbon was recorded in treatment with lime applied based on SMP method under both systems at panicle initiation.
- Under both the systems organic carbon status at harvest was almost same as that at initial stage.
- Under aerobic rice, at active tillering, the treatment with lime as per ΔpH recorded significantly higher available P status. Application of lime as per SMP buffer method significantly decreased the available P than that of the initial status.
- Under flooded condition, at active tillering, lime as per SMP buffer method was found superior in increasing the available P status among the three doses of lime.
- The available P was found significantly higher in flooded rice in comparison with that in aerobic rice at active tillering.
- At panicle initiation, under aerobic condition, the available P status was found decreased in comparison with that at the active tillering
- Under both systems of rice cultivation, fertilizers applied as per POP was found to increase the available P status of the soil, when compared with the treatment where fertilizers were applied as per soil test (F_2) at panicle initiation
- At harvest, under aerobic condition, the quantity of lime applied as per SMP buffer method was found to improve the available P status of the soil.

- Under flooded condition, at harvest, lime applied as per ΔpH, was found to improve the available P status of the soil significantly, followed by application of lime as per POP. Lime applied as per SMP buffer method (L_3), recorded the lowest available P.
- The available P was found significantly higher in aerobic rice in comparison with flooded rice at harvest of the crop.
- Under both systems of rice cultivation, fertilizers applied as per POP (F_1) resulted in significant increase in available K status at active tillering.
- Under aerobic system, lime treatment as per ΔpH recorded the highest available K at AT and PI. At harvest, lime as per SMP buffer method recorded the highest available K.
- Under flooded system, lime as per SMP buffer method recorded the highest available K at all the stages of sampling.
- The aerobic system recorded higher available K than that in flooded system during all the stage of sampling.
- Lime applied as per SMP buffer method recorded significantly the highest available Ca under both systems at all the stages of sampling.
- Flooded system recorded higher available Ca at all the stages of sampling except that at harvest.
- Under both systems of rice cultivation, fertilizers applied as per soil test increased the available Mg status of the soil at all the stages of sampling.
- Lime applied as per SMP buffer method recorded highest available Mg under both systems at all the stages of sampling.
- Fertilizers applied as per soil test increased the available sulphur status of the soil at all the stages of sampling under both systems of rice cultivation.
- Application of lime as per SMP buffer method was significantly superior in enhancing available sulphur status of the soil under both systems.

- Available sulphur in flooded system was significantly higher than that under aerobic system during all the stages of sampling.
- Application of lime as per SMP buffer method recorded the lowest available sulphur status of the soil under both the systems.
- Cultivation of rice under aerobic condition was significantly better in decreasing available Fe than the flooded system.
- Quantity of lime applied as per SMP buffer method, was found to decrease the available Mn status of the soil under both systems.
- Flooded condition recorded lower available Mn than that of aerobic system at all the stages.(The initial status of available Mn was also lower under flooded system)
- At active tillering, lime applied as per SMP buffer method recorded lowest available Zn under flooded system, while the same treatment recorded significantly the highest available Zn under aerobic system. At panicle initiation, lime applied as per SMP buffer method was found to decrease the available Zn under both systems.
- Under both systems, the available Zn at harvest was found decreased than that of previous stages of sampling.
- Flooded system of rice cultivation recorded significantly lower available copper in comparison with aerobic system.
- Available boron content was significantly higher in the treatments where fertilizers were applied as per soil test under both systems.
- Lime applied as per SMP buffer method recorded the lowest available boron under both systems at all the stages of sampling.
- The available boron was significantly higher in flooded rice in comparison with aerobic rice at all the stages.
- Application of lime as per SMP buffer method recorded the highest nitrogen content in plant under both systems during all the stages.

- Rice cultivation under aerobic condition recorded significantly higher nitrogen content in plant than under flooded condition.
- Under both systems, lime incorporated based on ΔpH recorded the highest phosphorus content in plant. Lime as per SMP buffer method (L_3) recorded the lowest P at AT and PI stages.
- The P content in plant was higher in flooded rice in comparison with that in aerobic rice
- At harvest, under aerobic system, the amount of lime incorporated as per SMP buffer method recorded significantly the highest phosphorus content in straw.
- Fertilizers applied as per soil test recorded higher potassium content in plant under both systems.
- Higher K content in plant was recorded in aerobic system than that in flooded system.
- Lime as per SMP buffer method recorded the highest calcium content in plant under both systems.
- Flooded system of rice recorded significantly higher calcium content than that of aerobic system.
- Under both systems, fertilizers applied as per soil test recorded the higher Mg content in plant than that of fertilizers as per POP.
- Aerobic system recorded higher Mg content in plant in comparison with that in flooded rice.
- Under both systems, fertilizers applied as per soil test recorded higher sulphur content in plant.
- Lime applied as per SMP buffer method recorded significantly the highest sulphur content under both systems.
- Cultivation of rice under flooded condition recorded significantly more sulphur than in aerobic rice

- Lime applied as per SMP buffer method recorded significantly the lowest Fe content in plant under both systems.
- Aerobic system of rice cultivation significantly decreased the Fe content in plant in comparison with flooded system.
- Lime applied as per SMP buffer method recorded significantly the lowest Mn content in plant under both systems.
- Cultivation of rice under aerobic condition recorded lower Mn content in plant than that in flooded system.
- The aerobic system recoded significantly higher zinc content in plant than that of flooded system
- Flooded system recorded higher Cu content in plant in comparison with that of aerobic system.
- Under both the systems, fertilizers applied as per soil test (F_2) recorded higher boron content in plant than that of fertilizer as per POP.
- The boron content in plant was significantly higher in flooded rice in comparison with that in aerobic rice.
- Under aerobic system, the major fraction contributing to available pool was Fe-P.
- The major fractions contributing to available P under flooded condition were Fe-P, Al-P and sesquioxide occluded P.
- The major fractions contributing to available Fe pool were, OM bound Fe, water soluble + exchangeable Fe, MnO occluded Fe and AmFeO-Fe under both systems.
- The major fractions contributing to available Zn were water soluble + exchangeable, organic matter occluded, specifically adsorbed and amorphous FeO occluded ones under aerobic system.
- Under flooded system, the major fractions which contributed to available pool were MnO-Zn, OM-Zn and AmFeO-Zn.

- The major fractions contributing to available boron under flooded system were RS-B, SA-B, OX-B, and residual B.
- The major fraction contributing to available boron under aerobic system were RS-B and OX-B.
- Aerobic rice recorded significantly higher number of tillers per hill, number of panicles per hill, number of grains per panicle, straw yield and grain yield.
- Decline in tillers during the growth phase from AT to PI was observed flooded environment which was absent in aerobic system.
- The fresh root CEC was significantly higher under aerobic environment than under flooded environment.
- Lime application based on ΔpH (L_2) recorded significantly superior apparent free space under both the systems
- The parameters shoot mass, root mass, root length and root volume at active tillering were higher under aerobic system
- Well developed aerenchyma tissues were observed under flooded system in comparison with that in aerobic rice.

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Appendices

Correlations of soil nutrients with plant nutrients at corresponding stages under flooded systems (wet and dry analysis)

Table 181. Correlation coefficients of soil organic carbon with plant nitrogen

Method of application of fertilizers and lime	Method of analysis	AT	PI	Harvest	
				Straw	Grain
A1	wet	**0.463***	**0.539****	**0.473***	**0.460***
	dry	0.444*	0.425*	0.431	0.398
A2	wet	0.694*	0.678*	0.733**	0.552**
	Dry	0.654*	0.092	0.658**	0.733**

Table 182. Correlation coefficients of Available P with plant P

Method of application of fertilizers and lime	Method of analysis	AT	PI	Harvest	
				Straw	Grain
A1	wet	**0.581****	**0.886****	**0.809****	**0.930****
	dry	0.871**	0.838**	0.799**	0.852**
A2	wet	-0.552**	0.901**	0.811**	0.799**
	Dry	0.798**	-0.722**	0.498*	0.888**

Table 183. Correlation coefficients of Available K with plant K

Method of application of fertilizers and lime	Method of analysis	AT	PI	Harvest	
				Straw	Grain
A1	wet	**0.885****	**0.818****	**0.871****	**0.822****
	dry	0.922**.	0.239	0.832**	0.290
A2	wet	0.857**	0.848**	0.777**	0.700*
	Dry	0.841**	-0.359	0.388	0.248

Table 184. Correlation coefficients of Available Ca with plant Ca

Method of application of fertilizers and lime	Method of analysis	AT	PI	Harvest	
				Straw	Grain
A1	wet	**0.920****	**0.983****	**0.988****	**0.932****
	dry	0.873**	0.984**	0.959**	0.980**
A2	wet	0.949**	0.965**	0.985**	0.919**
	Dry	0.902**	-0.335	0.953**	0.896**

Table 185. Correlation coefficients of Available Mg with plant Mg

Method of application of fertilizers and lime	Method of analysis	AT	PI	Harvest	
				Straw	Grain
A1	wet	**0.902****	**0.896****	**0.993****	**0.992****
	dry	0.892**	0.894**	0.994**	0.995**
A2	wet	0.898**	0.893**	0.995**	0.996**
	Dry	0.888**	0.425*	0.993**	0.997**

Table 186. Correlation coefficients of Available Sulphur with plant sulphur

Method of application of fertilizers and lime	Method of analysis	AT	PI	Harvest	
				Straw	Grain
A1	wet	**0.472***	**0.824****	**0.684****	**0.711****
	dry	0.847**	0.509*	0.836**	0.510*
A2	wet	0.654**	0.800**	0.595**	0.638**
	Dry	0.865**	0.078	0.863**	0.538**

Table 187. Correlation coefficients of Available Fe with plant Fe

Method of application of fertilizers and lime	Method of analysis	AT	PI	Harvest	
				Straw	Grain
A1	wet	**0.620****	**0.873****	**0.914****	**0.914****
	dry	0.465*	0.901**	0.535**	0.899**
A2	wet	0.632**	0.876**	0.932**	0.932**
	Dry	0.777**	-0.344	0.412*	0.892**

Table 188. Correlation coefficients of Available Mn with plant Mn

Method of application of fertilizers and lime	Method of analysis	AT	PI	Harvest	
				Straw	Grain
A1	wet	**0.595****	**0.834****	**0.918****	0.918**
	dry	0.849**	0.809**	0.890**	0.809**
A2	wet	0.555**	0.855**	0.885**	0.885**
	Dry	0.851**	-0.431*	0.553**	0.802**

Table 189. Correlation coefficients of Available Cu with plant Cu

Method of application of fertilizers and lime	Method of analysis	AT	PI	Harvest	
				Straw	Grain
A1	wet	**-0.273**	**-0.065**	**-0.071**	**-0.063**
	dry	0.061	-0.07	0.280	0.062
A2	wet	-0.145	-0.245	-0.260	-0.25
	Dry	0.163	0.358	-0.089	0.117

Table 190. Correlation coefficients of Available Zn with plant Zn

Method of application of fertilizers and lime	Method of analysis	AT	PI	Harvest	
				Straw	Grain
A1	wet	**0.901****	**0.555****	**0.960****	**0.342**
	dry	0.954**	0.786	0.880*	-0.788**
A2	wet	0.917**	0.672**	0.074	0.654**
	Dry	0.947**	0.053	-0.886**	-0.818**

Table 191. Correlation coefficients of Available B with plant B

Method of application of fertilizers and lime	Method of analysis	AT	PI	Harvest	
				Straw	Grain
A1	wet	**0.823****	**0.904****	**0.911****	**0.210**
	dry	0.948**	0.950**	0.947**	0.950**
A2	wet	0.862**	0.932**	0.231	0.924**
	Dry	-0.227	0.053	-0.22	0952**

Treatment	Aerobic Rice - Fractions of phosphorus (mg kg^{-1})														
	Active tillering					Panicle initiation					Harvest				
	Sol P	Al-P	Fe-P	Occlu ded P	Ca-P	Sol P	Al-P	Fe-P	Occlu ded P	Ca-P	Sol P	Al-P	Fe-P	Occlud ed P	Ca-P
$F_1L_1R_1$	14.95	32.4	130.4	81.2	29.6	12.43	30.2	125.2	79.4	31.7	16.1	1.0	31.6	133.2	83.1
$F_1L_2R_1$	15.95	25.6	124.4	82.4	35.6	13.28	22.1	119.6	80.2	37.9	19.6	3.2	24.1	127.2	84.8
$F_1L_3 R_1$	9.46	21.6	121.2	83.6	46.4	9.45	16.7	108.4	81.4	47.2	21.3	2.2	20.9	109.6	86.1
$F_2L_1 R_1$	13.75	33.1	131.2	82.5	30.2	12.83	30.6	124.6	78.6	30.8	17.3	1.1	32.1	135.6	82.1
$F_2L_2 R_1$	16.05	26.1	122.1	86.9	36.4	13.45	22.8	119.4	81.7	37.2	18.8	3.2	23.4	128.2	83.7
$F_2L_3 R_1$	6.91	21.4	108.6	87.1	47.2	9.42	18.1	105.8	83.2	48.1	21.3	2.0	18.7	119.2	85.9
$F_1L_1 R_2$	14.46	32.6	131.2	81.2	30.2	12.35	29.5	124.6	78.2	32.1	16.6	1.0	31.2	133.3	82.7
$F_1L_2 R_2$	16.05	25.9	122.4	82.8	35.7	14.26	20.4	118.6	79.9	38.1	19.8	3.1	22.1	128.2	84.6
$F_1L_3 R_2$	9.56	21.4	110.2	83.9	45.7	9.46	16.8	106.4	82.6	46.5	22.5	2.1	21.2	115.2	85.9
$F_2L_1 R_2$	13.86	32.6	131.8	82.8	30.6	12.95	30.2	124.5	79.8	30.4	17.0	1.0	32.8	133.2	81.9
$F_2L_2 R_2$	16.21	27.9	121.4	84.6	35.7	13.98	22.9	118.4	80.7	36.5	18.2	3.1	23.6	129.2	83.8
$F_2L_3 R_2$	7.28	21.8	105.4	85.7	46.9	9.38	18.8	103.1	82.1	47.2	20.9	2.1	18.1	117.2	86.0
$F_1L_1 R_3$	14.56	33.4	130.9	82.1	30.7	12.79	28.4	126.4	79.6	32.5	15.9	0.9	31.2	133.3	82.8
$F_1L_2 R_3$	15.98	25.8	121.4	82.9	36.2	13.96	20.1	119.4	80.8	37.4	20.0	3.0	22.2	127.9	84.5
$F_1L_3 R_3$	9.75	21.3	108.2	83.2	44.9	9.37	16.7	105.2	83.1	45.7	21.3	2.1	22.1	116.2	86.4
$F_2L_1 R_3$	13.74	33.4	132.6	82.4	30.4	13.21	29.9	124.5	80.1	30.5	16.9	0.9	33.1	134.2	82.2
$F_2L_2 R_3$	16.07	24.4	120.8	84.9	36.4	13.88	23.2	118.4	80.5	36.8	18.9	3.0	23.4	129.6	84.2
$F_2L_3 R_3$	8.41	20.9	103.2	86.2	47.0	9.64	19.2	103.1	82.9	46.8	20.7	2.2	17.9	119.6	86.2
$F_1L_1 R_4$	14.72	31.4	131.4	81.9	30.9	12.46	29.2	125.4	78.5	32	16.2	1.1	31.6	134.2	82.5
$F_1L_2 R_4$	16.02	25.4	122.6	83.1	35.4	13.45	20.1	119.5	81.2	36.9	19.5	2.9	22.6	128.2	84.0
$F_1L_3 R_4$	9.82	21.2	106.4	83.1	45.2	9.44	16.8	103.4	83.7	46.9	21.4	2.0	22.2	116.2	86.1
$F_2L_1 R_4$	14.22	33.4	133.4	82.6	30.3	12.87	30.4	123.5	78.8	30.7	16.5	0.9	32.6	135.2	81.8
$F_2L_2 R_4$	16.01	25.8	121.4	85.6	36.9	14.1	23.8	119.2	80.8	37.1	19.0	2.9	22.9	129.4	84.4
$F_2L_3 R_4$	8.88	20.5	105.6	87.1	46.7	9.32	18.8	101.2	83.8	47.9	21.5	2.1	17.6	120.1	85.9

Treatment	Flooded rice - Fractions of phosphorus (mg kg^{-1})														
	Active tillering					Panicle initiation					Harvest				
	Sol P	Al-P	Fe-P	Occluded P	Ca-P	Sol P	Al-P	Fe-P	Occluded P	Ca-P	Sol P	Al-P	Fe-P	Occluded P	Ca-P
$F_1L_1R_1$	16.7	18.3	157.4	56.4	22.1	16.6	1.9	160.2	31.4	55.2	13.2	1.7	30.4	166.4	58.4
$F_1L_2R_1$	17.1	15.3	123.4	54.2	29.3	20.6	3.5	124.5	26.4	54.1	14.3	3.0	24.1	132.6	57.3
$F_1L_3 R_1$	22.6	11.1	100.2	49.4	36.4	10.6	5.0	108.4	21.4	49.0	11.3	4.8	18.4	117.8	52.2
$F_2L_1 R_1$	17.0	24.2	152.4	55.2	22.0	17.1	1.7	161.2	30.8	56.4	13.9	1.7	29.6	167.2	59.6
$F_2L_2 R_1$	18.2	17.7	124.4	51.2	28.8	21.2	3.0	127.6	25.4	51.4	14.7	3.2	23.4	133.4	54.6
$F_2L_3 R_1$	22.6	10.8	100.8	48.2	38.2	13.0	4.5	110.2	19.9	48.6	11.0	4.5	17.6	119.2	51.8
$F_1L_1 R_2$	16.0	18.9	152.6	55.9	22.4	16.6	1.9	161.4	30.8	57.4	13.4	1.7	29.6	167.2	60.0
$F_1L_2 R_2$	17.2	16.7	124.1	54.0	28.9	20.2	3.4	124.5	26.2	53.8	15.0	3.3	23.2	134.2	56.4
$F_1L_3 R_2$	22.5	11.3	99.8	49.5	37.2	7.4	4.8	108.9	21.9	49.8	11.4	4.2	17.2	119.2	52.4
$F_2L_1 R_2$	17.4	23.9	153.4	54.7	22.1	16.6	1.6	162.4	31.0	56.8	13.9	1.6	29.4	169.2	59.4
$F_2L_2 R_2$	18.5	17.4	124.8	50.8	28.9	21.5	3.0	125.4	25.4	51.2	15.0	3.0	23.1	135.2	53.8
$F_2L_3 R_2$	22.4	11.6	100.4	49.1	37.6	11.8	4.6	109.2	20.4	48.7	10.9	4.0	17.7	119.4	51.3
$F_1L_1 R_3$	14.2	18.5	152.6	56.2	22.7	16.7	2.0	162.8	31.6	57.8	13.9	1.5	28.5	167.9	59.9
$F_1L_2 R_3$	17.6	16.9	124.1	53.8	28.8	19.9	3.5	126.4	26.5	53.6	15.2	3.0	23.8	135.2	55.7
$F_1L_3 R_3$	22.8	10.9	99.8	49.6	37.6	10.2	4.8	110.4	21.7	49.9	11.6	4.4	17.6	120.1	52.0
$F_2L_1 R_3$	17.6	24.2	98.5	54.5	21.7	16.5	1.7	164.8	31.2	56.9	13.6	1.4	29.5	168.6	59.0
$F_2L_2 R_3$	18.3	17.4	154.4	50.9	29.1	21.0	3.1	124.5	25.6	51.0	15.2	2.6	22.9	136.2	53.1
$F_2L_3 R_3$	22.6	11.2	122.4	48.5	37.9	11.1	4.5	110.4	20.6	48.5	11.2	3.9	17.5	121.2	50.6
$F_1L_1 R_4$	16.8	18.6	100.9	56.4	22.8	18.4	2.1	160.8	31.2	57.9	13.6	1.5	28.8	167.5	61.0
$F_1L_2 R_4$	17.2	15.8	121.5	53.7	29.4	21.0	3.4	126.4	26.4	53.7	15.1	2.8	24.1	134.9	56.8
$F_1L_3 R_4$	23.0	12.6	94.6	49.7	37.8	10.5	4.8	112.8	21.8	50.1	11.9	4.3	17.5	119.8	53.2
$F_2L_1 R_4$	17.2	23.8	156.4	54.9	21.9	17.9	1.7	165.4	30.6	56.9	13.4	1.3	29.7	168.4	60.0
$F_2L_2 R_4$	18.3	17.9	124.5	51.7	29.2	21.0	3.2	126.5	23.4	51.4	15.0	2.7	22.5	135.8	54.5
$F_2L_3 R_4$	22.4	11.9	100.2	49.6	37.6	10.6	4.5	109.8	20.5	48.2	11.3	3.7	17.2	122.2	51.3

Treatment	Aerobic rice - Fractions of iron (mg kg^{-1})															
	Active tillering								Panicle initiation							
	Ws+ Exch-Fe	Sp Ad-Fe	Acid sol-Fe	Mno-Fe	OM-Fe	Am FeO - Fe	CrFeO-Fe	Res	Ws+ Exch-Fe	Sp Ad-Fe	Acid sol-Fe	Mno-Fe	OM-Fe	Am FeO - Fe	CrFeO -Fe	Res
$F_1L_1R_1$	68	2	38	107	181	223	4253	7688	69	3	5	105	195	268	4278	7627
$F_1L_2R_1$	65	3	15	102	252	176	4256	6803	68	2	29	103	207	161	4281	6813
$F_1L_3R_1$	61	2	26	96	144	157	4322	6844	60	3	16	95	178	115	4347	6828
$F_2L_1R_1$	69	3	13	104	252	247	4325	6411	68	3	9	103	332	374	4350	6175
$F_2L_2R_1$	68	4	16	103	209	197	4421	6401	68	2	8	102	228	221	4446	6329
$F_2L_3R_1$	60	2	14	90	166	153	4416	6524	55	2	7	86	190	199	4441	6438
$F_1L_1R_2$	69	2	21	111	186	245	4312	6490	71	3	5	103	200	280	4337	6428
$F_1L_2R_2$	65	3	12	105	257	198	4126	6806	68	2	37	100	212	173	4150	6821
$F_1L_3R_2$	60	2	25	91	149	179	4116	6807	61	3	17	92	183	127	4140	6795
$F_2L_1R_2$	68	3	12	107	257	269	4165	6556	69	3	16	101	337	387	4190	6325
$F_2L_2R_2$	69	4	16	101	214	219	4234	6562	68	3	10	99	233	234	4259	6499
$F_2L_3R_2$	62	2	14	90	171	176	4245	6667	59	2	8	83	195	211	4270	6590
$F_1L_1R_3$	71	2	14	108	185	213	4266	7599	71	3	7	103	199	255	4254	7556
$F_1L_2R_3$	66	3	10	102	257	166	4269	6699	69	2	16	102	211	148	4257	6757
$F_1L_3R_3$	60	2	18	90	148	147	4334	6750	58	3	13	93	182	102	4322	6766
$F_2L_1R_3$	70	3	8	106	257	237	4338	6304	69	3	8	104	336	361	4326	6104
$F_2L_2R_3$	67	4	11	103	214	187	4433	6297	69	3	8	101	233	208	4421	6260
$F_2L_3R_3$	61	3	11	90	170	144	4429	6416	56	2	7	89	194	185	4417	6366
$F_1L_1R_4$	68	2	24	109	184	227	4324	6396	71	3	6	104	198	268	4312	6362
$F_1L_2R_4$	66	3	12	103	255	180	4138	6713	69	2	27	101	210	161	4126	6765
$F_1L_3R_4$	57	2	23	92	147	161	4128	6716	59	3	15	94	181	114	4116	6734
$F_2L_1R_4$	69	3	11	106	255	251	4178	6463	70	3	11	103	335	374	4165	6263
$F_2L_2R_4$	67	4	14	103	212	201	4246	6468	68	3	8	101	232	221	4234	6435
$F_2L_3R_4$	60	2	13	90	169	158	4258	6575	55	2	7	86	193	198	4245	6530

Treatment	Aerobic rice - Fractions of iron (mg kg^{-1})								Flooded rice - Fractions of iron (mg kg^{-1})							
	Harvest								Active tillering							
	Ws+ Exch -Fe	Sp Ad-Fe	Acid sol-Fe	Mno-Fe	OM-Fe	Am FeO - Fe	CrFeO -Fe	Res	Ws+ Exch-Fe	Sp Ad-Fe	Acid sol-Fe	Mno -Fe	OM -Fe	Am FeO - Fe	CrFe O-Fe	Res
$F_1L_1R_1$	65	3	14	98	164	301	4270	7855	137	1	14	151	373	148	4311	7335
$F_1L_2R_1$	64	2	10	88	254	171	4273	6889	124	2	13	136	365	203	4379	6168
$F_1L_3R_1$	59	2	9	70	189	204	4338	6887	105	1	4	98	293	353	4479	6031
$F_2L_1R_1$	66	3	14	94	202	315	4342	6594	124	4	14	151	395	156	4370	6260
$F_2L_2R_1$	67	2	7	87	252	171	4438	6473	120	1	3	135	348	205	4173	6483
$F_2L_3R_1$	60	2	5	67	174	182	4433	6590	112	0	6	96	315	410	4292	6229
$F_1L_1R_2$	66	3	14	99	157	303	4329	6678	184	1	11	150	378	150	4287	7330
$F_1L_2R_2$	63	3	9	90	261	173	4142	6912	163	2	14	134	364	205	4355	7194
$F_1L_3R_2$	58	2	8	66	196	205	4132	6867	137	1	6	97	337	355	4454	7092
$F_2L_1R_2$	67	3	15	97	209	316	4182	6764	180	4	13	149	395	158	4345	7222
$F_2L_2R_2$	65	3	5	83	259	173	4251	6658	167	1	4	134	347	207	4149	7451
$F_2L_3R_2$	61	2	4	63	181	184	4262	6759	137	0	5	94	310	412	4267	7218
$F_1L_1R_3$	67	3	10	46	164	300	4284	7918	180	1	11	153	377	146	4306	7281
$F_1L_2R_3$	63	2	8	38	265	170	4350	6875	171	2	13	138	362	201	4375	7125
$F_1L_3R_3$	58	2	8	48	200	202	4353	6906	137	1	6	100	336	351	4474	7033
$F_2L_1R_3$	65	3	11	63	213	314	4449	6541	176	4	15	153	372	154	4365	7193
$F_2L_2R_3$	66	2	5	91	263	170	4444	6474	168	2	3	137	333	204	4169	7409
$F_2L_3R_3$	62	3	4	35	185	181	4340	6726	131	0	5	97	303	409	4287	7177
$F_1L_1R_4$	67	3	12	46	162	303	4153	6925	178	1	12	151	376	148	4297	7308
$F_1L_2R_4$	64	2	9	39	260	172	4143	6985	169	2	13	136	364	203	4365	7150
$F_1L_3R_4$	60	2	8	48	195	205	4193	6848	142	1	5	98	355	353	4465	7048
$F_2L_1R_4$	66	3	17	93	208	316	4262	6710	176	4	14	151	388	155	4356	7204
$F_2L_2R_4$	67	2	6	62	258	173	4273	6678	165	1	3	135	343	205	4159	7428
$F_2L_3R_4$	61	2	4	64	180	183	4277	6766	133	0	5	96	310	410	4278	7205

Treatment	Flooded rice - Fractions of iron (mg kg^{-1})															
	Panicle initiation								Harvest							
	Ws+ Exch -Fe	Sp Ad- Fe	Acid sol- Fe	Mno- Fe	OM- Fe	Am FeO - Fe	CrFeO -Fe	Res	Ws+ Exch-Fe	Sp Ad- Fe	Acid sol- Fe	Mno -Fe	OM -Fe	Am FeO - Fe	CrFe O-Fe	Res
$F_1L_1R_1$	131	3	5	136	303	260	4297	7239	119	6	5	125	198	422	4311	7142
$F_1L_2R_1$	122	2	16	129	224	396	4365	6211	115	4	10	118	159	262	4380	6372
$F_1L_3R_1$	101	2	9	40	203	621	4465	5789	98	2	9	79	168	198	4479	6151
$F_2L_1R_1$	131	2	1	132	361	265	4356	5802	113	2	10	121	227	466	4370	5895
$F_2L_2R_1$	121	3	7	112	289	407	4159	6146	109	2	29	101	157	326	4173	6299
$F_2L_3R_1$	100	1	3	67	269	675	4278	5836	93	2	11	66	166	224	4292	6330
$F_1L_1R_2$	155	3	5	139	299	276	4301	7196	118	5	5	124	203	447	4291	7136
$F_1L_2R_2$	140	1	15	134	220	412	4369	6174	113	4	9	119	163	287	4359	6367
$F_1L_3R_2$	116	2	7	51	199	637	4469	5750	93	2	9	96	172	222	4458	6132
$F_2L_1R_2$	154	3	1	133	357	281	4360	5762	112	2	9	68	232	491	4349	5942
$F_2L_2R_2$	137	3	9	119	284	422	4163	6104	107	3	14	104	162	350	4153	6305
$F_2L_3R_2$	113	1	2	73	264	691	4282	5803	92	2	9	58	170	248	4271	6333
$F_1L_1R_3$	151	3	3	136	301	281	4319	7194	117	6	5	119	193	422	4310	7169
$F_1L_2R_3$	136	1	14	133	222	417	4387	6168	113	3	8	117	153	262	4378	6398
$F_1L_3R_3$	115	2	6	54	201	641	4487	5736	92	2	8	38	162	198	4478	6220
$F_2L_1R_3$	153	3	1	134	359	286	4378	5750	112	2	8	117	222	466	4369	5921
$F_2L_2R_3$	128	3	10	100	286	427	4181	6121	105	3	11	83	152	326	4172	6359
$F_2L_3R_3$	108	1	3	73	266	696	4300	5796	90	2	8	56	160	224	4291	6366
$F_1L_1R_4$	142	3	4	139	301	288	4311	7227	117	6	5	123	198	453	4322	7147
$F_1L_2R_4$	134	1	15	135	222	424	4380	6197	114	4	9	118	158	293	4391	6376
$F_1L_3R_4$	102	2	7	51	201	649	4479	5780	93	2	9	34	167	228	4490	6203
$F_2L_1R_4$	150	3	1	136	359	293	4370	5781	110	2	9	119	227	497	4381	5902
$F_2L_2R_4$	133	3	9	113	286	435	4173	6132	107	3	18	96	157	356	4184	6319
$F_2L_3R_4$	110	1	3	74	266	703	4292	5822	88	2	9	57	165	254	4303	6347

Treatment	Aerobic rice - Fractions of Zn (mg kg^{-1})															
	Active tillering								Panicle initiation							
	Ws+ Exch -Zn	Sp Ad- Zn	Acid Zn	Mno- Zn	OM- Zn	Am FeO - Zn	CrFeO - Zn	Res	Ws+ Exch - Zn	Sp Ad- Zn	Acid sol- Zn	Mno - Zn	OM - Zn	Am FeO - Zn	CrFe O- Zn	Res
$F_1L_1R_1$	0.1	0.2	0.4	5.7	3.5	3.7	3.0	27.0	0.1	0.3	0.3	5.4	3.3	3.5	2.9	26.9
$F_1L_2R_1$	0.1	0.2	0.7	5.0	3.4	3.8	3.0	27.2	0.1	0.3	0.4	5.1	3.2	3.6	2.9	27.4
$F_1L_3 R_1$	0.2	0.3	0.7	4.8	3.2	3.8	2.9	27.5	0.1	0.4	0.5	5.0	2.8	3.6	2.8	27.9
$F_2L_1 R_1$	0.1	0.2	0.3	5.2	3.3	3.7	2.9	27.8	0.1	0.3	0.3	5.6	3.1	3.6	2.9	27.4
$F_2L_2 R_1$	0.1	0.2	0.5	4.8	3.0	3.8	2.9	27.9	0.1	0.3	0.4	5.5	2.9	3.6	2.9	27.3
$F_2L_3 R_1$	0.1	0.3	0.4	4.7	2.9	3.9	2.9	28.0	0.1	0.4	0.6	5.4	2.3	3.7	2.9	27.6
$F_1L_1 R_2$	0.1	0.1	0.7	5.1	3.3	3.8	3.0	27.3	0.1	0.2	0.3	5.9	3.2	3.6	2.9	27.0
$F_1L_2 R_2$	0.1	0.1	0.6	4.9	3.2	3.7	2.9	27.8	0.1	0.2	0.4	5.5	3.0	3.5	2.8	27.7
$F_1L_3 R_2$	0.2	0.2	0.9	4.7	3.0	3.9	2.9	27.5	0.2	0.3	0.6	4.9	2.7	3.7	2.9	27.7
$F_2L_1 R_2$	0.1	0.2	0.5	5.3	3.2	3.8	2.9	27.6	0.1	0.2	0.3	6.0	3.0	3.6	2.8	27.0
$F_2L_2 R_2$	0.2	0.2	0.5	5.0	3.0	3.9	2.9	27.8	0.1	0.3	0.4	5.2	2.8	3.7	2.9	27.9
$F_2L_3 R_2$	0.2	0.3	0.5	4.9	2.7	3.9	2.9	28.0	0.2	0.4	0.6	5.1	2.5	3.8	2.9	27.4
$F_1L_1 R_3$	0.1	0.2	0.5	5.2	3.4	3.7	3.0	27.3	0.1	0.2	0.2	5.4	3.2	3.5	2.9	27.5
$F_1L_2 R_3$	0.2	0.2	0.9	4.9	3.2	3.9	2.9	27.2	0.1	0.3	0.5	5.2	3.0	3.7	2.8	27.4
$F_1L_3 R_3$	0.2	0.3	0.7	4.7	2.9	3.9	3.1	27.4	0.2	0.4	0.6	4.9	2.7	3.8	3.0	27.5
$F_2L_1 R_3$	0.1	0.2	0.6	5.2	3.2	3.8	2.9	27.7	0.1	0.2	0.5	5.5	3.0	3.6	2.9	27.4
$F_2L_2 R_3$	0.2	0.3	0.3	4.8	3.0	3.9	2.9	28.1	0.1	0.4	0.6	5.5	2.8	3.7	2.9	27.5
$F_2L_3 R_3$	0.1	0.1	0.5	4.6	2.3	4.0	3.0	28.7	0.1	0.2	0.6	5.2	2.2	3.8	2.9	28.2
$F_1L_1 R_4$	0.1	0.1	0.6	5.2	3.3	3.8	3.0	27.6	0.1	0.2	0.4	5.6	3.2	3.6	2.9	27.8
$F_1L_2 R_4$	0.1	0.2	0.7	5.1	3.2	3.9	3.0	27.2	0.1	0.3	0.4	5.3	3.0	3.7	3.0	27.3
$F_1L_3 R_4$	0.2	0.3	0.8	4.8	2.9	4.0	3.0	27.4	0.1	0.4	0.6	4.9	2.7	3.8	2.9	27.7
$F_2L_1 R_4$	0.1	0.2	0.5	5.1	3.2	3.8	3.0	27.6	0.1	0.3	0.4	5.7	3.0	3.6	2.9	26.9
$F_2L_2 R_4$	0.2	0.3	0.4	4.9	3.0	3.7	3.0	27.9	0.2	0.4	0.5	5.4	2.8	3.5	2.9	27.3
$F_2L_3 R_4$	0.3	0.3	0.5	4.7	2.3	4.0	3.0	28.1	0.3	0.4	0.6	5.3	2.2	3.8	2.9	27.5

Treatment	Aerobic rice								Flooded rice - Fractions of zinc (mg kg^{-1})							
	Harvest								Active tillering							
	Ws+ Exch -Zn	Sp Ad- Zn	Acid sol- Zn	Mno- Zn	OM- Zn	Am FeO - Zn	CrFeO -Zn	Res	Ws+ Exch- Zn	Sp Ad- Zn	Acid sol- Zn	Mno -Zn	OM -Zn	Am FeO - Zn	CrFe O-Zn	Res
$F_1L_1R_1$	0.1	0.2	0.4	5.7	3.5	3.7	3.0	27.0	0.1	0.3	0.8	5.9	2.0	7.0	3.2	24.0
$F_1L_2R_1$	0.1	0.2	0.7	5.0	3.4	3.8	3.0	27.2	0.2	0.2	0.5	5.7	1.9	6.7	3.6	24.6
$F_1L_3R_1$	0.2	0.3	0.7	4.8	3.2	3.8	2.9	27.5	0.1	0.5	0.9	4.9	1.7	6.5	4.1	24.2
$F_2L_1R_1$	0.1	0.2	0.3	5.2	3.3	3.7	2.9	27.8	0.1	0.2	0.5	6.5	2.2	6.9	3.0	23.6
$F_2L_2R_1$	0.1	0.2	0.5	4.8	3.0	3.8	2.9	27.9	0.2	0.1	0.6	6.0	2.1	6.5	3.7	24.0
$F_2L_3R_1$	0.1	0.3	0.4	4.7	2.9	3.9	2.9	28.0	0.1	0.2	0.1	4.5	2.0	5.5	3.5	27.1
$F_1L_1R_2$	0.1	0.1	0.7	5.1	3.3	3.8	3.0	27.3	0.1	0.3	0.8	6.9	2.1	6.9	2.9	23.3
$F_1L_2R_2$	0.1	0.1	0.6	4.9	3.2	3.7	2.9	27.8	0.2	0.3	0.6	5.6	1.9	6.5	2.3	26.0
$F_1L_3R_2$	0.2	0.2	0.9	4.7	3.0	3.9	2.9	27.5	0.1	0.1	0.9	4.5	1.7	6.4	2.7	26.5
$F_2L_1R_2$	0.1	0.2	0.5	5.3	3.2	3.8	2.9	27.6	0.1	0.5	0.3	6.6	2.2	7.0	2.3	24.2
$F_2L_2R_2$	0.2	0.2	0.5	5.0	3.0	3.9	2.9	27.8	0.2	0.1	0.6	6.2	1.9	6.7	2.5	25.2
$F_2L_3R_2$	0.2	0.3	0.5	4.9	2.7	3.9	2.9	28.0	0.1	0.3	0.4	4.7	1.6	6.4	2.1	27.4
$F_1L_1R_3$	0.1	0.2	0.5	5.2	3.4	3.7	3.0	27.3	0.1	0.2	0.8	7.1	2.2	7.1	3.1	22.7
$F_1L_2R_3$	0.2	0.2	0.9	4.9	3.2	3.9	2.9	27.2	0.2	0.2	0.6	6.5	2.0	6.5	3.3	24.0
$F_1L_3R_3$	0.2	0.3	0.7	4.7	2.9	3.9	3.1	27.4	0.1	0.4	1.1	5.5	1.4	6.4	3.7	24.2
$F_2L_1R_3$	0.1	0.2	0.6	5.2	3.2	3.8	2.9	27.7	0.1	0.4	1.0	8.0	1.6	8.0	3.5	20.5
$F_2L_2R_3$	0.2	0.3	0.3	4.8	3.0	3.9	2.9	28.1	0.2	0.2	0.6	7.8	1.9	7.8	3.4	21.3
$F_2L_3R_3$	0.1	0.1	0.5	4.6	2.3	4.0	3.0	28.7	0.1	0.4	0.3	7.3	1.7	7.3	3.2	22.6
$F_1L_1R_4$	0.1	0.1	0.6	5.2	3.3	3.8	3.0	27.6	0.1	0.3	0.8	7.0	2.2	7.0	3.1	22.9
$F_1L_2R_4$	0.1	0.2	0.7	5.1	3.2	3.9	3.0	27.2	0.2	0.2	0.6	5.9	2.1	6.5	3.2	24.6
$F_1L_3R_4$	0.2	0.3	0.8	4.8	2.9	4.0	3.0	27.4	0.2	0.3	1.0	5.0	1.8	6.3	3.6	24.7
$F_2L_1R_4$	0.1	0.2	0.5	5.1	3.2	3.8	3.0	27.6	0.1	0.4	0.6	6.7	2.3	6.7	3.1	23.3
$F_2L_2R_4$	0.2	0.3	0.4	4.9	3.0	3.7	3.0	27.9	0.2	0.1	0.6	6.3	1.9	6.3	3.4	24.4
$F_2L_3R_4$	0.3	0.3	0.5	4.7	2.3	4.0	3.0	28.1	0.1	0.3	0.3	5.5	1.8	6.2	3.0	25.9

Treatment	Flooded rice - Fractions of zinc (mg kg^{-1})															
	Panicle initiation								Harvest							
	Ws+ Exch -Zn	Sp Ad- Zn	Acid sol- Zn	Mno- Zn	OM- Zn	Am FeO - Zn	CrFeO -Zn	Res	Ws+ Exch- Zn	Sp Ad- Zn	Acid sol- Zn	Mno -Zn	OM -Zn	Am FeO - Zn	CrFe O-Zn	Res
$F_1L_1R_1$	1.39	0.1	0.5	0.8	6.9	2.0	4.0	3.6	0.1	0.3	6.2	5.4	1.8	3.9	3.4	20.0
$F_1L_2R_1$	1.51	0.1	0.3	0.5	6.7	1.8	3.8	3.7	0.1	0.4	7.2	5.2	1.6	3.7	3.5	19.7
$F_1L_3R_1$	1.71	0.1	0.3	0.8	5.9	1.4	3.3	3.8	0.1	0.4	8.7	6.4	1.3	5.2	3.6	15.8
$F_2L_1R_1$	2.46	0.1	0.2	0.5	7.0	2.0	4.4	3.5	0.1	0.3	6.7	6.0	1.8	3.3	3.3	19.6
$F_2L_2R_1$	3.20	0.1	0.3	0.6	6.7	1.7	4.3	3.6	0.1	0.6	12.8	5.6	1.6	6.2	3.4	11.5
$F_2L_3R_1$	0.02	0.1	0.1	0.1	6.5	1.2	3.6	3.6	0.1	0.2	4.1	12.2	1.1	6.5	3.4	13.5
$F_1L_1R_2$	1.37	0.1	0.3	0.8	6.8	2.0	3.7	3.8	0.1	1.3	0.3	5.4	1.8	3.6	3.7	25.1
$F_1L_2R_2$	0.97	0.1	0.4	0.6	6.5	1.7	3.6	3.9	0.1	0.0	0.4	5.1	1.5	5.5	3.8	24.8
$F_1L_3R_2$	1.68	0.1	0.1	0.9	6.4	1.6	2.9	4.0	0.1	0.4	0.6	6.4	1.4	7.8	3.9	20.9
$F_2L_1R_2$	0.69	0.1	0.2	0.3	6.9	1.9	3.8	3.7	0.1	0.4	0.7	5.8	1.8	2.9	3.6	26.4
$F_2L_2R_2$	1.37	0.1	0.3	0.6	6.8	1.7	3.0	3.8	0.1	0.6	0.8	6.3	1.5	6.8	3.7	21.4
$F_2L_3R_2$	0.28	0.1	0.0	0.4	6.7	1.6	2.3	3.8	0.1	0.4	0.6	11.8	1.4	6.2	3.7	17.7
$F_1L_1R_3$	1.34	0.1	0.4	0.8	7.1	2.0	3.8	3.3	0.1	0.3	0.2	5.8	1.8	3.7	3.2	26.1
$F_1L_2R_3$	1.35	0.1	0.3	0.6	6.8	1.8	3.0	3.4	0.1	0.5	0.2	5.1	1.7	2.9	3.3	27.6
$F_1L_3R_3$	0.67	0.1	0.4	1.1	6.5	1.7	2.8	3.5	0.1	0.5	0.7	6.2	1.6	4.7	3.4	24.3
$F_2L_1R_3$	2.57	0.1	0.2	1.0	8.0	1.9	3.6	3.2	0.1	0.3	0.6	6.0	1.8	3.1	3.0	26.6
$F_2L_2R_3$	2.00	0.1	0.3	0.6	7.8	1.6	3.4	3.3	0.1	0.6	0.6	5.9	1.4	6.3	3.1	23.5
$F_2L_3R_3$	0.34	0.1	0.7	0.3	7.3	1.5	2.6	3.3	0.1	0.4	0.4	10.6	1.3	5.7	3.2	19.5
$F_1L_1R_4$	1.32	0.1	0.4	0.8	7.0	2.0	3.9	3.5	0.1	0.3	0.3	5.5	1.8	3.7	3.4	26.6
$F_1L_2R_4$	1.24	0.1	0.3	0.6	6.8	1.7	3.1	3.7	0.1	0.3	0.4	5.1	1.6	4.0	3.5	26.2
$F_1L_3R_4$	0.79	0.1	0.3	1.0	6.0	1.6	2.6	3.7	0.1	0.4	0.6	6.3	1.4	5.9	3.6	22.9
$F_2L_1R_4$	2.54	0.1	0.2	0.6	7.7	1.9	4.2	3.4	0.1	0.3	0.6	5.9	1.8	5.8	3.3	23.4
$F_2L_2R_4$	2.06	0.1	0.3	0.6	7.3	1.6	3.6	3.5	0.1	0.6	0.8	5.9	1.5	6.4	3.4	22.8
$F_2L_3R_4$	0.37	0.1	0.3	0.3	6.5	1.4	3.3	3.5	0.1	0.3	0.5	6.7	1.3	6.1	3.4	23.2

Treatment	Aerobic Rice - Fractions of boron (mg kg^{-1})														
	Active tillering					**Panicle initiation**					**Harvest**				
	RS- B	SA-B	OX-B	OM -B	Res B	RS- B	SA-B	OX-B	OM -B	Res B	RS- B	SA-B	OX -B	OM - B	Res B
$F_1L_1R_1$	0.1	0.2	5.6	4.1	90.1	0.0	0.1	5.9	3.8	90.3	0.0	0.1	6.5	3.6	89.8
$F_1L_2R_1$	0.1	0.2	5.6	4.2	89.9	0.0	0.1	6.0	3.9	90.0	0.0	0.1	6.6	3.6	89.7
$F_1L_3 R_1$	0.0	0.2	5.8	4.5	89.5	0.0	0.1	6.0	4.1	89.8	0.0	0.1	7.0	3.8	89.1
$F_2L_1 R_1$	0.6	0.3	5.9	5.1	88.0	0.7	0.3	7.8	4.6	86.7	0.7	0.2	8.5	4.2	86.4
$F_2L_2 R_1$	0.6	0.3	6.0	5.3	87.7	0.7	0.3	8.2	4.7	86.1	0.7	0.2	9.1	4.3	85.6
$F_2L_3 R_1$	0.6	0.3	6.0	5.5	87.5	0.6	0.3	8.7	4.9	85.5	0.7	0.2	9.0	4.4	85.7
$F_1L_1 R_2$	0.1	0.2	5.6	4.1	90.1	0.0	0.1	5.8	3.8	90.2	0.0	0.1	6.5	3.5	89.9
$F_1L_2 R_2$	0.1	0.2	5.7	4.2	89.9	0.1	0.1	6.0	3.9	89.9	0.0	0.1	6.7	3.6	89.6
$F_1L_3 R_2$	0.0	0.2	5.8	4.5	89.4	0.0	0.1	6.2	3.9	89.8	0.0	0.1	6.8	3.7	89.3
$F_2L_1 R_2$	0.6	0.3	6.0	5.2	87.9	0.7	0.3	7.9	4.6	86.6	0.7	0.2	8.6	4.2	86.2
$F_2L_2 R_2$	0.6	0.3	6.1	5.3	87.6	0.7	0.3	8.2	4.7	86.1	0.7	0.2	9.1	4.3	85.7
$F_2L_3 R_2$	0.6	0.3	6.2	5.6	87.3	0.6	0.3	8.9	4.9	85.3	0.7	0.2	9.1	4.4	85.6
$F_1L_1 R_3$	0.1	0.2	5.5	4.1	90.2	0.0	0.1	5.9	3.9	90.1	0.0	0.1	6.5	3.5	89.8
$F_1L_2 R_3$	0.1	0.2	5.7	4.2	89.9	0.0	0.1	6.1	3.9	89.9	0.0	0.1	6.8	3.7	89.4
$F_1L_3 R_3$	0.0	0.2	5.7	4.4	89.6	0.0	0.1	6.2	4.0	89.6	0.0	0.1	6.8	3.8	89.3
$F_2L_1 R_3$	0.6	0.3	6.1	5.1	87.9	0.7	0.3	7.8	4.5	86.8	0.7	0.2	8.6	4.3	86.2
$F_2L_2 R_3$	0.6	0.3	6.2	5.2	87.6	0.7	0.3	8.3	4.7	86.0	0.7	0.2	9.1	4.4	85.6
$F_2L_3 R_3$	0.6	0.3	6.2	5.5	87.3	0.6	0.3	8.9	4.9	85.3	0.7	0.2	9.2	4.4	85.5
$F_1L_1 R_4$	0.1	0.2	5.6	4.1	90.1	0.0	0.1	5.9	3.7	90.2	0.0	0.1	6.6	3.6	89.7
$F_1L_2 R_4$	0.1	0.2	5.8	4.3	89.6	0.1	0.1	6.2	3.9	89.8	0.0	0.1	6.9	3.6	89.4
$F_1L_3 R_4$	0.0	0.2	5.8	4.5	89.5	0.0	0.1	6.2	4.1	89.5	0.0	0.1	6.9	3.8	89.2
$F_2L_1 R_4$	0.6	0.3	6.1	5.1	87.8	0.7	0.3	8.0	4.6	86.4	0.7	0.2	8.7	4.2	86.1
$F_2L_2 R_4$	0.6	0.3	6.3	5.3	87.4	0.7	0.3	8.4	4.8	85.8	0.7	0.2	9.2	4.4	85.5
$F_2L_3 R_4$	0.6	0.3	6.4	5.6	87.1	0.6	0.3	9.0	5.0	85.1	0.7	0.2	9.2	4.5	85.4

NUTRIENT DYNAMICS AND TRANSFORMATION IN AEROBIC AND FLOODED SYSTEMS OF RICE IN LATERITIC SOILS OF KERALA

By

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ABSTRACT OF THE THESIS

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Abstract

Field experiments on aerobic and flooded systems of rice were conducted in second crop season with the objectives to study the nutrient dynamics and transformations in these systems in second crop season with rice (variety Jyothi), in farmer's field, at Nellikkattiri, Thirumittakode panchayat, Palakkad district. The treatments with two doses of fertilizers (as per Package of Practices Recommendations, KAU and based on soil test) and three doses of lime (as per POP, as per ΔpH and as per SMP buffer method) were imposed in plots of $20m^2$ area in Randomized Block Design with four replications. Under flooded condition, two field experiments were conducted to standardize the method of sampling and analysis for soil test based application of lime and fertilizers. One was based on sampling and soil testing on wet basis keeping the anaerobic environment unchanged, while the other was based on routine sampling and analysis after air drying. Better correlations with respect to available nutrients and plant nutrient content were obtained for wet analysis based recommendation and hence the data from this experiment were considered for comparison of the nutrient dynamics with that of the experiment on aerobic rice.

In situ measurement of pH, electrical conductivity and redox potential was done under both systems of rice cultivation. Redox potential was measured from three different depths under flooded system (15, 30 and 45 cm) and from two different depths under aerobic system (30 and 45 cm). The soil and plant samples were collected at three stages *viz.* at active tillering, panicle initiation and at harvest of the crop. The soil samples collected were analysed for pH, EC, OC available nutrients (P, K, Ca, Mg, S, Fe, Cu, Mn Zn and B), and were also assayed to estimate fractions of soil phosphorus, iron, zinc and boron. The plant samples were analysed for N, P, K, Ca, Mg, S, Fe, Mn, Zn, Cu and B. At harvest straw and grain samples were analysed separately.

The increase in pH in both systems was in proportion to the quantity of lime applied. Higher rate of increase in pH was observed under aerobic system. Increase in

EC was in proportion to the quantity of lime and fertilizers added, and it was more in aerobic system due to less dilution. The redox potential became negative due to reduced environment in flooded system within two weeks of transplanting while it was consistently positive under aerobic system. The organic carbon content was higher under aerobic environment at active tillering and panicle initiation due to quicker decomposition of applied organic matter especially in presence of lime while it was lower under flooded condition initially due to slower rate of decomposition.

Available P was highest under flooded system due to release of bound P from Fe and Mn by reduction of these elements to their respective soluble forms. Under aerobic condition, the available P recorded at active tillering and panicle initiation was lower than that of the initial value, due to its precipitation as tri calcium phosphate [$Ca_3(PO_4)_2$].

The available K status was higher under aerobic condition throughout the crop growth because of reduced rate of leaching under this environment. The rate of increase in available K was concurrent to the quantity of fertilizer added under both systems of rice cultivation. Highest K content in plant was recorded under aerobic rice system.

The highest available Ca was recorded at active tillering and panicle initiation in flooded system of rice cultivation, because of the solubilization of applied lime. At harvest, the available Ca became precipitated as tri calcium phosphate which decreased the availability of both Ca and P under flooded condition. The transformation of tri calcium phosphate to mono calcium phosphate occurred only under aerobic condition during later stages. The highest Mg in plant was recorded in treatment where fertilizer application was done based on soil test under both systems of rice cultivation. The available sulphur status was higher under flooded condition during all the stages of sampling because of the increased solubility of applied factomphos and $MgSO_4$.

The status of available Fe was higher under flooded environment because of the reduction of Fe^{3+} to soluble Fe^{2+}, while the available Fe status was found to decrease under aerobic condition due to oxidation of Fe^{2+} to insoluble Fe^{3+}. The available Mn status under flooded environment decreased when compared to that of aerobic condition because of enhanced absorption by rice. The lower status of available Zn under aerobic condition resulted from more absorption of Zn by the crop, because of decreased competition from cations such as Fe^{3+} and Mn^{4+} under aerobic condition. The available boron status and boron content in plant was high under flooded condition because of the enhanced solubility of applied borax.

Ultimately, aerobic rice recorded significantly higher grain and straw yield (6.23 t ha^{-1} and 6.35 t ha^{-1} respectively) than that under flooded system (5.12 t ha^{-1} and 5.52 t ha^{-1} respectively). The treatment with fertilizer application based on soil test and with lime as per SMP buffer method under aerobic situation recorded significantly higher grain yield of 6.8 t ha^{-1} because of balanced nutrition in this treatment combination. Higher root CEC, root mass, shoot mass root volume and root length were recorded under aerobic system. The decline in productive tillers during active growth phase was observed under flooded environment. Well developed aerenchymatic tissue in the roots was observed only under flooded environment. The water requirement was reduced by 57 % in aerobic rice, than that in flooded rice.