DYNAMICS AND INTERACTION OF ZINC AND BORON WITH PHOSPHORUS IN ULTISOL

BY

SEMSHEER M.

(2013-11-141)

THESIS

Submitted in partial fulfillment of the

requirement for the degree of

MASTER OF SCIENCE IN AGRICULTURE

Faculty of Agriculture

Kerala Agricultural University

DEPARTMENT OF SOIL SCIENCE AND AGRICULTURAL CHEMISTRY
COLLEGE OF HORTICULTURE
VELLANIKKARA, THRISSUR – 680 656
KERALA, INDIA

2015

DECLARATION

I hereby declare that this thesis entitled **"Dynamics and interaction of zinc and boron with phosphorus in Ultisol"** is a bonafide record of research done by me during the course of research and that the thesis has not previously formed the basis for the award of any degree, diploma, fellowship or other similar title, of any other University or Society.

Place: Vellanikkara

Date: 18 / 08 /2015

SEMSHEER M.

(2013-11-141)

CERTIFICATE

Certified that this thesis, entitled **"Dynamics and interaction of zinc and boron with phosphorus in Ultisol"** is a record of research work done independently by **Mr. Semsheer M.(2013-11-141)** under my guidance and supervision and that it has not previously formed the basis for the award of any degree, diploma, fellowship or associateship to him.

Place: Vellanikkara

Date: 18/08 /2015

Dr. P.Sureshkumar

Professor and Head &

Radiological Safety Officer

Radio Tracer Laboratory

College of Horticulture

Vellanikkara

CERTIFICATE

We, the undersigned members of the advisory committee of **Mr. Semsheer M. (2013-11-141)** a candidate for the degree of **Master of Science in Agriculture** with major field in **Soil Science and Agricultural Chemistry** agree that this thesis entitled **"Dynamics and interaction of zinc and boron with phosphorus in ultisol"** may be submitted by **Mr. Semsheer M.** in partial fulfillment of the requirement for the degree.

18/8/15
Dr. P. Sureshkumar
Professor and Head
& Radiological Safety Officer
Radio Tracer Laboratory
College of Horticulture, Vellanikkara

18/8/15
Dr. P. K. Sushama
Professor & Head
Department of Soil Science and
Agricultural Chemistry
College of Horticulture, Vellanikkara

Dr. Betty Bastin 18/8/15
Professor
Department of Soil Science and
Agricultural Chemistry
College of Horticulture, Vellanikkara

18/8/15
Dr. A. Latha
Associate Professor (Agronomy)
ARS, Mannuthy
College of Horticulture
Vellanikkara

18/8/2015
EXTERNAL EXAMINER

ACKNOWLEDGEMENT

I humbly bow my head before the ***Lord Almighty*** *whose grace had endowed me the inner strength and confidence, blessed me with a helping hand to complete this venture successfully.*

It is with great respect and devotion, I record my deep sense of gratitude to ***Dr.P.Sureshkumar,*** *Professor and Head, Radiological Safety Officer, Radiotracer Laboratory, College of Horticulture and Chairman of my Advisory committee for his expert advice, valuable suggestions, inspiring guidance, enthusiastic approach, constructive criticisms, unreserved help and kind concern during the conduct of this research work and preparation of thesis. I value his knowledge and wisdom which nurtured this research in right direction without which fulfillment of this endeavor would not have been possible. Always looking for perfection, he corrected me several times with his understanding and forbearance. He has been a support to me during each step of this venture and my obligation to him lasts forever.*

It is with immense pleasure, I express my whole hearted gratitude and never ending indebtedness to **Dr. P.K. Sushama**, *Professor and Head, Department of Soil Science and Agricultural Chemistry and member of my Advisory Committee for her expert guidance, patient hearing, constructive criticisms, valuable suggestions and above all her support and encouragement throughout the course of study.*

I think it is my privilege to express my heartfelt thanks to ***Dr.Betty Bastin*** *Professor, Department of Soil Science and Agricultural Chemistry and member of my Advisory Committee for her critical evaluation of manuscript, constant encouragement, sincere help and support in times of need especially in the preparation of this thesis.*

*I thankfully acknowledge **Dr. A. Latha,** Associate Professor, Agronomy for her esteemed advice, timely help, and valuable suggestions throughout this programme.*

*My heartfelt thanks to **Dr. Jayasree Shankar, Dr. Beena V. I,Dr.Durgadevi, Dr. Sreelatha, Shri. Visweshwaran, and Smt. Bindhu P.S** of the Department of Soil Science and Agricultural Chemistry for their ever willing help rendered at various phases of my study.*

*I express my gratitude to **Dr.S.Krishnan,** Associate Professor and Head Department of Agricultural Statistics for their valuable suggestions and help in doing the statistical analysis and interpretation of data.*

*My gratitude to my friends and colleagues especially**Aswin, Jamal, Arjun, Sarath, Akshay, Jishnu, Boss, Shafeeque, Roch, Tincy** and all well wishers who were of great help during the hours of need.*

*I owe special thanks to my seniors **Maya,Geetha, Irene, Anooja,Indu,Chris** classmates **Ashwathy, Bhavya, Nithya** and to my juniors **Beena, Rincy, Adithya, Sreedhar,** for their valuable suggestions and timely help.*

*A word of thanks to **Juby, Ashwini, Nayana, Iby, Sini, Shyam, Sabareesh, Remya and other staffs in Radio Tracer Laboratary**for their sincere help and support.*

*I would like to record my sincere gratitude to the **library** facilities, librarian **Dr. A. T. Francis.** all teaching and non teaching staffs of College of Horticulture, Vellanikkara*

***KAU Junior Fellowship** is greatefully acknowledged.*

*Above all, I am forever behold to my loving **Uppa and Umma**, my brother **Jamsheer**, sisters **Salee and Poovi** and **all relatives** for their love, affection, personal sacrifices, incessant inspiration and constant prayers which helped me to complete this venture successfully.*

SEMSHEER M.

CONTENTS

LIST OF TABLE

LIST OF FIGURES

LIST OF PLATES

Introduction

1. INTRODUCTION

Phosphorus is one of the major essential elements required in plant nutrition. It is involved in the synthesis of sugars, ATP being the energy currency in plants. Phosphorus is absorbed by plants as monovalent $H_2PO_4^-$ ion from the soil solution. However, its concentration in soil solution seldom exceeds 10^{-6} to 10^{-7} moles L^{-1}.In soil it exists in different forms, which in turn is dictated by pH. In acidic soils it mainly exists as phosphates of iron and aluminium. In alkaline soils the main form is calcium phosphate. The capacity of soil to supply with soluble monocalcium phosphate $(CaH_2PO_4)_2$ decides the phosphate potential of the soil which is also a function of pH.

With respect to fertility of soil,it is equally important to have optimum levels of other nutrients including secondary and micronutrients. Being an anion which can make compounds with other essential mineral nutrients, the phosphorus availability is decided by the levels of other ions like Fe, Mn, Al, Ca etc.

On the other hand phosphorus can antagonistically affect the availability of micronutrients like Zn, B etc. High levels of soluble P can induce the deficiency of these micronutrients.

Antagonistic interaction of P with Zn has well established the recent soil fertility assessment of the entire State under the project Soil Based Plant Nutrient Management (SBPNM) and has revealed that more than 60% of the soils in the state are having high P status due to continuous application of P fertilizers like factomphos and bone meal. It was also established that 15% of the soils are deficient in zinc and about 60% of soils are deficient in boron (Rajasekharan *et al.*,2013).

Phosphorus, zinc and boron exist in different forms in soil solution and are in a dynamic equilibrium. These forms are either soluble or insoluble in the soil solution. Plant absorbs the soluble forms from the soil solution and the insoluble forms indirectly contribute to the soil solution through soluble forms, when the soluble forms depleted due to plant absorbtion.

In lateritic soils high levels of P in soil solution can induce B deficiency due to anionic competition between phosphate ($H_2PO_4^-$) and borate ($H_3BO_3^-$) ions(Kaya *et* al.,2009).It also can induce Zn deficiency due to formation of insoluble zinc phosphate(Rupa *et al.*, 2003). Antagonistic interaction of P with zinc has already been well established. However studies on interaction of P with boron are limited.

In the above background, the present study will help to understand the chemistry, dynamics and bioavailability of zinc and boron with respect to phosphorus status of the soil, which in turn will help in modifying the fertilizer prescription in terms of quantity and method of application of these nutrients. Hence this study aims atelucidating

- The dynamics of zinc and boron as influenced by the phosphorous status of lateritic soil
- Optimizing the level of phosphorous for balanced nutrition of cowpea with respect to zinc and boron

Review of Literature

2. REVIEW OF LITERATURE

Phosphorus is a major nutrient required for root formation and growth, synthesis of starch, protein and fat. Also, being a constituent of nucleic acids, it is closely concerned with vital plant growth processes. Like any other nutrient, P availability to crops is largely influenced by soil pH. The ideal soil pH is close to neutral and neutral soils are considered to fall within a range from a slightly acidic pH of 6.5 to slightly alkaline pH of 7.5. It has beenfound that most plant nutrients are optimally available to plants within this pH range 6.5–7.5. Also, this range is generally compatible to plant root growth (Malik, 2014). An interaction occurs when the level of one production factor influences the response to another factor. A positive interaction occurs when the influence of the combined practices exceeds the sum of the influences of the individual practices. Positive and negative interactions of phosphorus with other essential nutrients have been documented in research studies on many crops. Crop response to applied P can be improved by making adjustments for time, rate, and method of application. It varies with physicaland chemical properties of the soil, high yield crop management practices, and crop stress conditions such as drought or nutrient deficiencies.

Detailed review of the works regarding the dynamics and interaction of phosphorus with micronutrients are being discussed in this section. The review on P nutrition related to the present study is discussed under following subheads:

2.1.Factors affecting availability of phosphorus

2.2.Interaction of zinc with phosphorus

2.3.Interaction of boron with phosphorus

2.4.Fractions ofphosphorus contributing to available pool

2.5.Fractions of zinc contributing to available pool

2.6.Boron fractions contributing to available pool

2.1. Factors affecting availability of Phosphorus

The ability of the plant to absorb phosphorous depends on the concentration of phosphorous ions in the soil solution at the root surface and the area of absorbing surface in contact with the solution. Mass flow and diffusion govern the movement of P ions in soil, with diffusion being of primary importance (Barber *et al.*, 1963; Barber 1984).

The P ions near the root hairs are absorbed quickly, resulting in a depletion zone with a decreasing P concentration gradient near the root surface (Walker and Barber 1962; Bagshaw *et al.*, 1972).

Parfitt (1989) described that in acidic soils, P can be dominantly adsorbed by Al/Fe oxides and hydroxides, such as gibbsite, hematite, and goethite. Phosphorus can be first adsorbed on the surface of clay minerals and Fe/Al oxides by forming various complexes.

Singh and Gilkes (1991) found a negative correlation between phosphate sorption by soil and Soil Organic Matter (SOM) content. Dubus and Bacquer (2001) also found a significant negative correlation between phosphate sorption and SOM content.

Gahoonia *et al.* (1992) reported that the decreasing pH in alkaline soils causes increased P uptake by plant due to the dissolution of P minerals, whereas in acid soils an increase in pH increases P uptake because of desorbing P from metaloxids.

Cassman *et al.* (1993) found that the application of 100 kg phosphorous/ha to an Ultisol produced maximum yield of soybean, although the recommended P application rate, based on the Fox and Kamprath method (1970) was more than 500 kg phosphorous/ha (Cassman *et al.*, 1981).

Grant *et al.* (2001) described that phosphorus supply to the crop is affected by phosphorus present in the soil, phosphorus fertilizer management and also by the soil and environmental conditions influencing phosphorus phytoavailability.

Morel (2002) summarized that phosphorus supply to a crop will be influenced by the ability of the soil to replenish the depletion zone at the root surface and he also reported that in the depleted zone, the transfer of P ions appeared to become very low after a few days. The release of depleted P ions drastically decreased after a few days.

Vance *et al.* (2003) reported that limited phosphorus availability in Ultisols and Oxisols has been identified as one of the major problems for plant growth in tropical and subtropical regions of the world. It was also reported that high rate of P fixation and formation of insoluble complexes with aluminum and iron under acid conditions are recognized as the important factor contributing to the low P availability.

Phosphorus uptake in many crops is improved by associations with arbuscular mycorrhizal fungi (Grant *et al.*, 2005).Studies by Avila *et al.* (2006) showed that common bean growth under limiting phosphate availability in soil exhibited lower biomass yield and higher concentration of nutrients in shoot tissues, which may be due to concentration effect since accumulation of nutrients in shoot was not increased.

The application of phosphorus containing fertilizers in the soils is a necessary practice for adequate crop yields in many instances and foliar applied phosphorus may increase use efficiency (Girma *et al.*, 2007; Mosali *et al.*, 2006).

Yusran (2009) reported that in lateritic soils, soluble organic carbon (OC) from organic matter may also reduce phosphate adsorption capacity, a process that also releases P in soil solution. It was also reported that the addition of organic matter to the soils may increase the phosphate availability by decomposition and mineralisation of organic-P (OP), or by abiotic processes such as ligand-exchange effects on phosphate adsorption.

Based on the works of Panahpour (2012), it was stated that soil alkalinity of a region had effect on the absorbability of absorbable P, Zn and Mn in soil and by passing time it resulted in decreasing the absorbability of these elements in soil.

Conde *et al.*(2014) reported that rice-legume rotation was significantly influenced by P availability on the newly cultivated acidic soils. Sufficient P application promoted rice growth. It was also proved that the growth of following crop soybean was also influenced positively by P supply.

2.2.Interaction of zinc with phosphorus

Phosphorus is the most important element which interferes on zinc uptake by plants. Zinc and phosphorus imbalance is caused in the plants when there is excessive accumulation of phosphorus, causing zinc imposed deficiency.Phosphorus (P) and zinc (Zn) deficiencies are widespread nutritional constraints on crop production in many parts of the world, and phosphorus-zinc interactions have been widely investigated (Marschner, 1995).

High levels of available P or the heavy application of P to the soil induced Zn deficiency in plants (Olsen, 1972). This P x Zn interaction, also known as "P-induced Zn deficiency", has been recognized incrops likemaize (Langin *et al.*, 1962), potatoes (Boawn and Legget, 1964), tomatoes (Martin *et al.*, 1965), soya bean (Paulson and Rotimi, 1968), flax (Moraghan, 1980), beans (McKenzie and Soper, 1983) and wheat (Singh *et al.*, 1986).

Pot experiments on maize conducted by Dwivedi *et al.* (1975) by inducing zinc deficiency, showed that there was significant reduction in yield at a high level of P application. In zinc-deficient plants, the concentration of zinc significantly increased in the roots and nodes and decreased in the leaves and internodes.

A study conducted by Haldar and Mandal (1981) on three lowland alluvial rice soils revealed that the application of phosphorus and zinc significantly increased the dry matter yield of shoots, grains and roots. It was also reported that application of phosphorus caused a decrease in the concentration of zinc, copper, iron and manganese both in shoots and roots. Similarly application of zinc lowered the concentration of phosphorus, copper and iron, but increased that of manganese in shoots and roots.

Robson and Pitman(1983), stated that the increased availability of P in the growth medium could induce Zn deficiency in plants by altering soil and plant factors. Phosphorus interacts with many nutrients and the most commonly studied antagonistic interaction is with Zn. When excess P binds with a large amount of Zn which is normally available to the plant, there will be a P-induced Zn deficiency (James *et al.*, 1995; Brown and Tiffin, 1962).

Robson *et al.*(1983) reported that the increased availability of P in the growth medium can induce Zn deficiency in plants by altering both physico-chemical and biológical factors in soil–plant systems.

Singh *et al.*(1988) proved that the Zn concentration in bean plant tops was significantly reduced due to application of P fertilizers and the magnitude of the reduction was greatest with the first increment of applied P.

Applications of large amounts of P fertilizers also caused a reduction in the bioavailability of Zn in grains as well as in plant tissues. Phosphorus induced Zn deficiency in plant tissues will be exacerbated by soil Zn deficiency (Buerkert *et al.*, 1998).

Huang *et al.* (2000) demonstrated that Zn deficiency caused an increase in the expression of P transporter genes in both P deficient and P sufficient barley roots. Zhu *et al.* (2001) found that P uptake efficiency may affect Zn uptake.

Phosphorus uptake and transport increased in the shoot and leaves in the absence or low concentrations of zinc which in turn causes toxicity in the plant. This increase occurred only with zinc deficiency and was not observed withany other micronutrient deficiencies. (Webb and Loneagan, 1988; Marschner, 1995; Hu *et al.*, 1996; Bukvi *et al.*, 2003).

Barben *et al.* (2007) proved that high P levels in potato did not directly reduce Zn content or caused Zn deficiency but they reduced the activity of Zn by interacting with other micronutrients such as Mn. It was again proved that phosphorus is the important element that interferes with zinc uptake and zinc uptake by plants was reduced by increased phosphorus in soil.

Zinc transmission from plant roots to shoot wasreduced by high concentration of phosphorus and hence the zinc wasaccumulated in roots and its uptake is decreased. Metabolism defect in plant cellswas related to zinc and phosphorus imbalance. Increased phosphorus concentration adversely affects zinc tasks at specific positions in the cells (Sharma *et al.*, 1986; Marschner *et al.*, 1990; Das *et al.*, 2005; Mirvat *et al.*, 2006; Alloway, 2008; Mousavi, 2011).

Different studies have proved that phosphorus is the most important element that interferes with zinc uptake. Zincuptake by plants was reduced by increased phosphorus concentrationin the soil. The excessive accumulation of phosphorus, causes zinc imposed deficiency. (Salimpour *et al.*, 2010; Das *et al.*, 2005; Marschner *et al.*, 1990; Sharma *et al.*, 1986; Stukenholts *et al.*, 1996)

Based on the works on potato, Barben *et al.* (2010) showed that Zn and P had negative interaction on yield and uptake of nutrients. At the same time Trehan and Grewal (1983) showed that balanced application of P and Zn could increase yield by translocation of assimilates from shoot to tubers.

Excessive use of phosphate fertilizers in soils with micronutrient deficiencies causes imposed deficiency of micronutrients in the plants. (Salimpour *et al.*, 2010; Khorgamy and Farnis, 2009; Hopkins and Ellsworth, 2003).

Mousavi (2011) stated that zinc absorption capacity was reduced by high phosphorus utilization.Zinc in plant and soil has an antagonism state with phosphorus (negative interaction) and therefore zinc utilization was essential to obtain high yield and quality in crops.

High levels of phosphorus may decrease the availability of zinc.Onset of zinc deficiency associated with phosphorus fertilization may be due to plant physiological factors. Applying zinc to plants grown under potentially zinc deficient soils is effective in reducing uptake and accumulation of phosphorus in plants (Mousavi *et al.*, 2012).

2.3. Interaction of boron with phosphorus

Bingham and Garber (1960) and Bingham *et al.* (1958) reviewed that excessive phosphorous (P) additions reduced uptake of Boron (B) in citrus. Boron and phosphorous were also involved in complex adsorption and precipitation reactions with sesquioxides and clay minerals in the soil.

The excessive application of P reduced uptake of B in citrus (Bingham and Garber, 1960; Bingham *et al.*, 1958) and in strawberry (May and Pritts, 1993).

Pollard *et al.* (1977) reported that phosphorus can also interact with B. Boron is essential for root-tip elongation which, in turn, affects P uptake. However, phosphorus also influences boron uptake from the soil.

High B reduced P content in spinach and peanut leaves (Blamey and Chapman, 1979). In tomato and other crops, B concentration in leaves decreased with an increase in P supply (Yamanouchi, 1980).

Singh *et al.* (1990), reported that high B reduced P concentration in wheat. The same effect was studied in kiwifruit plants by Sotiropoulos *et al.*(1999).

Synergistic effects of P and B were observed on various metabolic phenomena in maize (Gunes and Alpaslan, 2000)

For higher plants, both P and B are essential nutrients and several reports suggest that interaction between these two nutrients is highly significant for many crop plants (Yamanouchi, 1980; Gunes and Alpaslan, 2000).

A significant antagonistic relationship between the effects of the application B and P was observed by Gunes and Alpaslan (2000) in maize. He reported that increased level of P in the soil resulted in an increase in both the concentration and uptake of P in all cultivars, but it resulted in a decreased concentration and uptake of B.

Studies by Gunes and Alpaslan (2000) proved that when B was present at toxic levels in the soil and has the potential to inhibit competitively the uptake of essential P, application of greater levels of P to the soil could reverse this effect by promoting a competition resulting in greater P uptake than B uptake.

The works by Sinha *et al.*(2003) has proved that excess supply of P reduced B concentration and has resulted in decreased dry weight and economic yieldon mustard.

Experiment by Kaya *et al.* (2009) clearly showed that there was an interaction between B and P on biomass of tomato plant. High boron application increased B content and reduced P content in plant but application of supplement P reduced B content and increased P content. Fruit yield, number and average fruit weight decreased in the plants grown under high boron conditions. Interactions between B and P were significant for fruit yield, but not for number of fruit and average fruit weight. Concentrations of Ca, P and K were significantly lower in the leaves of plants grown at high B than those in the control plants.

2.4.Fractions of phosphorus contributing to available phosphorus

The inter-relationships among the various P fractions in soil are complex and information about these fractions is used to understand the P sinks and sources in soil and are furtherutilized for an efficient management of phosphorous in the soil for different crops.

Tandon (1987) reported that Al-P and Fe-P were more abundant in acid soils while Ca-P dominated in alkaline soils. Significant relationship of P uptake by wheat was reported with saloid P, Al-P and Fe-P (Jaggi 1991).

Kumaraswamy and Sreeramulu (1991) studied the relationship between P fractions and P uptake by rice crop in different soil series of Tamil Nadu. They reported that in Koduveri and Vyalogam soil series Fe-P and Al-P accounted for 82-89 % of P uptake by rice, with greater contribution from Fe-P, while in Kalathru and Maddukkar soil series, Al-P accounted for 77 to 84 per cent of the P uptake by crop.

Sharma and Tripathi (1992) reported that Al-P and Fe-P fractions contributed towards dry matter yield and P uptake by wheat to a greater extent while the contribution of Ca-P was comparatively less.

Rokima and Prasad (1991) found that all the forms of P were significantly correlated with grain and straw yields and P uptake by rice and wheat.

In acidic soils, the soil P is bound in compounds, such as Fe and Al phosphates, which are essentially insoluble under aerobic or upland conditions (Sanchez and Uehara, 1980; Slaton *et al.*, 2002).

Patiram *et al.* (1990) studied the relationship among the different forms of soil P and available P indices by chemical extractants and showed that Al-P and Fe-P were the main sources of available P. Ca-P did not have any significant positive relationship while reductant soluble P was positively and significantly related to available P in the Entisols. Stepwise regression analysis gave the indication that Al-P was the dominant inorganic form of P which contributed to available P.

Works by Sharma *et al.* (1995) on an acid Alfisol, showed that Al-P and Fe-P were the main sources of available P. They further observed that only Fe-P had significant relationship with grain and straw yield of wheat and total P uptake.

Tran and N'dayegamiye (1995) found that labile P pools (Resin Pi and NaHCO3-Pi), moderately labile Pi (NaOH-Pi) and total P were strongly correlated with P uptake in silage corn.

Gupta and Srivastava (1998) indicated that available P was significantly and positively correlated with total P and all inorganic-P fractions except occluded Al-P. Path coefficient analysis showed that Al-P and organic P directly influenced available soil P while other soil inorganic P fractions showed their effect indirectly through Al-P.

Rhue and Harris, (1999) stated that under anaerobic conditions, Fe plays a major role in P dynamics and hence reduction of Fe and its re-precipitation to form ferrous (Fe^{2+}) minerals are dominant processes under anaerobic conditions

Reddy *et al.* (1999) reported that the changes in NaHCO3-Pi, NaOH-Pi and NaOH-Po fractions were significantly correlated with the apparent P balance and were thought to represent biologically dynamic soil P and act as major sources and sinks of plant available P.

Verma, *et al.* (2005) described that the buildup of plant-available P as determined by the Olsen method due to the continuous use of fertilizer P, calls for the need to reduce P fertilizer application rates so as to avoid unnecessary expenditure and environmental problems such as P leaching. The $NaHCO_3$-P_i (labile pool of Al-P and Fe-P) was the most important fraction contributing to plant-available P and subsequently P uptake by the crop. FYM addition reduced the fixation of P as NaOH-P_i by increasing the $NaHCO_3$-P_i pool.

Saavedra and Delgado (2005) revealed that the ratio of P fractions, which includes the more labile P forms to combined non-organic P fractions, was negatively correlated with the soil pH and positively correlated with the portion of combined Fe fractions related to poorly crystalline oxides.

Setia and Sharma (2007) studied the relationship between inorganic fractions and uptake of P by wheat at different crop stages. They reported that total P content at tillering stage was significantly associated with P concentration and its uptake. The Ca-P at ear initiation stage was significantly related with P uptake by wheat grain and straw. A significant relationship between saloid-P and its uptake by straw was also observed at harvesting.

Setia and Sharma (2007) also reported that application of P increased all the P forms, whereas, N and K application caused decrease in P fractions. The relative abundance of inorganic P fractions was in the order of soluble P < Fe-P < Al-P < Ca-P.

The various inorganic P fractions tended to decline with the crop age. A significant build up of available P was observed in soils receiving NPK alone or in combination with FYM (Mishra *et al.*, 2008)

Based on the studies conducted on riceAbolfazli (2012) reported that the amount of Fe-P fraction in calcareous soils was very low in comparison with acidic soil. He also observed that that Ca-P was the predominant form of P in calcareous soil while, Fe-P and Al-P were predominated in acidic soils. Furthermore, the application of organic fertilizers significantly increased reductant soluble phosphorous and Olsen-P fractions in calcareous soil and fraction of reductant soluble phosphorous in acidic soil.

Phosporus fractionation studies by Dharumarajan and Singh (2014) on the soils under three cropping systems of lower Indo Gangetic plains showed that soils of plantation system recorded a high Olsen-P and Ca-P whereas paddy paddy cropping system had high Iron-P fraction.

2.5.Fractions of zinc contributing to available zinc

Zinc is found to occur in soils as (i) Water soluble plus exchangeable, (ii) organically bound, (iii) amorphous iron oxide bound, (iv) crystalline iron oxide bound, (v) manganese oxide bound, (vi) carbonate and sulphide bound and (vii) residual forms (Shuman, 1985).

At low pH under reducing conditions, Sims and Patrick (1978) showed that Zn moves into the exchangeable and organic fractions from the inorganic fractions.

Plant availability of Zn in soils is influenced by numerous soil properties with soil pH as one of the most important factors (Anderson and Christensen, 1988). The removal of either organic matter or Mn-oxides decreased Zn sorption, but that Fe-oxide removal *increased sorption (Shuman, 1988).*

Lindsay (1991) has reported thatzinc is available at acidic pH and becomes less available at alkaline pH as the mineral and organic form has low solubility. High solubility of Zn is maintained in acid soils of pH 5 or below and Zn deficiency may occur because of the leaching of Zn from root zone. The solubility of soil Zn decreases 100 fold with a unit increase in soil pH

Liang *et al.* (1991) studied chemical fractions of Zn in acidic soils and Zn uptake by navy bean plants. They concluded that Zn uptake by plants grown on the acid soils was from exchangeable, Pb-displaceable, acid soluble and possibly from Mn oxide associated fractions.

The element Zinc may be adsorbed as Zn^{2+}, $ZnOH^{+}$ or $ZnCl^{+}$ and zinc retained on exchange sites and chemisorbed by organic matter and hydrous oxides is believed to be readily available to plants (Soon, 1994).

According to Das (1996), zinc occurs in soils in different chemical pools, which differ in their solubility and availability to plants.

Prasad *et al.* (1996) described that the amount of Zn recovered in water soluble and exchangeable, organically bound, oxide bound Zn recorded a progressive decrease with an increase in residual forms upon submergence.

Das (1996) reported that the higher recovery of organic matter bound Zn may be due to higher rate conversion of amorphous sesquioxide bound Zn and subsequent low recovery of organic fractions of Zn at the later period of submergence may also be due to greater microbial immobilization as well as formation of insoluble complexes with soil organic matter.

Sureshkumar *et al.* (2004) has reported that water-soluble, exchangeable, and organically complexed forms were considered to be available; amorphous sesquioxide-bound form is potentially available and crystalline sesquioxide-bound and residual Zn forms are unavailable to plants.

The works by Verma and Subema (2005) to study the zinc availability in an acid Alfisol as influenced by long term fertilizer trial on different zinc fractions in maize-wheat cropping led to a conclusion that residual zinc and Al and Fe-oxide bound zinc are the predominant fractions that collectively contributed about 70% of the different zinc fractions. The same study also revealed that the major fractions contributing to the DTPA-Zn are the water soluble plus exchangeable and Al and Fe-oxide bound zinc.

Adhikari and Rattan (2007) also recorded higher concentration of water soluble and exchangeable Zn in an acidic soil of Cooch Behar, India. Extractable Zn concentrations in soils may decrease with an increase in soil pH (Alloway, 2008).

As reported by Wijebandara *et al.* (2011), water soluble plus exchangeable zinc and available zinc were correlated significantly and negatively with pH and $CaCO_3$ and positively with organic carbon and clay content of the paddy growing soils in Northern Dry and Hill Zones of Karnataka.

Results based on the experiments conducted by Behera*et al.* (2011) on acid soils from four states of India revealed that concentrations of total as well as extractable Zn varied widely among the acids soils and the amount of Zn extracted by different extractants also differed. Zinc deficiency was observed in 7 to 82% soils extracted using Diethylene Triamine Penta Acaeticacid (DTPA) and 2 to 57% soils extracted using 0.1M hydrochloric acid (HCl) Correlation analysis revealed that the extracted Zn by DTPA, Mehlich 1, Mehlich 3, 0.1N HCl and ammonium bicarbonate DTPA (ABDTPA) extractants was significantly correlated. The contribution of soil organic carbon (OC) content towards total and DTPA-Zn was higher as compared to soil pH.

Rahmani *et al.* (2012) has reported that the residual Zn and oxide bound Zn were the more stable fractions while the exchangeable Zn and water soluble Zn fractions were rather more soluble.

Studies by Mandal and Das (2013) on zinc availability in rice wheat irrigated ecosystem proved that zinc availability decreased in submerged condition which might be attributed to the formation of insoluble franklinite ($ZnFe_2O_4$); sphalerite (ZnS); $ZnCO_3$, $Zn(OH)_2$, $Zn_3(PO4)_2$ and adsorption by oxides, hydrous oxides, organic matter, carbonates, sulphates and clay minerals.

In the same experiment by Mandal and Das (2013) it was observed that all Zn fractions except the residual mineral Zn showed significant positive correlation with each other and with Zn uptake by rice. The Zn uptake was recorded highest when N and K (along with Zn) was applied followed by application of Zn in combination with N and P.

Based on the studies by Joshi *et al.* (2014), it was reported that in acidic soils, residual Zn was the most dominant fraction followed by (in descending order of concentration) crystalline Fe oxide bound; Pb displaceable; amorphous Fe oxide bound; Mn oxide occluded; acid soluble; organically bound; exchangeable and water soluble Zn fractions. Among chemical fractions of soil Zn, lead displaceable and acid soluble chemical fractions of soil Zn showed a significant and positive correlation with Zn uptake by maize. Path coefficient analysis also revealed that the acid soluble Zn fraction showed the highest positive and direct effect on Zn uptake.

The studies conducted by Fathi *et al.* (2014) on acid soils of Iran showed that, Zn in the acid soils mainly existed in the residual fraction (75-78%), followed by the carbonate fraction (5-7%) and the crystalline Fe-oxidefraction (5.2- 6.1%).The results also proved that the soil organic matter and pH were highly and significantly correlated with the different forms of zinc and hence it seemed to be the main factors affecting the Zn pools in acid soil of Iran.

Ramzan *et al.*(2014) described that soil Zn concentrations in different fractions were influenced by the colloidal properties of the soils such that soils with lower pH and those with high organic matter were more likely to have higher Zn concentration in the available fractions.

2.6. Boron fraction contributing to available to boron

Bingham (1982) reported that boron is an essential element for normal plant growth but the range between boron (B) concentrations in soil solution causing deficiency or toxicity symptoms in plants is relatively narrow. They commented that B is readily absorbed by soils and adsorbed B being unavailable to plants is considered not toxic. Also, maintaining B in the soil solution is important for plant nutrition and it is controlled by the pools of B in other soil fractions and their equilibration with the soil solutions.

Bingham *et al.* (1971) studied B deficiency in soils rich in Al oxides. They also reported that B can be effectively leached from soil although the rate of removal is much slower than for non-reacting element.

Al $(OH)_3$ is one of the main fractions that adsorb B in soils and B iron and aluminum hydroxide through adsorption depends on pH. It has been suggested that the B adsorption of iron hydroxides rises to a maximum level around pH of 8-9, and the B adsorption of aluminum hydroxides raises to maximum levels around pH of 7 (Keren and Mezuman, 1981).

Bingham (1982) came into a conclusion that hot water extractable B has been regarded as a suitable index of plant available boron. Sequential fractionation procedure for separate extraction of soil B fractions, were developed by Jin *et al.* (1987).

In the acid soils, soluble B occurs as non-ionized boric acid [$B(OH)_3$], whereas formation of borate anion [$B(OH)_4$ −] takes place with a rise in soil pH. Thus leaching of B primarily as $B(OH)_3$ under high precipitation and adsorption of soluble B on Al and Fe oxides are the major causes of B deficiency in acid soils (Goldberg and Glaubig, 1985).

It was observed that coarse textured acid soils of humid and per-humid regions, calcareous soils and those with low organic matter content are more prone to B deficiency (Dwivedi *et al.*, 1990; Mondal *et al.*, 1991; Niaz *et al.*, 2007).

Boron is an essential micronutrient which is present in minerals and in soil solutions. Only the B present in soil solution can be readily available to plants and also it should constitute only less than 3% of the total soil B (Jin *et al.*, 1987; Tsadilas *et al.*, 1994).

Tsalidas *et al.* (1994) commented that boron is found in soils under various forms, which have different availability to plant, such as nonspecifically and specifically adsorbed, occluded in Mn oxyhydroxides, and amorphous and crystalline Fe and Al oxides. They also reported that a variety of factors such as pH, organic matter, clay minerals, Fe and Al oxides, carbonates, and tillage management may change the content of extractable B and transformations among different soil B fractions. The content of water soluble B in soils tends to increase with soil pH, but not always in a consistent manner, because B adsorption by soil components also increases with increase of soil pH, and reaches maximum in the alkaline pH range.

The method for chemical fractionation of soil boron was further modified byHou *et al.* (1996).Among the B fractions, nonspecifically adsorbed B (NSA-B), specifically adsorbed B (SPA-B), and B occluded in Mn oxyhydroxide fractions may be the most available forms to plants, and B fractions occluded in Al and Fe oxyhydroxides are relatively unavailable forms.

SPA-B fraction, which may be specifically adsorbed on clay surfaces or associated with organic matter in soil showed the similar distribution with NSA-B fraction(Jin *et al.*, 1987; Tsadilas *et al.*, 1994; Rahmatullah and Salim,1999; Zerrari *et al.*, 1999; Datta *et al.*,2002).

Mortvedt *et al.* (1999) reported that at a pH range of 5.50 to 7.5, the activeness or avalibilty of B is the highest.

Scientists have reported that soil parameters like type of clay, cation exchange capacity (CEC), organic matter, Fe and Al oxides, carbonates, moisture status, etc. also affected the transformation of different B fractions into one another. (Keren and Bingham, 1985; Hou *et al.*, 1996; Yermiyahu *et al.*,2001; Communar and Keren, 2008)

The transformations among the forms (NSA-B,SPA-B, occluded in Mn oxyhydroxides, and amorphous and crystalline Fe and Al oxides) were found to be affected by a variety of factors such as pH, organic matter, clay minerals, and Fe and Al oxides (Xu *et al.*, 2001).

Akin (2009) reported that there were significant positive relationships between the soil pH and specifically adsorbed readily soluble B and B fractions; whereas, negative relationships were found between the oxides bound B and calcium carbonate content of soils.

Santhosh (2013) has reported that the different fractions of boron *viz.,* readily soluble, specifically adsorbed, organic bound ,oxide bound and residual boron account a mean status of 0.59,0.86, 1.79, 2.31, 94.45% of total boron respectively in soils of different agro ecological units of Kerala. He also reported that plant absorption of boron mainly takes place from readily soluble, specifically adsorbed, organic bound boron in that order due to the existence of dynamic equilibrium between these fractions.

Materials and Methods

3. MATERIALS AND METHODS

3.1. Soil sampling

In order to achieve the objectives of the present investigation, soil samples (100 no's) of lateritic origin (Ultisol) were collected from different locations in Thrissur, Malappuram, and Kozhikode districts. These samples were assayed for available phosphorus by Bray-1 extraction. From these samples six soil samples each coming under three fertility classes was used for the present study. The location of these samples is given below.

Table 1. Locations of the selected soil samples for the study

No	Soil
1	Cashew Research Station (CRS 1)
2	CashewResearch Station (CRS 2)
3	Cashew Research Station(S1)
4	Cashew Research Station (CRS 4)
5	Cashew Research Station (CRS 5)
6	Cashew Research Station (CRS 6)
7	Cocoa plantation (Horticulture college)
8	Malappuram (parappur panchyath)
9	Thrissur (Vellanikkara) (S2)
10	Malappuram (pookotur panchayath)

11	Cashew Research Station (CRS 7)
12	Cashew Research Station (CRS 8)
13	Instructional Farm (block)
14	Instructional Farm (block) (S3)
15	Malappuram (vengara panchayath)
16	Department of Olericultue field
17	Mango orchard (Horticulture college)
18	Coconut farm(Agronomy)

These soils (3×6) were characterized with respect to pH, electrical conductivity (EC), cation exchange capacity (CEC) and exchangeable cations, available nutrient status (Organic carbon, P, K, Ca, Mg, Fe, Ca, Mn, Zn), and major fractions of P, Zn and B. The materials used and themethods adopted to assess the above said chemical characteristics, are detailed below.

3.1.1. Soil pH

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

3.1.2. Electrical conductivity

Electrical conductivity was estimated in the supernatant liquid of the soil water suspension (1:2.5) used for pH estimation with the help of a conductivity meter (Jackson, 1958).

3.1.3. Organic carbon

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

3.1.4. Available phosphorus

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

3.1.5.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 (Jackson, 1958).(Model: Elico CL365)

3.1.6. 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 g soil with 40 ml of 0.1M HCl was shaken for 5 minutes. It was filtered through Whatmann No.1 filter paper and the filtrate was collected and analysed for Fe, Cu, Mn and Zn using atomic absorption spectrophotometer (Model: Perkin Elmer Analyst 400).

3.1.7. Exchangeable cations and cation exchange capacity

The cation exchange capacity in the soil was estimated by the method proposed by Hendershot and Duquette (1986). The cations (Ca, Mg, Na, K, Al, Fe, Mn, Cu and Zn) present in the exchangeable sites in the soil were replaced by 0.1M $BaCl_2$ solution and thus extracted cations were estimated. Four grams of soil samples were taken in a centrifuge tube and 40 ml of 0.1M $BaCl_2$ was added. It was shaken for two hours and filtered through Whatman No.42 filter paper. Filtrate was used for aspiration to an atomic absorption spectrrophotometer (Model: Perkin Elmer Analyst

400) for the determination of exchangeable Ca, Mg, Fe, Mn, Cu and Zn. Exchangeable Na and K were estimated with the help of flame photometer (Model: Elico CL361). Exchangeable Al was estimated colorimetrically using Aluminon (Jayman and Sivasubramanian, 1974). The sum of exchangeable cations expressed in cmol (P^+) kg^{-1} was recorded as the CEC of the soils.

3.2. 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) 1M NH4Cl to remove soluble P

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

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

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

v) 0.25M H_2SO_4 to remove the Ca-P

3.2.1. Extraction of P fractions

Flow chart for the P fractionation is depicted in Fig.1. The sequential path of extraction of one gram soil was taken in a 100 ml centrifuge tube. To this 50 ml of 1M 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 0.5M 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 bound P, Extract B).

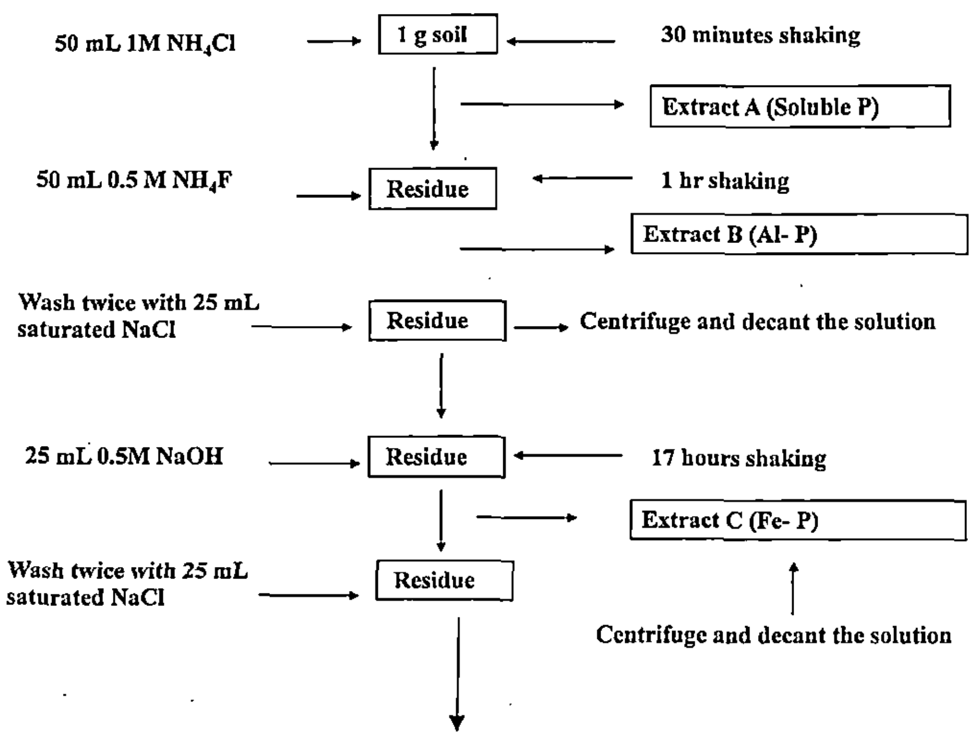
To the soil residue 50 ml 0.1M NaOH was added and shaken for 17 hours. The solution was centrifuged and decanted. The residue was again washed twice with

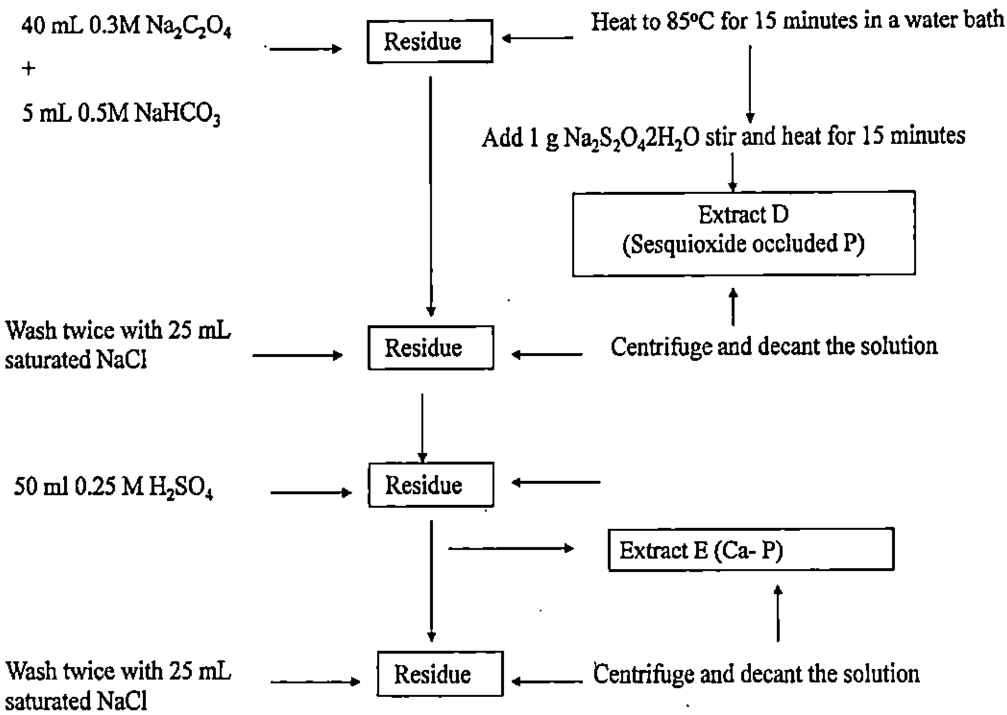
25 ml saturated NaCl solution and after centrifugation and decanting they were mixed together and made up the volume to 100 ml (Fe bound-P, Extract-C).

To the soil residue, 40 ml of 0.3M citrate solution and 5ml of 1M $NaHCO_3$ solution were added and heated in a water bath to 85°C. To this, 1g 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).

Figure 1. Flow chart of fractionation of soil phosphorus

(Soil 1 g < 2 mm) in to100 ml centrifuge tube





Fifty ml 0.25M H_2SO_4 was added to the soil residue 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).

3.3. Estimation of P fractions

3.3.1. Concentration P in soluble and Ca-P fractions

Five ml 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.

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

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

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

Fiveml of the extracts were pipetted out. The solution pH was adjusted using 2M HCl in presence of 0.25% paranitrophenol. For this a separate 5 ml aliquot was pipetted out to which 2 drops 0.25% P-nitrophenol was added and 2M HCl was added drop wise from a burette till the colour changed from yellow to colourless. This estimated amount of 2M HCl was added to the aliquot (5 ml) pipetted for estimation. The P was estimated using ammonium molybdate ascorbic acid reduced blue colour method. The intensity of blue colour was read in spectrophotometer at 660 nm.

3.4. Fractionation of soil zinc

To study the distribution of zinc, in the soil sequential fractionation method outlined by Iwasaki and Yoshikawa (1993), 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.

3.4.1. Water soluble + exchangeable (neutral salt) fraction (WS+Exc)

1.5 g soil sample was weighted in to a centrifuge tubeadded with25 ml (0.5M $CaNO_3)_2$ andwas shaken for 16 hours. The filtrate was collected after centrifugation for 2 minutes at 3000 rpm

3.4.2.Specifically adsorbed Pb displaceable fraction (Sp.Ad-Zn)

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

3.4.3. Acid soluble fraction (Acid.sol)

Twenty five ml of 2.5 per cent CH_3COOH was added to the soil residue and was shaken for 2 hours. The filtrate was collected as described above.

3.4.4 Manganese oxide occluded fraction (MnO-Zn)

1.5 g soil residue was added with50 ml of 0.1M NH_2OH HCl at pH 2 and was shaken for 0.5 hours and the filtrate was collected and analysed for Zn, Mn, Fe and Cu.

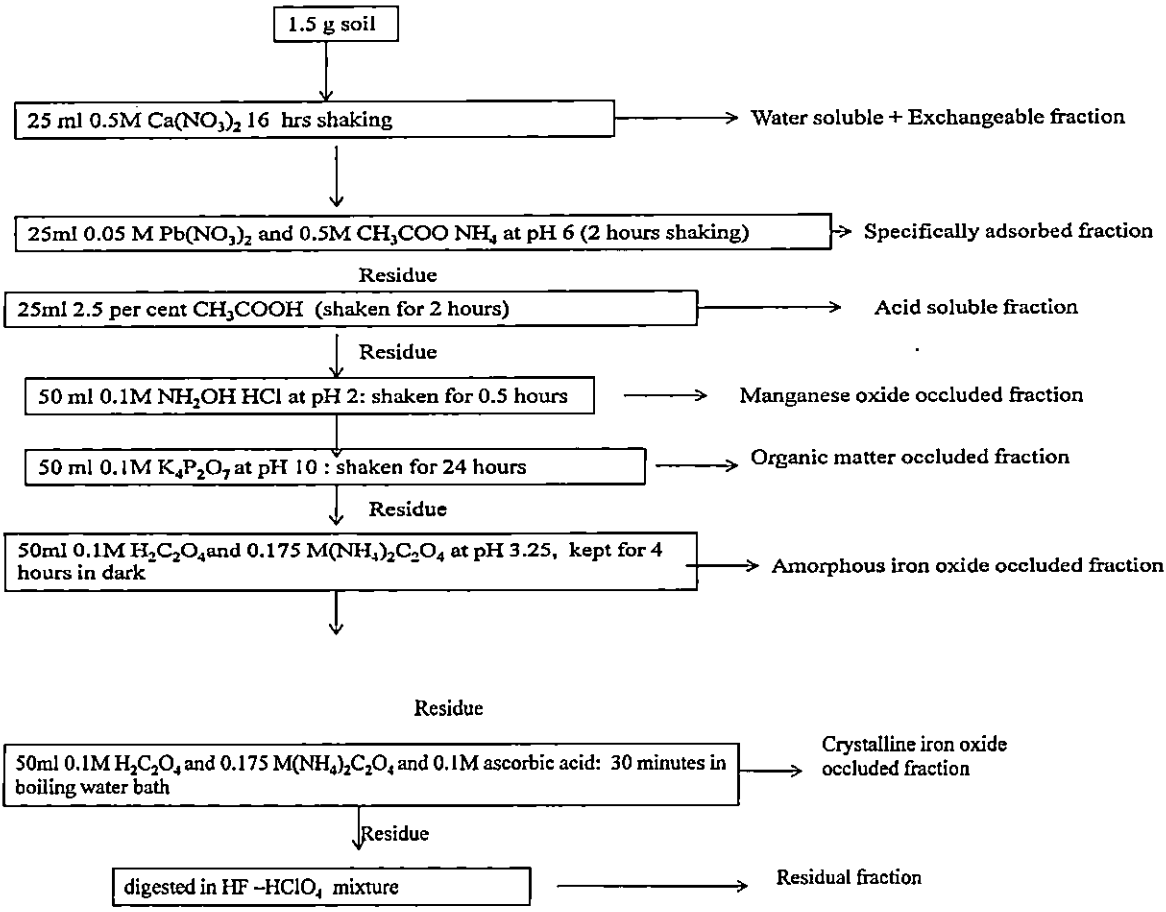
3.4.5. Organic matter occluded fraction (OM-Zn)

Fiftyml of 0.1M $K_4P_2O_7$ at pH 10 was shaken for 24 hours. The filtrate was collected after centrifuging at 3000 rpm for 2 minutes

3.4.6. Amorphous iron oxide occluded fraction (AmFeO-Zn)

The soil residue was added with50ml of 0.1M $H_2C_2O_4$and 0.175 M$(NH_4)_2C_2O_4$ at pH 3.25, was 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



3.5. Fractionation of soil Boron

3.5.1. Readily soluble B (RS - B)

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

3.5.2. Specifically adsorbed B (Sp.Ad- B)

The residue from 3.2.1 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 filtered through whatman No.42 filter paper. Boron was determined in the clear extracts using azomethine-H (Bingham, 1982).

3.5.3. Oxide bound B (OX- B)

The residue from 3.2.2 was extracted with 20 ml of 0.175M ammonium oxalate, pH 3.25 (Jin *et al.*, 1987; McLaren and Crawford, 1973) by shaking for 4 hours (Hou *et al.*, 1994). The yellow to reddish colour of the extracts due to the dissolution of Fe and organic matter was eliminated by treating with NaOH and $HClO_4$.

3.5.1.1. Elimination of colour of the extracts

To remove the colour, 14 ml aliquot of the extract was taken in 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. Nine ml aliquot of the filtrate was taken in 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 135^0C 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 centrifuge tube 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)

3.5.4. Organically bound B (OM- B)

A subsample 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 3.2.3.1. 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.

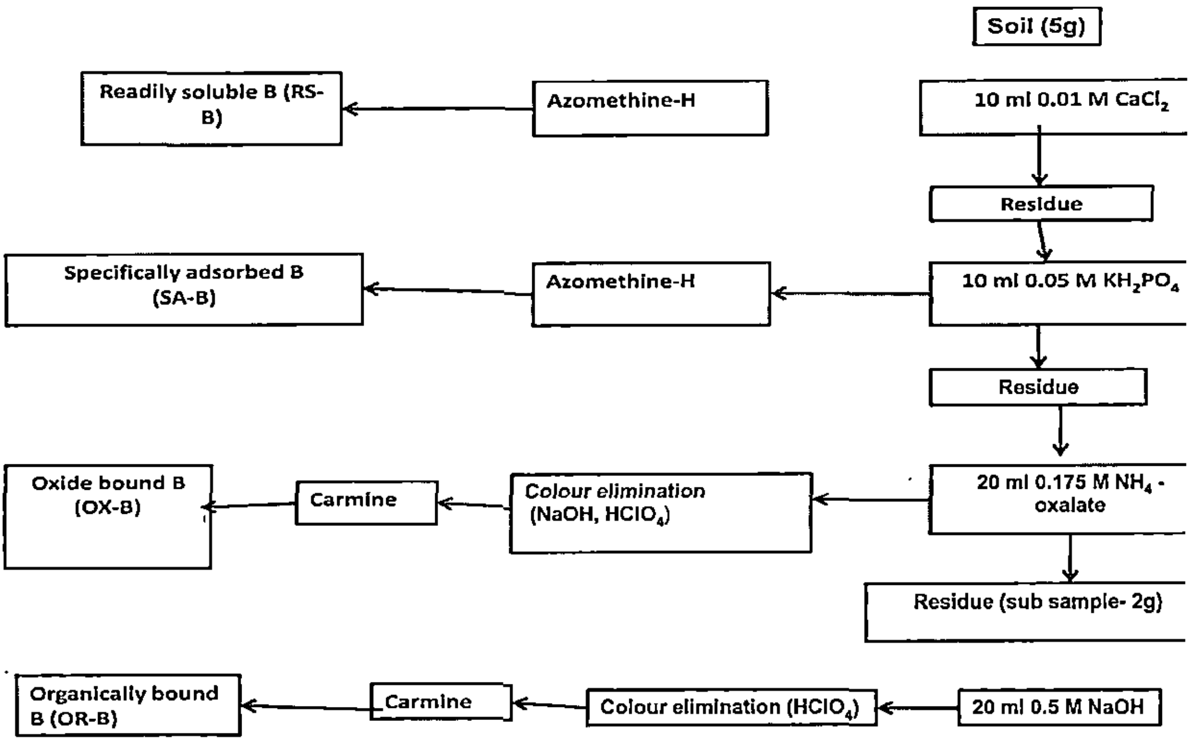
3.5.5. Total B (TB)

Exactly 0.2 gram of the soil sample was taken in 50 ml teflon beaker and 3 ml aqua regia (Datta *et al.*, 2002) was added and kept overnight for wet digestion and digested at 135^0C for 2 hr and filtered through Whatman no. 42 and diluted with distilled water and B was estimated with carmine.

3.5.6. Residual B (Resd-B)

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

Figure. 3. Flow diagram of fractionation of B in soil



Residual B (RES-B) = TOTAL B – (RS-B + Sp.Ad-B + OX-B + OM-B)

3.6. Pot culture experiment

A pot culture experiment with cowpea (var. Kanakamony) was carried out at the net house of the Radio Tracer Laboratory, College of Horticulture using the above three selected soils from the 18 soils mentioned in Table1. Plastic pots of uniform size (5kg capacity) were used for the study. These pots were filled with 5 kg of processed soil.

The treatments were superimposed in these soils as detailed below:

1. Soil

a) S_1 (low P soil)

b) S_2 (medium P soil)

c) S_3 (high P soil)

2. Two levels of P

a) 0 kg P_2O_5 ha^{-1} (P_0)

b) 30 kg P_2O_5 ha^{-1} (P_1)

2. Two levels of Zinc

a) 0 kg ha-1 (Zn_0)

b) 20 kg ha^{-1} (Zn_1)

3. Two levels of Boron

a) 0 kg ha^{-1} (B_0)

b) 10 kg ha^{-1}(B_1)

Treatment combinations were 3 x 2 x 2 x 2= 24 and the experiment was laid out in a completely randomized design with 24 treatment replicated four times.

Table 2. Treatment combinations in the experiment

Treatment	Notations	Treatment	Notation	Treatment	Notation
T_1	$S_1P_0Zn_0B_0$	T_9	$S_2P_0Zn_0B_0$	T_{17}	$S_3P_0Zn_0B_0$
T_2	$S_1P_0Zn_0B_1$	T_{10}	$S_2P_0Zn_0B_1$	T_{18}	$S_3P_0Zn_0B_1$
T_3	$S_1P_0Zn_1B_0$	T_{11}	$S_2P_0Zn_1B_0$	T_{19}	$S_3P_0Zn_1B_0$
T_4	$S_1P_0Zn_1B_1$	T_{12}	$S_2P_0Zn_1B_1$	T_{20}	$S_3P_0Zn_1B_1$
T_5	$S_1P_1Zn_0B_0$	T_{13}	$S_2P_1Zn_0B_0$	T_{21}	$S_3P_1Zn_0B_0$
T_6	$S_1P_1Zn_0B_1$	T_{14}	$S_2P_1Zn_0B_1$	T_{22}	$S_3P_1Zn_0B_1$
T_7	$S_1P_0Zn_1B_0$	T_{15}	$S_2P_0Zn_1B_0$	T_{23}	$S_3P_1Zn_1B_0$
T_8	$S_1P_0Zn_1B_1$	T_{16}	$S_2P_0Zn_1B_1$	T_{24}	$S_3P_1Zn_1B_1$

3.7. Fertilizer and manure application

Organic manure, N and K were applied as per POP for cowpea (20:30:10 kgha^{-1}).Lime was applied as per soil test based recommendation (ΔpH method).

3.8. Plant analysis

Plant samples were also collected from different treatments at flowering and at harvesting stages. Destructive sampling of three replications was done in both the stages. The samples were oven dried to a constant weight and ground for analysis.

Table 3. Methods of plant analysis

Sl. No.	Element	Method
1	Nitrogen	Modified Kjeldhal's digestion method (Jackson, 1973)
2	Phosphorus	Diacid digestion of leaf sample followed by filtration. vanabdomolybdate phosphoric yellow colour in nitric acid system (Piper, 1966)
3	Potassium	Diacid digestion of leaf sample followed by filtration. 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)
5	Sulphur	Diacid digestion of leaf sample followed by filtration and estimation by turbidimetry (Massoumi and cornfield,1963)
6.	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)
7.	Boron	Determined by dry ashing (Gaines and Mitchell, 1979) and then colorimetricallybyAzomethine-H(Bingham,1982)

3.9. Biometric observations

Plant height, number of leaves, number of grains per pod, grain yield per plant,100 grain weight, pod length, pod yield per plant were recorded.

3.10. Statistical analysis

Analysis of variance in CRD was done using MSTATC package. Correlation studies of data were carried out by the method suggested by Panse and Sukatme (1978). Path coefficient analysis was carried out in SPAR1 package.

Results

4. RESULTS

The data on the characterization of eighteen selected soils from three classes of fertility with respect to phosphorus and the data from the pot culture experiment are presented here.

4.1. Characterization of initial soil samples

4.1.1. pH

The pH of the soils ranged from 4.03 to 5.70. The lowest pH was recorded in sample11 and the highest in sample 17. (Table 4)

4.1.2. Electrical conductivity (EC)

The electrical conductivity of the soils ranged from 0.06 (sample 14) to 0.21 dSm^{-1}(sample 4). (Table 4)

4.1.3. Available nutrient status

The organic carbon content of the soils ranged from 0.09 (sample 11) to 1.96 percent (sample 16).The available phosphorus of the soils ranged from 3.40 (sample 2) to 225.40 $kgha^{-1}$ (sample 17).

In the case of available potassium content, the range was from 53.10(sample 12) to 276 $kgha^{-1}$ (sample 6). (Table 4)

The available Ca in the soils ranged from 61.80 mg kg^{-1} (sample 11) to 425.00 mg kg^{-1}(sample 4). With respect to available Mg content, the range was from 48.50 mg kg^{-1}(sample5) to 162.60 mg kg^{-1}(sample 4). The available sulphur content ranged from 4.40 mg kg^{-1}(sample10) to 62.00 mg kg^{-1}(sample 9).

4.1.4. Available micronutrient status

The available (0.1N HCl extractable) micronutrient status of the selected soils are given in table 1. Available iron (Fe) content of the soils ranged from 3.80 (sample13) to 41.80 mg kg^{-1}(sample 16). Available Mn was found to range from 8.6

0(sample 3) to 68.68 mg kg^{-1}(sample 13). Available Cu content of the soils ranged from 1.25(sample 16) to 13.33 mg kg^{-1} (sample 17). The amount of available Zn in the soils ranged from 0.13 (sample 10) to 14.40 mg kg^{-1}(sample 9).The hot water extractable B was found to vary from 0.08 (sample1) to 2.43 mg kg^{-1}(sample 17). (Table 4)

Table 4.Electrochemical properties of selected soils

Sample No.	pH	EC (dSm^{-1})	OC (%)	($kg\ ha^{-1}$)		$mg\ kg^{-1}$							
				P	K	Ca	Mg	S	Fe	Mn	Zn	Cu	B
1	4.70	0.14	0.85	3.63	130.00	298.00	88.90	6.25	25.20	28.40	1.78	4.56	0.08
2	4.90	0.16	1.08	3.40	202.00	257.00	48.80	11.00	28.40	15.12	1.46	3.69	0.09
3	4.80	0.08	1.30	3.91	231.80	89.50	84.20	7.60	9.31	8.60	1.32	5.20	0.13
4	5.50	0.21	0.83	3.69	163.00	425.00	162.60	5.70	35.10	8.60	1.50	2.72	0.17
5	4.40	0.17	1.01	3.64	172.00	166.00	16.05	4.60	24.30	10.02	1.29	2.85	0.19
6	5.40	0.12	1.14	4.58	276.00	215.80	68.95	21.30	25.90	14.20	1.08	5.79	0.21
7	5.60	0.14	0.99	17.00	191.00	129.95	83.15	36.40	4.52	11.94	1.20	4.52	0.81
8	5.15	0.10	1.04	20.00	95.30	124.95	74.80	20.30	7.81	4.63	1.83	3.61	1.05
9	4.90	0.19	1.40	17.00	137.80	171.20	120.45	6.20	13.10	14.66	14.43	4.16	0.46
10	5.20	0.13	0.75	15.00	80.30	85.65	79.45	4.33	9.45	15.04	0.13	8.53	0.88
11	4.03	0.07	0.09	14.60	53.60	61.25	74.70	4.59	9.14	8.59	0.33	4.86	0.11
12	4.15	0.19	1.20	16.20	53.10	98.40	53.30	4.40	10.30	13.20	0.81	4.27	1.18
13	5.20	0.11	0.68	147.60	252.60	127.45	106.00	44.20	3.81	68.68	1.52	4.40	1.01
14	5.60	0.06	1.07	52.70	134.80	97.75	82.65	6.25	10.60	17.49	2.15	3.76	0.61
15	4.80	0.11	1.46	135.50	121.30	72.25	78.61	4.69	24.80	14.00	1.29	10.10	1.48
16	5.50	0.10	1.96	153.20	137.80	131.35	43.50	40.00	41.80	12.48	2.99	1.25	0.65
17	5.70	0.13	1.51	225.40	245.80	167.45	44.57	14.00	23.70	52.50	2.35	13.13	2.43
18	4.40	0.01	0.99	166.60	148.30	88.00	49.59	18.20	9.77	8.79	1.97	6.92	1.41

4.2. Exchangeable cations and cation exchange capacity (CEC)

The 0.01M $BaCl_2$ extractable exchangeable cations of the soils under study are presented in table 5. The exchangeable potassium ranged from 0.16 cmol(+) kg^{-1} to 2.34 cmol(+) kg^{-1}). The highest exchangeable K was found in sample No. 3. The amount of exchangeable Na was found to vary from 0.48 cmol(+) kg^{-1}) to 2.02cmol(+) kg^{-1}). The exchangeable calcium ranged from 1.17 to 6.15 cmol(+) kg^{-1}. The exchangeable magnesium was observed in the range of 0.02 to 2.84 cmol(+) kg^{-1} and in case of exchangeable aluminium 0.01 to 1.26 cmol(+) kg^{-1} were recorded. The exchangeable Fe, Mn, Cu, and Zn recorded very low with values less than 0.002 cmol(+) kg^{-1}.

Table 5. Exchangable cations of the selected soils

Sample No.	CEC [cmol(p+)kg^{-1}]	Exchangeable cations [cmol(p+)kg^{-1})]								
		Na	K	Ca	Mg	Al	Fe	Cu	Mn	Zn
1	8.19	0.67	0.22	6.15	1.08	0.04	0.01	0.02	0.002	0.001
2	8.11	1.06	0.30	6.14	0.49	0.01	0.11	0.01	0.001	0.001
3	5.60	1.27	2.34	1.17	0.45	0.18	0.16	0.02	0.007	0.002
4	10.09	0.89	0.19	6.08	2.84	0.05	0.01	0.04	0.002	0.001
5	5.57	0.79	0.46	3.66	0.57	0.01	0.01	0.08	0.004	0.001
6	8.96	1.63	0.20	6.07	0.99	0.03	0.01	0.04	0.004	0.001
7	7.22	0.99	0.17	5.89	0.07	0.03	0.01	0.05	0.008	0.001
8	5.08	0.77	0.19	3.50	0.09	0.44	0.01	0.09	0.002	0.001
9	7.36	1.07	0.25	5.74	0.14	0.15	0.01	0.01	0.003	0.001
10	3.15	0.63	0.18	1.93	0.06	0.23	0.02	0.09	0.004	0.001
11	2.37	0.48	0.16	1.68	0.02	0.00	0.01	0.01	0.007	0.001
12	2.71	0.57	0.26	1.45	0.11	0.27	0.02	0.04	0.004	0.001
13	8.84	2.02	0.21	5.96	0.40	0.11	0.03	0.10	0.006	0.001
14	5.51	0.55	0.16	3.41	0.05	1.26	0.01	0.06	0.003	0.002

15	4.38	0.73	0.17	2.83	0.04	0.56	0.01	0.04	0.003	0.001
16	7.75	0.92	0.17	5.74	0.08	0.80	0.01	0.03	0.005	0.001
17	7.16	0.68	0.18	5.74	0.28	0.21	0.01	0.05	0.004	0.001
18	3.65	0.69	0.19	2.37	0.04	0.33	0.01	0.02	0.008	0.001
Range	**2.37 to 10.09** [cmol(p+)kg^{-1}]	**0.48to 2.02**	**0.16 - 2.3**	**1.17-6.15**	**0.02-2.84**	**0.01-1.26**	**0.01-0.16**	**0.01-0.1**	**0.001-0.008**	**0.001-0.002**

4.3. Fractions of phosphorus

The data on various inorganic P fractions of the 18 soils are presented in table 6. The soluble P fraction in the soils ranged from 8.00 mg kg^{-1}(sample 1) to 35.60 mg kg^{-1}(sample 11). The Al-P fraction of the soils varied from 23.00 mg kg^{-1}(sample 3 and 6) to75.60 mg kg^{-1}(sample 14). These selected soils had Fe-P fraction in the range of 106.20 (sample 1) to 397.70 mg kg^{-1}(sample 16).The occluded P fraction in the soils varied from 16.40 mg kg^{-1}(sample 10)to 78.00 mg kg^{-1} (sample 5). The Ca- P fraction in the soils ranged from 12.20 mg kg^{-1}(sample 11) to 49.40 mg kg^{-1}(sample 4). The highest total inorganic P was recorded in sample 16 which was recorded as 560.00 mg kg^{-1}.

Table 6. Inorganic P fractions in different soil samples under study

Sample No	Sol-P(mg kg^{-1})	Al-P(mg kg^{-1})	Fe-P(mg kg^{-1})	Reductant P(mg kg^{-1})	Ca-P(mg kg^{-1})	Total inorganic P(mg kg^{-1})
1	8.00	38.40	106.20	26.60	32.50	227.70
2	15.20	26.90	183.60	59.50	29.40	329.40
3	19.80	23.00	154.80	34.60	15.40	269.70
4	15.00	22.80	144.40	29.20	49.40	279.00
5	17.40	26.20	131.00	78.10	30.90	301.20
6	11.90	23.00	135.10	28.40	34.20	251.80
7	18.40	29.10	138.80	67.60	25.40	295.70
8	20.90	23.60	143.60	37.00	23.80	264.70
9	12.30	26.50	165.20	26.20	31.20	279.70
10	12.50	23.30	140.30	16.40	14.30	222.40
11	35.60	29.70	148.40	20.00	12.20	260.10

12	12.90	24.60	146.20	37.30	24.90	262.90
13	29.40	66.00	142.50	21.00	24.60	298.10
14	12.70	75.60	177.00	58.20	15.60	355.90
15	9.90	30.80	145.80	34.60	13.10	249.10
16	16.00	60.50	397.70	37.30	26.20	560.40
17	16.00	79.50	276.60	79.50	27.60	500.10
18	18.80	30.40	170.00	61.30	15.80	318.40

4.3.1. Distribution of P expressed as percentage of total inorganic P in soil

The distribution of fractions of P at initial stage was detailed below:

In low P soils: Fe-P(55.60%)>occludedP(14.70%)>Ca-P(13.15%)>Al-P(10.10%)>soluble P(6.20%)

Medium P soils: Fe-P (61.60)>occluded P(12.4%)Al-P(10.47)>>Ca-P(9.05%)>soluble P(6.30%)

High P soils: Fe-P(57.40%)> Al-P(16.20)>Occluded P(13.70%)>Ca-P(6.05%)>soluble P(6.35%)

4.3.2. Correlation between different fractions of soil Phosphorus

Available P was found to be significantly and positively correlated with Fe-P (0.66**), Al-P (0.77**), occluded P (0.33*) and total P (0.74**). Significant and positive correlation was also observed for Al-P with Fe-P (0.55**), occluded P (0.28**), and total inorganic P (0.71**). The correlation of Fe-P was positive with total inorganic P (0.94**). The occluded P also had a significant positive correlation with total inorganic P (0.46**).

Table 7. Correlation coefficients between different fractions of P in soil

		Avail- P	Sol-P	Al-P	Fe-P	OC-P	Ca-P	Total inorganicP
Available P	Pearson Correlation	1						
Soluble P	Pearson Correlation	**.01**	1					
Al-P	Pearson Correlation	**0.77****	**0.043**	1				
Fe-P	Pearson Correlation	**0.66****	**-0.033**	**0.550****	1			
OC-P	Pearson Correlation	**0.33***	**-0.080**	**0.279***	**0.220**	1		
Ca-P	Pearson Correlation	**-0.16**	**-0.161**	**-0.024**	**0.071**	**0.069**	1	
Total inorganic P	Pearson Correlation	**0.73****	**0.074**	**0.707****	**0.937****	**0.461****	**0.142**	1

4.4. Fractions of B in soil

The data on the various fractions as well as the total B in the selected soils are given in the table 8. The readily soluble B (RS-B) ranged from 0.005 to (sample 5) 1.86 mg kg^{-1}(sample 17). Specifically adsorbed B (Sp.Ad-B) was found to range from 0.12 (sample 1) to 1.91 mg kg^{-1}(sample17).For oxide bound boron, the sample1 recorded the lowest value of 0.23 mg $kg^{-1}$and sample17 recorded the highest value of 2.90 mg kg^{-1}. Organically bound B varied from 0.21 (sample 11) to 3.91 mg kg^{-1} (sample 18).

Among the five fractions of soil B, the dominant fraction was Resd-B which varied from 40.80 (sample 1) to 61.33 mg kg^{-1} (sample 17). The total B was found to vary from 41.20 to 71.60 mg kg^{-1}.

4.4.1. Distribution of B expressed as percentage of total B in soil

The distribution of fractions of B at initial stage was as follows:

In low P Soil: Residual boron (97.00%)>OM bound B (1.24%)>OX bound B(0.96%)>specifically adsorbed B(0.34%)>readily soluble B(0.18%)

Medium P soil: Residual B (93.10%)>OM bound B (2.50%)>OX bound B (1.90%)>specifically adsorbed B (1.04%)>readily soluble B (0.89%).

High P soil: Residual B (89.00%)>OM bound B (4.00%)>OX bound B (2.73%)>specifically adsorbed B (1.94%)>readily soluble B (1.75%).

Table 8. Fractions of B in different soil samples under study(mg kg^{-1})

Sample No	RS-B	Sp.Ad. B	OX-B	OM-B	Resd-B	Total B
1	0.006	0.12	0.23	0.36	40.48	41.20
2	0.005	0.15	0.51	0.78	45.86	47.30
3	0.11	0.17	0.36	0.42	50.14	51.20
4	0.15	0.23	0.49	0.63	53.80	55.30
5	0.14	0.18	0.69	0.73	53.16	54.90
6	0.16	0.20	0.68	0.89	55.19	57.12
7	0.35	0.36	0.79	1.20	58.60	61.30
8	0.81	0.92	1.36	1.62	61.39	66.10
9	0.19	0.39	1.4	1.91	51.91	55.80
10	0.73	0.61	0.99	1.36	56.61	60.30
11	0.005	0.12	0.39	0.21	39.48	40.90
12	1.02	1.23	1.69	2.39	55.57	61.90
13	1.09	1.03	1.87	2.87	53.64	60.50
14	0.49	0.66	0.87	0.95	53.922	56.90
15	1.34	1.43	1.93	3.12	58.58	66.40
16	0.59	0.63	0.38	0.49	54.01	56.10
17	1.86	1.91	2.9	3.60	61.33	71.60
18	1.23	1.69	2.48	3.91	56.09	65.40

Table 9. Correlation between different fractions of B in soil

		Avail- B	RS-B	Sp.Ad. B	OX-B	OM-B	Resd- B	Total-B
Available B	Pearson Correlation	1						
RS-B	Pearson Correlation	0.975**	1					
Sp.Ad.B	Pearson Correlation	0.955**	0.977**	1				
OX-B	Pearson Correlation	0.914**	0.914**	0.939**	1			
OM-B	Pearson Correlation	0.875**	0.893**	0.927**	0.980**	1		
Resd-B	Pearson Correlation	0.707**	0.682**	0.632**	0.611**	0.586*	1	
Total-B	Pearson Correlation	0.860**	0.847**	0.817**	0.807**	0.786**	0.958**	1

4.4.2.Correlation of different fractions of B in soil

Available B was found to be significantly and positively correlated with readily soluble B (0.98**), specifically adsorbed B (0.96**), oxide bound B (0.91*), organic matter bound B (0.88**), residual B (0.71**) and total P (0.86**). Significant and positive correlation was observed for readily soluble B with specifically adsorbed B (0.97**), oxide bound B (0.91**), organic matter bound B (0.89**), residual B(0.68**), and the total B (0.85**). Specifically adsorbed B was positively correlated with oxide bound B (0.939**), organic matter bound B (0.93**), residual B (0.63**) and total B (0.82**). Oxide bound B had a significant positive correlation with organic matter bound B (0.98**), residual B (0.61**) and total B (0.81**). The organic matter occluded B also correlated positively with residual B and total B which recorded the values (0.59**) and (0.79**) respectively. Residual B was also found to have significant correlation with total B (0.96**).

The fractions which had shown significant correlation with available B were subjected to path analysis and the respective path coefficients, direct and indirect effects of each fraction on available B are presented in Table 10. The data indicated that the direct effect of residual B and oxide bound B were very high and positive where as direct effects of OM bound and residual B were very high and negative. Total B also gave very high direct effects. The indirect effect of all other fraction Sp.Ad., oxide bound, residual and total B through residual B is very high. Sp.Ad.- B failed to have any effects of both direct and indirect through other fractions. The indirect effects of fractions of RS, Sp.Ad.OM bound, and readily soluble boron through oxide bound was either very high or high. The direct effects of OM bound B as well as the indirect effect through OM bound B was very high but negative, similar trends were observed with RS -B also.

Table 10. Path coefficient of fractions of boron with available boron

Variables	RS-B	Sp.Ad.B	OX -B	OM –B	Resd-B	Total-B	corre coefficient
RS-B	**0.65**	0.02	0.40	-0.54	-0.50	0.94	0.975**
Sp.Ad.B	0.63	**0.01**	0.36	-0.49	-0.46	0.90	0.955**
OX -B	0.60	0.03	**0.46**	-0.51	-0.52	0.85	0.914**
OM -B	0.58	0.01	0.45	**-0.42**	-0.62	0.87	0.875**
Resd- B	0.44	0.12	0.31	-0.61	**-0.59**	1.03	0.707**
Total-B	0.54	0.03	0.37	-0.48	-0.70	**1.10**	0.860**

4.5. Fractions of zinc

The data on various fractions as well as the total Zn in the selected soils are given in the table 11.

The exchangeable plus water soluble fraction of Zn varied from 0.002 mg kg^{-1} (sample 12) to 2.60 mg kg^{-1} (sample 9). Specifically adsorbed fraction of Zn ranged from0.07 mg kg^{-1} (sample 15) to 12.20 mg kg^{-1} (sample 9). Specifically adsorbed fraction of Zn in sample 10 recorded the lowest value (0.003 mg kg^{-1}). These selected soils had acid soluble Zn in the range of 0.08 (sample 4) to 1.00 mg kg^{-1} (sample 9).The Mn-occluded Zn fraction in the soils varied from 0.03 mg kg^{-1}(sample 2) to 1.96 mg kg^{-1} (sample 9). The range of OM- occluded fraction in the soils was from 0.04 mg kg^{-1} (sample 10) to1.96 mg kg^{-1} (sample 9).The amorphous Fe occluded fraction was found in the range of 0.20(sample 1) to 2.6 mg kg^{-1}(sample 9). The crystalline Fe occluded fraction of Zn was estimated in the range of 0.36 (sample 11) to 1.50 mg kg^{-1} (sample 9).

Table 11. Fractions of zinc in different soil samples under study(mg kg^{-1})

Sample No	Ws + Exch--Zn	Sp.Ad.--Zn	Acid sol	Mno-Zn	Om-Zn	AmFeO-Zn	Cr-FeO-Zn	Resd.Zn	Total Zn
1	0.08	0.21	0.26	0.06	0.61	0.20	0.80	40.98	43.20
2	0.11	3.20	0.31	0.03	0.53	0.46	1.00	34.16	39.80
3	0.06	0.46	0.23	0.49	0.36	0.86	0.70	45.84	49.00
4	0.03	0.12	0.08	0.29	0.51	0.36	0.70	43.21	45.30
5	0.14	2.50	0.88	0.23	0.44	0.73	0.60	47.68	53.20
6	0.13	1.50	0.18	0.36	0.39	1.00	0.66	40.98	45.20
7	0.09	0.006	0.33	0.93	0.41	9.60	0.66	29.57	41.60
8	0.006	0.93	0.26	0.39	0.66	1.00	0.63	53.02	56.90
9	2.60	12.20	1.00	1.96	2.40	2.60	1.50	61.04	85.30
10	0.003	0.003	0.60	0.66	0.04	0.46	0.70	34.33	36.80
11	0.006	0.05	0.68	0.53	0.08	0.36	0.36	38.53	40.60
12	0.002	0.50	0.54	0.30	0.10	0.96	0.43	42.97	45.80
13	0.19	0.80	0.48	1.50	0.59	0.69	0.46	52.19	56.90
14	0.29	2.00	0.20	0.40	0.77	1.00	0.66	55.98	61.30
15	0.22	0.07	0.44	0.60	0.41	0.76	0.70	56.50	59.70
16	0.64	1.50	0.41	0.03	0.81	1.46	0.20	58.45	63.50
17	0.49	0.44	0.78	0.26	0.79	1.69	0.33	61.32	66.10
18	0.005	0.08	0.61	0.60	0.69	0.33	1.00	56.39	59.70

4.5.1. Distribution of Zn expressed as the percentage of total Zn in soil

In low P soil: Residual Zn (91.6%)> Sp.Ad.(3.00%)>crystalline Fe occluded (1.64%)> Am Fe bound (1.3%)> OM bound (1.04%)> acid soluble (0..68%)>Mn occluded (0.57%> Ws+Exch, (0.2%)

Medium P soil: Residual Zn (86.3%)>Am Fe bound (5.35%)> Sp.Ad. (2.86%)>Mn occluded (1.5%>crystalline Fe occluded (1.36 %)>acid soluble (1.1%)>OM bound (0.91%)> Ws+Exch, (0.55%)

High P soil: Residual Zn (92.8%)>Am Fe bound (1.6%)> Sp.Ad. (1.32%)>OM bound (1.1%)>Mn occluded (0.95%>crystalline Fe occluded (0.92%)>acid soluble (0.79%) Ws+Exch, (0.48%)

Table 12. Correlation between different fractions of soil zinc

		Avail Zn	WS +Exch	Sp.Ad	Acid-sol	MnO-Zn	Om-Zn	AmFeO-Zn	Cr FeO-Zn	Total
Avail. Zn	Pearson Correlation	1								
WS +Exch	Pearson Correlation	0.98**	1							
Sp.Ad.	Pearson Correlation	0.94**	0.93**	1						
Acid-sol	Pearson Correlation	0.48*	0.53*	0.48*	1					
MnO-Zn	Pearson Correlation	0.65**	0.64**	0.58*	0.43	1				
Om-Zn	Pearson Correlation	0.96**	0.93**	0.88**	0.39	0.58*	1			
AmFeO-Zn	Pearson Correlation	0.14	0.16	0.08	0.003	0.32	0.13	1		
Cr FeO-Zn	Pearson Correlation	0.66**	0.56*	0.69**	0.17	0.48*	0.63**	0.05	1	
Total	Pearson Correlation	.776**	.785**	.653**	.470*	.484*	.846**	-.002	.297	1

4.5.2. Correlation between different fractions of soil zinc

Correlation coefficient of available zinc with different zinc fraction is given in Table 12. Available zinc was significantly and positively correlated with all the fractions except Am Fe-occluded zinc. Significant and positive correlation was also observed for total zinc also Ws+Exch. and Sp.Ad. zinc also showed the same trend. Acid soluble fraction was significant and positive only with total zinc while Mn occluded fraction gave significant and positive correlation with Om occluded, crystalline Fe occluded as well as with total Zinc. Ws+Exch, OM occluded zinc was significant positively correlated all the fractions except Am Fe occluded and SPAD fractions of zinc. Am Fe occluded zinc did not give significant correlation with any of the other zinc fractions barring acid soluble, Am Fe occluded fractions. Total zinc was significantly and positively correlated with all the fractions except Am Fe occluded, Crystalline Fe occluded fractions of zinc. Path coefficient was worked for those fractions which were significantly correlated with available zinc and the data presented in Table 13.

Table13. Path coefficient of fractions of zinc with available zinc

Variables	Ws+Exch-Zn	Sp.Ad-Zn	Acid-Sol	MnO–Zn	Om-Zn	CrFeO-Zn	Total zinc	corr. Coef.
Ws+Exch	**0.6**	0.03	0.003	0.02	0.3	0.05	-0.02	0.98**
Sp.Ad	0.59	**0.03**	0.003	0.02	0.28	0.04	-0.02	0.94**
Acid soluble	0.32	0.01	**0.007**	0.01	0.12	0.02	-0.01	0.48**
MnO occluded	0.28	0.02	0.004	**0.18**	0.15	0.05	-0.04	0.65**
OM occluded	0.56	0.02	0.002	0.02	**0.31**	0.06	-0.02	0.96**
Crystalline FeO	0.33	0.02	0.001	0.01	0.2	**0.1**	-0.009	0.66**
Total zinc	0.47	0.02	0.003	0.01	0.27	0.03	**-0.003**	0.77**

The data showed that only Ws+Exch zinc has got very high direct effect 0.60 with available zinc; further the direct effect OM occluded zinc (0.31) was also high. None of the other direct effects were significant however the indirect effects of the fractions through Ws+Exch were very high.

4.6. Pot culture experiment

The experiment was conducted as detailed in Chapter 2. Three soils *viz.*, one each with high, medium, and low P status were included in pot culture experiment. The samples were taken for both soil and plant analysis at two stages of the experimentation at flowering and at harvesting stage.

4.6.1. Electrochemical properties and available nutrient status

The electrochemical properties and available nutrient status of experimental soils at flowering and harvest are presented here under.

4.6.1.1. Soil pH

The influence of applied fertilizers and lime on soil pH at flowering and at harvest is presented in table 14 to 15.

4.6.1.1.1. Flowering stage

The data on pH at flowering stage presented in table 14a and 14b showed that none of the main effects or interaction effects was found to have significant influence on the pH at this stage. However, the pH increased to 6.03 from an initial value of 4.80 in S_1 (low P soil), 6.22 from 4.90 in S_2 (medium P soil) and 6.11 from 5.60 in S_3 (high P soil).

Table 14a. Effect of applied P, Zn and B on pH at flowering

Soils/sources	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	6.03	6.04	6.09	5.97	6.04	6.03	**6.03**
S_2	6.22	6.23	6.27	6.17	6.22	6.23	**6.22**
S_3	6.09	6.13	6.16	6.06	6.11	6.11	**6.11**
Mean	**6.11**	**6.13**	**6.20**	**6.10**	**6.10**	**6.10**	**6.12**

CD S NS CD P NS CD Zn NS CD B NS

Table 14b. Effect of applied Zn and B with applied P on pH at flowering

Sources	Zn_0	Zn_1	B_0	B_1	Mean
P_0	6.20	6.10	6.00	6.20	**6.11**
P_1	6.20	6.10	6.20	6.10	**6.13**
MEAN	**6.20**	**6.10**	**6.10**	**6.10**	**6.12**

CD. P × Zn NS CD. P× B NS

4.6.2.2. Harvesting stage

The data on pH at harvesting stage are given Table 15a and 15b. The data showed that none of the main effects or interaction effects are found to significantly influence the pH at this stage, However , the pH increased to 6.18 from flowering stage 6.03 in S_1 (low P soil) , 6.27 from 6.22 in S_2 (medium P) and 6.27 from 6.11 in S_3 (high P).

Table 15a. Effect of applied P, Zn and B on pH at flowering

Soils/sources	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	6.20	6.16	6.22	6.15	6.20	6.17	**6.18**
S_2	6.27	6.26	6.35	6.18	6.31	6.22	**6.27**
S_3	6.31	6.22	6.23	6.30	6.30	6.23	**6.27**
Mean	**6.26**	**6.21**	**6.27**	**6.21**	**6.27**	**6.21**	**6.24**

CD S　　CD P NS　　CD Zn NS　　CD B NS

Table 15b. Effect of applied Zn and B with applied P on pH at harvest

sources	Zn_0	Zn_1	B_0	B_1	Mean
P_0	6.31	6.30	6.22	6.32	**6.26**
P_1	6.32	6.18	6.31	6.12	**6.21**
Mean	**6.27**	**6.21**	**6.27**	**6.21**	**6.23**

CD. P × Zn NS　　CD. P ×B NS

4.6.1.2. Electrical conductivity (EC)

The influence of main effects of P, Zn, B and interaction effects of zinc and boron with phosphorus on electrical conductivity at flowering and harvesting stage are presented in table 16 to 17.

4.6.1.2.1. Flowering stage

The data on EC at flowering stage are presented in the table 16a and 16b. The main effects of doses of P, Zn, B and the types of soil were not found to have any effect on EC.

Table 16a. Effect applied P, Zn and B on EC at flowering (dSm^{-1})

Soils/sources	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	0.12	0.09	0.11	0.10	0.09	0.12	**0.10**
S_2	0.11	0.09	0.10	0.10	0.09	0.11	**0.10**
S_3	0.12	0.09	0.10	0.10	0.09	0.11	**0.10**
Mean	**0.12**	**0.09**	**0.10**	**0.10**	**0.09**	**0.11**	**0.10**

CD S NS CD P NS CD Zn NS CD B NS

However, the interaction effects of combined application of P and B (P_1B_1) and P and Zn (P_1Zn_1) were found to increase ($0.13 dSm^{-1}$) the EC at this stage when compared with treatment without any of these elements.

Table 16b. Effect of applied Zn and B with applied P on EC at flowering (dSm^{-1})

Sources	Zn_0	Zn_1	B_0	B_1	Mean
P_0	0.11	0.09	0.11	0.13	**0.12**
P_1	0.08	0.13	0.08	0.10	**0.09**
Mean	**0.10**	**0.10**	**0.09**	**0.11**	**0.10**

CD. P × Zn 0.03 CD. P × B 0.03

4.6.1.2.2. Harvesting stage

EC at harvesting stage are given table 17a and 17b. The main effects of doses of P, Zn,B and the type of soil were found to have no effect on EC.

Table 17a. Effect of applied P, Zn and B on EC at harvest (dSm^{-1})

Soils/sources	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	0.12	0.10	0.12	0.10	0.10	0.13	**0.11**
S_2	0.13	0.10	0.12	0.11	0.11	0.12	**0.12**
S_3	0.12	0.17	0.12	0.17	0.12	0.19	**0.15**
Mean	**0.12**	**0.12**	**0.12**	**0.13**	**0.11**	**0.13**	**0.12**

CD S NS CD P NS CD Zn NS CD B NS

However, the interaction effects of combined application of P and B (P_1B_1) and P and Zn (P_1Zn_1) were found to increase EC to a value of (0.14 dSm^{-1}) the EC at this stage.

Table 17b. Effect of applied Zn and B with applied P on EC at harvest (dSm^{-1})

sources	Zn_0	Zn_1	B_0	B_1	Mean
P_0	0.14	0.11	0.12	0.12	**0.12**
P_1	0.09	0.14	0.09	0.14	**0.12**
Mean	**0.12**	**0.13**	**0.11**	**0.13**	**0.12**

CD. P × Zn 0.02 CD. P ×B 0.02

4.6.1.3. Organic carbon

The influence of main effects of P, Zn, B and interaction effects of zinc and boron with phosphorus on organic carbon at flowering and harvesting stage are presented in table 18to 19

4.6.1.3.1 Flowering stage

Table 18a and 18b showed the organic carbon (OC) at flowering stage. The main effects of doses of P, Zn, B and the type of soil did not influence the OC at this stage.

Table 18a. Effect of applied P, Zn and B on OC at flowering (%)

Soils/sources	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	1.31	1.34	1.38	1.27	1.35	1.31	**1.33**
S_2	1.38	1.46	1.44	1.41	1.47	1.38	**1.42**
S_3	1.35	1.40	1.40	1.34	1.41	1.33	**1.37**
Mean	**1.35**	**1.40**	**1.41**	**1.34**	**1.41**	**1.34**	**1.37**

CD S NS CD P NS CD Zn NS CD B NS

Among the interaction effects, application of P without Zn (P_1Zn_0) recorded the highest OC (1.46%) when compared to all the other treatment combinations of P and Zn. Application of phosphorus with zinc (P_1Zn_1) recorded the lowest organic carbon (1.34%) compared to other treatments and both were significantly different. Application of P and B showed the highest OC (1.43%) than the treatment without both P and B (P_0B_0).

Table 18b. Effect of applied Zn and B with applied P on OC at flowering (%)

Sources	Zn_0	Zn_1	B_0	B_1	Mean
P_0	1.36	1.34	1.43	1.27	**1.35**
P_1	1.46	1.34	1.39	1.41	**1.40**
Mean	**1.41**	**1.34**	**1.41**	**1.34**	**1.37**

CD. P× Zn 0 .11 **CD. P ×B 0.11**

4.6.1.3.2. Harvesting stage

The OC estimated at harvesting stage are given table 19a and 19b. The main effects of doses of P, Zn and B did not influence the OC at this stage. The soil with high P (S_3) recorded the highest OC at this stage (3.20%) which is significantly different from that of other soil. The interaction effects were not significant.

Table 19a. Effect of applied P, Zn and B on OC at harvest (%)

Soils/sources	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	1.00	0.99	1.00	0.99	0.99	1.00	1.00
S_2	0.94	0.89	0.93	0.90	0.90	0.93	0.92
S_3	3.22	3.19	3.17	3.23	3.20	3.20	3.20
Mean	**1.72**	**1.69**	**1.70**	**1.71**	**1.70**	**1.71**	**1.70**

CD S 0.3 CD P NS CD Zn NS CD B NS

Table19b. Effect of applied Zn and B with applied P on OC at harvest (%)

sources	Zn_0	Zn_1	B_0	B_1	Mean
P_0	1.72	1.72	1.74	1.70	**1.72**
P_1	1.68	1.70	1.66	1.72	**1.69**
Mean	**1.70**	**1.71**	**1.70**	**1.71**	**1.71**

CD. P ×Zn NS **CD. P× B NS**

4.6.1.4. Available phosphorus

The influence of main effects of P, Zn, B and interaction effects of zinc and boron with phosphorus on available phosphorus at flowering and harvesting stage are presented in table 20 to 21.

4.6.1.4.1. Flowering stage

In comparison with the initial levels, the available P increased from 3.9 kg ha^{-1} to 26.08 kg ha^{-1} in S_1, 17 kg ha^{-1} to 39.18 kg ha^{-1} in S_2 and decreased in S_3 from 52.70 kg ha^{-1} to 20.26 kg ha^{-1} .The data on available P is presented in the table 20a and 20b.The data show that the treatment without application of P (P_0) recorded the highest available P (31.5 kg ha^{-1}). Application of Zn was found to decrease the available P (24.59 kgha^{-1}) in comparison to the treatment without Zn (32.33 kg ha^{-1}). Application of B was also found to reduce the available P (26.98 kg ha^{-1}) in comparison to the treatment without B (30.24 kg ha^{-1}). The soil with medium P (S_2) recorded the highest available P content at this stage (39.18 kg ha^{-1}) which is significantly different from that on other soils.

Table 20a. Effect of applied P, Zn and B on available P at flowering (kg ha^{-1})

Soils/sources	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	29.85	21.98	32.43	19.43	26.80	26.04	**26.08**
S_2	43.45	34.93	45.18	33.21	42.80	35.51	**39.18**
S_3	21.34	19.18	19.40	21.13	21.13	19.40	**20.26**
Mean	**31.54**	**25.36**	**32.33**	**24.59**	**30.24**	**26.98**	**28.51**

CD S 1.15 CD P 0.90 CD Zn 0.90 CD B 0.90

Among the interaction effects, the treatment without the application of P and Zn (P_0Zn_0) recorded the highest available P (36.88 $kgha^{-1}$) in comparison to all the other treatment combinations. Application of P with Zn (P_1Zn_1) recorded the lowest available P (22.84 $kgha^{-1}$) at this stage. The treatment without application P and B (P_0B_0) recorded the higher available P (32.27 $kgha^{-1}$) than the treatment P with B (P_1B_1) which is significantly different.

Table 20b. Effect of applied Zn and B with applied P on available P at flowering (kg ha^{-1})

Sources	Zn_0	Zn_1	B_0	B_1	Mean
P_0	36.88	26.22	32.27	31.09	**31.54**
P_1	27.80	22.84	28.41	23.12	**25.36**
Mean	**32.33**	**24.59**	**30.24**	**26.98**	**28.36**

CD. P ×Zn 1.58 CD. P ×B 1.58

4.6.1.4.2. Harvesting stage

In comparison with flowering stage the available P decreased from 26.08 $kgha^{-1}$ to 17.08 $kgha^{-1}$ in S1, 17.08 $kgha^{-1}$ to 14.98 $kgha^{-1}$ in S2 and 20.26 $kgha^{-1}$ to 11.52 $kgha^{-1}$ in S3.The data on the available P is presented in the table 21a and 21b .The data showed that the treatment with P (P_1) recorded the highest available P (15.67 $kgha^{-1}$). Application of Zn was found to decrease available P (13.35 $kgha^{-1}$) in comparison to the treatment without Zn (16.29 $kgha^{-1}$). Application of B also was also found to decrease the available P (13.04 $kgha^{-1}$) in comparison to the treatment without B (16.60 $kgha^{-1}$). The soil with low P (S_1) recorded the highest available P content at this stage (17.84 $kgha^{-1}$) which is significantly different from that of other soil.

Table 21a. Effect of applied P, Zn and B on available P at harvest (kg ha^{-1})

Soils/sources	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	12.93	22.75	16.71	18.98	20.17	15.51	**17.84**
S_2	16.00	14.08	18.58	11.50	19.92	10.16	**15.04**
S_3	12.94	10.19	13.57	9.57	9.71	13.43	**11.57**
Mean	**13.96**	**15.67**	**16.29**	**13.35**	**16.60**	**13.04**	**14.82**

CD S 0.78 CD P 0.66 CD Zn 0.66 CD B 0.66

Among the interaction effects, the treatment without the application of P and Zn (P_0Zn_0) recorded the highest available P (16.14 $kgha^{-1}$) in comparison to the treatment with the application of P and Zn (P_1Zn_1) recorded the lowest available P (14.91 $kgha^{-1}$) at this stage. The treatment with P and without B (P_1B_0) recorded higher available P (17.93 $kgha^{-1}$) than the treatment P with B (P_1B_1) which is significantly different.

Table 21b. Effect of applied Zn and B with applied P on available P at harvest (kg ha^{-1})

sources	Zn_0	Zn_1	B_0	B_1	Mean
P_0	16.14	11.79	15.26	12.66	**13.96**
P_1	16.43	14.91	17.93	13.41	**15.67**
Mean	**16.29**	**13.35**	**16.60**	**13.04**	**14.82**

CD. P ×Zn 0.93 **CD. P× B 0.93**

4.6.1.5. Available Potassium

The influence of main effects of P, Zn, B and interaction effects of zinc and boron with phosphorus on available potassium at flowering and harvesting stage are presented in Table 22 to 23.

4.6.1.5.1. Flowering stage

The data on available K at flowering stage are presented table 22a and 22b. The data showed that the treatment with P decreased the available K (127.33 kg ha^{-1}) when compared to the treatment without P (158.10 kg ha^{-1}). It was also observed that in treatment where Zn was applied, available K decreased (125.11 kg ha^{-1}) significantly in comparison to the treatment without Zn (160 kg ha^{-1}).Main effects of B and types of soil did not influence the available K status of the soil at this stage.

Table 22a. Effect of applied P, Zn and B on available K at flowering (kg ha^{-1})

Soils/sources	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	158.00	127.00	161.80	123.14	146.9	138.10	**142.49**
S_2	158.20	127.68	158.70	127.10	143.30	142.50	**142.91**
S_3	158.10	127.30	160.30	125.10	145.10	140.30	**142.70**
Mean	**158.10**	**127.33**	**160.00**	**125.11**	**145.20**	**140.30**	**142.17**

CD S NS CD P 24.4 CD Zn 24.4 CD B NS

Among the interaction effects, the treatment without P and Zn (P_0Zn_0) recorded significantly higher (180kg ha^{-1}). Available K in comparison with all the other treatment combinations of P and Zn. The lowest available K (114.10 kgha^{-1}) was recorded in the treatment where both P and Zn (P_1Zn_1) was applied.

Table 22b. Effect of applied Zn and B with applied P on available K at flowering (kg ha^{-1})

Sources	Zn_0	Zn_1	B_0	B_1	Mean
P_0	180.00	136.00	155.40	160.80	**158.10**
P_1	140.00	114.10	135.00	119.80	**127.33**
Mean	**160.00**	**125.11**	**145.20**	**140.30**	**142.64**

CD. P× Zn 42.7 CD. P ×B NS

4.6.1.5.2. Harvesting stage

Available K estimated at harvesting stage are given in table 23a and 23b.The data showed that the treatment with P decreased the available K (98.10 $kgha^{-1}$) when compared to the treatment without P (120.3 $kgha^{-1}$). The main effects of doses of Zn, B and types of soil did not influence the available K at this stage.

Table 23a. Effect of applied P, Zn and B on available K at harvest (kg ha^{-1})

Soils/sources	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	125.3	94.80	117.20	103.00	116.60	103.50	**110.07**
S_2	117.2	96.60	114.90	98.90	113.40	100.50	**106.92**
S_3	118.4	102.90	113.50	107.70	115.30	105.90	**110.62**
Mean	**120.30**	**98.10**	**115.20**	**103.20**	**115.10**	**103.30**	**109.20**

CD S NS CD P 15.5 CD S Zn NS CD S B NS

Among the interaction effects, the treatment Zn without P (P_0Zn_0) was significantly higher (125.4 $kgha^{-1}$) than P with Zn (P_1Zn_1). The treatment without P and B recorded the highest available K (134.2 $kgha^{-1}$) which is significantly higher than all other treatment combinations of P and B.

Table 23b. Effect of applied Zn and B with applied P on available K at harvest (kg ha^{-1})

Sources	Zn_0	Zn_1	B_0	B_1	Mean
P_0	125.40	115.20	134.80	106.30	**120.30**
P_1	105.00	91.20	95.80	100.30	**98.10**
Mean	**115.20**	**103.20**	**115.10**	**103.30**	**109.25**

CD. P ×Zn 22.05 CD. P ×B 22.05

4.6.1.6. Available Calcium

The influence of main effects of P, Zn, B and interaction effects of zinc and boron with phosphorus on available calcium at flowering and harvesting stage are presented in table 24 to 25.

4.6.1.6.1. Flowering stage

The available Ca is presented in the Table 24a and 24b. The data showed that none of the main effects or interactions were significant.

Table 24a.Effect of applied P, Zn and B on available Ca at flowering (mg kg^{-1})

Soils/sources	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	332.20	355.30	344.00	343.60	337.00	350.60	**343.78**
S_2	343.80	364.00	353.20	354.50	339.30	368.30	**353.85**
S_3	331.60	356.30	347.30	340.60	344.20	343.60	**343.93**
Mean	**335.87**	**358.53**	**348.17**	**346.23**	**340.17**	**354.17**	**347.19**

CD S NS CD P NS CD Zn NS CD B NS

Table 24b. Effect of applied Zn and B with applied P on available Ca at flowering (mg kg^{-1})

Sources	Zn_0	Zn_1	B_0	B_1	Mean
P_0	341.70	330.00	315.70	356.00	**335.87**
P_1	354.60	362.40	364.60	352.40	**358.53**
Mean	**348.17**	**346.23**	**340.17**	**354.17**	**347.18**

CD. P ×Zn NS CD. P ×B NS

4.6.1.6.2. Harvesting stage

The available Ca is presented table 25 and 25b. The data showed that application of P was found to increase the available Ca (155.5 mg kg^{-1}) in comparison the treatment without P (129.90 mg kg^{-1}) which is significantly different. The main effects of doses of Zn, B, types of soils and interaction effects were not significant.

Table 25a. Effect of applied P, Zn and B on available Ca at harvest (mg kg^{-1})

Soils/sources	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	141.40	157.10	148.40	153.10	155.20	146.30	**145.75**
S_2	136.11	155.20	144.60	147.50	148.30	143.80	**145.92**
S_3	139.20	154.20	145.50	148.10	148.00	144.00	**146.50**
Mean	**140.23**	**155.50**	**146.17**	**149.57**	**150.50**	**144.70**	**146.06**

CD S NS CD P NS CD S Zn NS CD S B NS

Table 25b. Effect of applied Zn and B with applied P on available Ca at harvest (mg kg^{-1})

Sources	Zn_0	Zn_1	B_0	B_1	Mean
P_0	142.20	138.20	138.00	142.50	**140.23**
P_1	150.20	160.90	163.50	146.60	**155.50**
Mean	**146.17**	**149.57**	**150.50**	**144.70**	**144.70**

CD. P ×Zn NS CD. P ×B NS

4.6.1.7. Available magnesium

The influence of main effects of P, Zn, B and interaction effects of zinc and boron with phosphorus on available magnesium at flowering and harvesting stage are presented in table 26 to 27.

4.6.1.7.1. Flowering stage

The available magnesium estimated at flowering stage is given in the table 26a and 26b. The main effects of doses of P, Zn, B and the types of soil did not influence the available Mg at this stage.

Table 26a. Effect of applied P, Zn and B on available Mg at flowering (mg kg^{-1})

Soils/sources	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	98.60	82.70	87.40	94.00	100.60	80.80	**90.68**
S_2	98.60	82.70	87.40	94.00	100.60	80.80	**90.68**
S_3	97.40	87.26	90.20	94.40	102.40	82.20	**92.31**
Mean	**98.20**	**84.22**	**88.33**	**94.13**	**101.20**	**81.27**	**91.23**

CD S NS CD P NS CD Zn NS CD B NS

The interaction effect of P with Zn was not significant. The treatment without the application of P and B (P_0B_0) recorded the highest available Mg (109.20mg kg^{-1}) and the treatment with both P and B (P_1B_1) recorded the lowest available Mg (75.60 mg kg^{-1}) at this stage.

Table 26b. Effect of applied Zn and B with applied P on available Mg at flowering (mg kg^{-1})

Sources	Zn_0	Zn_1	B_0	B_1	Mean
P_0	99.10	97.30	109.20	87.20	**98.20**
P_1	77.60	90.92	93.20	75.60	**84.22**
Mean	**88.33**	**94.13**	**101.20**	**81.27**	**91.27**

CD. P ×Zn NS **CD. P× B 30.9**

4.6.1.7.2. Harvesting stage

The available magnesium estimated at harvesting stage is given in the table 27a and 27b. The main effects of doses of P, B and the types of soil did not influence the available magnesium at this stage. Application of Zn was found to decrease the available Mg (20.95) in comparison to the treatment without the application of Zn (23.59) which is significantly different. None of the interaction effects were significant.

Table 27a. Effect of applied P, Zn and B on available Mg at harvest (mg kg^{-1})

Soils/sources	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	21.5	20.70	22.01	20.20	20.89	21.43	**21.12**
S_2	23.7	22.90	25.03	21.60	21.76	24.88	**23.31**
S_3	22.12	22.73	23.73	21.13	21.50	23.36	**22.43**
Mean	**22.44**	**22.11**	**23.59**	**20.98**	**21.38**	**23.22**	**22.29**

CD S NS **CD P NS** **CD S Zn 1.46** **CD S B NS**

Table 27b. Effect of applied Zn and B with applied P on available Mg at harvest (mg kg^{-1})

Sources	Zn_0	Zn_1	B_0	B_1	Mean
P_0	23.80	22.08	21.30	23.56	**22.44**
P_1	23.36	20.94	21.42	22.89	**22.11**
Mean	**23.59**	**20.98**	**21.38**	**23.23**	**22.29**

CD. P ×Zn NS **CD. P ×B NS**

4.6.1.8. Available sulphur

The influence of main effects of P, Zn, B and interaction effects of zinc and boron with phosphorus on available sulphur at flowering and harvesting stage are presented in table 28 to 29.

4.6.1.8.1. Flowering stage

Data in the table 28a and 28b show the available S content at flowering stage. Main effect of P, B and types of soil were not having significant influence on the available sulphur. Application of Zn was found to increase the available S (47.4 mgkg^{-1}) in comparison to the treatment without Zn (32.3 mg kg^{-1}).

Table 28a. Effect of applied P, Zn and B on available S at flowering (mg kg^{-1})

Soils/sources	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	43.20	40.00	34.00	49.20	42.00	41.40	**41.63**
S_2	37.30	38.40	31.40	44.30	37.70	38.00	**37.85**
S_3	41.30	38.90	31.50	48.70	40.30	40.00	**40.12**
Mean	**40.60**	**39.10**	**32.30**	**47.40**	**40.00**	**39.80**	**39.87**

CD S NS CD P NS CD Zn 5.2 CD B NS

Among the interaction effects, the treatment of Zn without P (P_0Zn_1) recorded significantly higher available S while application of P without Zn (P_1Zn_0) recorded the lowest available S (31.30 mg kg^{-1}) at this stage.

Table 28b. Effect of applied Zn and B with applied P on available S at flowering (mg kg^{-1})

Sources	Zn_0	Zn_1	B_0	B_1	Mean
P_0	33.30	48.00	39.00	42.40	**40.60**
P_1	31.30	47.00	41.00	37.20	**39.10**
Mean	**32.30**	**47.40**	**40.00**	**39.80**	**39.91**

CD. P ×Zn 9.04 **CD. P ×B NS**

4.6.1.8.2. Harvesting stage

Data in the table 29a and 29b showed the available sulphur at harvesting stage. Main effects of P, B and types of soil were not significant. Application of Zn was found to increase the available S (42.47 mg kg^{-1}) in comparison to the treatment without Zn (29.38 mg $kg^{-1)}$

Table 29a. Effect of applied P, Zn and B on available S at harvest (mg kg^{-1})

Soils/sources	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	39.33	37.21	30.98	45.56	38.73	37.81	**38.27**
S_2	32.9	34.20	27.78	39.37	33.50	33.65	**33.57**
S_3	36.14	35.71	29.38	42.46	36.11	35.73	**35.92**
Mean	**36.12**	**35.71**	**29.38**	**42.46**	**36.11**	**35.73**	**35.92**

CD S NS **CD P NS** **CD S Zn 4.98** **CD S B NS**

Among the interaction effects, the treatment of Zn without P (P_0Zn_1) recorded significantly highest available S (42.78 mg kg^{-1}) while application of P without Zn (P_1Zn_0) recorded the lowest available S (29.6 mg kg^{-1}) at this stage.

Table 29b. Effect of applied Zn and B with applied P on available S at harvest (mg kg^{-1})

Sources	Zn_0	Zn_1	B_0	B_1	Mean
P_0	29.50	42.78	34.95	37.32	**36.12**
P_1	29.26	42.15	37.27	34.14	**35.71**
Mean	**29.38**	**42.46**	**36.11**	**35.73**	**35.92**

CD. P ×Zn 8.7 CD. P ×B NS

4.6.1.9. Available Iron

The influence of main effects of P, Zn, B and interaction effects of zinc and boron with phosphorus on available iron at flowering and harvesting stage are presented in table 30 to 31.

4.6.1.9.1. Flowering stage

The data on the available Fe at flowering stage is presented in the table 30a and 30b. From the data, it is clear that the main effects of doses of P, Zn, B and the types of soils did not influence the available iron at this stage.

Table 30a. Effect of applied P, Zn and B on available Fe at flowering (mg kg^{-1})

Soils/sources	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	14.81	13.00	14.80	12.97	13.00	14.76	**13.89**
S_2	17.00	13.97	17.21	13.84	14.91	16.13	**15.51**
S_3	16.11	13.64	16.41	13.39	13.99	15.82	**14.89**
Mean	**15.96**	**13.54**	**16.14**	**13.40**	**13.97**	**15.57**	**14.76**

CD S NS CD P NS CD Zn NS CD B NS

Among the interaction effects, the treatment of P with Zn (P_1Zn_1) was found to be significant in reducing the available Fe content (12.10 mg kg^{-1}) in comparison to the treatment without application of P and Zn (P_0Zn_0) which recorded a value of 17.37 mg kg^{-1}. Application of B without P (P_0B_1) was found to significantly increase the available Fe content (16.20 mg kg^{-1}) when compared with all the other treatment combinations of P and B.

Table 30b. Effect of applied Zn and B with applied P on available Fe at flowering (mg kg^{-1})

Sources	Zn_0	Zn_1	B_0	B_1	Mean
P_0	17.37	14.54	16.00	16.20	**15.96**
P_1	14.98	12.10	11.90	14.86	**13.54**
Mean	**16.15**	**13.37**	**13.95**	**15.53**	**14.75**

CD. P ×Zn 2.2 **CD. P ×B 2.2**

4.6.1.9.2. Harvesting stage

The data on available Fe at harvesting stage is presented in the table 31a and 31b. From the data it is clear that main effects of doses of P, Zn ,B and the types of soil did not influence the available Fe at this stage.

Table 31a. Effect of applied P, Zn and B on available Fe at harvest (mg kg^{-1})

Soils/sources	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	30.80	36.63	37.22	30.22	36.68	30.77	**33.72**
S_2	30.47	36.32	35.17	31.62	34.72	32.07	**33.40**
S_3	31.56	35.79	37.05	30.30	34.38	32.96	**33.67**
Mean	**30.95**	**36.25**	**36.48**	**30.71**	**35.26**	**31.93**	**33.60**

CD S NS **CD P NS** **CD S Zn NS** **CD S B NS**

Among the interaction effects, the treatment where P was applied with Zn (P_1Zn_1) was found to have significant effect in reducing the available Fe content (30.07 mg kg^{-1}) when compared to the treatment P without Zn (P_1Zn_0) which recorded a value of 42.42 mg kg^{-1}

Table 31b. Effect of applied Zn and B with applied P on available Fe at harvest (mg kg^{-1})

Sources	Zn_0	Zn_1	B_0	B_1	Mean
P_0	30.53	31.36	31.55	30.34	**30.95**
P_1	42.42	30.07	38.98	33.53	**36.25**
Mean	**36.48**	**30.71**	**35.26**	**31.93**	**33.60**

CD. P× Zn 11.9 **CD. P× B NS**

4.6.1.10. Available manganese

The influence on main effects of P, Zn, B and interaction effects of zinc and boron with phosphorus on available manganese at flowering and harvesting stage are presented in table 32 to 33.

4.6.1.10.1. Flowering stage

The available manganese estimated at flowering stage is given in the table 32a and 32b. The data revealed that the main effects of doses of Zn, B and the types of soil were not significant. Application of P was found to decrease the available Mn (24.80 mg kg^{-1}) when compared to the treatment without P which recorded a value of 35.65 mg kg^{-1} which was significantly different.

Table32a. Effect of applied P, Zn and B on available Mn at flowering (mg kg^{-1})

Soils/sources	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	35.40	24.00	29.09	30.40	26.77	32.77	**29.75**
S_2	36.00	25.00	30.20	30.80	27.60	33.47	**30.51**
S_3	35.51	25.41	29.80	30.85	27.96	32.69	**30.37**
Mean	**35.65**	**24.80**	**29.70**	**30.68**	**27.44**	**32.98**	**30.21**

CD S NS CD P 6.08 CD Zn NS CD B NS

Among the interaction effects, application of P with Zn (P_1Zn_1) showed significant reduction in available Mn (24.62 mg kg^{-1}) in comparison to the treatment without the application of P and Zn (P_0Zn_0). Application of B without P (P_0B_1) was found to have significantly higher available Mn (38.42 mg kg^{-1}) than all the other treatment combinations of P and B. Application of P without B (P_1B_0) recorded the lowest available Mn content at this stage.

Table 32b. Effect of applied Zn and B with applied P on available Mn at flowering (mg kg^{-1})

Sources	Zn_0	Zn_1	B_0	B_1	Mean
P_0	34.51	36.79	32.88	38.42	**35.65**
P_1	24.89	24.62	21.97	27.54	**24.80**
Mean	**29.70**	**30.68**	**27.44**	**32.98**	**30.20**

CD. P ×Zn 9.8 CD. P× B 9.8

4.6.1.10.2. Harvesting stage

The available manganese estimated at harvesting stage are given in the table 33a and 33b .The data revealed that the application of P was found to have significant effect in reducing the available Mn content (92.20 mg kg^{-1}) in comparison with the treatment without P (134.59 mg kg^{-1}) . The main effects of doses of Zn, B and the types of soil were not significant.

Table 33a. Effect of applied P, Zn and B on available Mn at harvest (mg kg^{-1})

Soils/sources	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	135.4	85.83	105.86	115.33	104.20	117.17	**110.63**
S_2	133.83	98.58	114.33	118.08	118.25	114.16	**116.21**
S_3	134.59	92.20	110.09	116.70	111.14	115.66	**113.40**
Mean	**134.59**	**92.20**	**110.09**	**116.70**	**111.20**	**115.66**	**113.41**

CD S NS CD P 26.4 CD S Zn NS CD S B NS

Among the interaction effects, application of P with Zn (P_1Zn_1) recorded significant reduction in available Mn (79.58 mg kg^{-1}) in comparison to the treatment Zn without P (P_0Zn_1) (34.51mg kg^{-1}). Application of B without P (P_0B_1) was found to have significantly higher available Mn (158.0 mg kg^{-1}) than all other treatment combinations of P and B. Application of P with B (P_1B_1) recorded the lowest available Mn content at this stage.

Table 33b. Effect of applied Zn and B with applied P on available Mn at harvest (mg kg^{-1})

sources	Zn_0	Zn_1	B_0	B_1	Mean
P_0	115.36	153.83	111.19	158.00	**134.59**
P_1	104.83	79.58	111.08	73.33	**92.20**
Mean	**110.09**	**116.70**	**111.20**	**115.66**	**113.40**

CD. P× Zn 45.24 **CD. P ×B 45.24**

4.6.1.11. Available zinc

The influence on main effects of P, Zn, B and interaction effects of zinc and boron with phosphorus on available zinc at flowering and harvesting stage are presented in the table 36 to 37.

4.6.1.11.1. Flowering stage

The data on the available Zn at flowering stage are presented in the Table34a and 35b. From the data it is clear that none of the main effects or interaction effects are found to have influence on available zinc at this stage.

Table 34a. Effect of applied P, Zn and B on available Zn at flowering (mg kg^{-1})

Soils/sources	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	7.57	7.84	7.52	7.89	7.52	7.89	**7.70**
S_2	8.19	8.37	7.96	8.61	7.79	8.77	**8.28**
S_3	7.98	8.23	7.97	8.41	7.88	8.33	**8.13**
Mean	**7.91**	**8.14**	**7.82**	**8.30**	**7.73**	**8.33**	**8.04**

CD S NS CD P NS CD Zn NS CD B NS

Table 34b. Effect of applied Zn and B with applied P on available Zn at flowering (mg kg^{-1})

Sources	Zn_0	Zn_1	B_0	B_1	Mean
P_0	7.99	7.84	7.41	8.42	**7.91**
P_1	7.71	8.77	8.05	8.24	**8.14**
Mean	**7.82**	**8.30**	**7.73**	**8.33**	**8.03**

CD. P ×Zn NS **CD. P ×B NS**

4.6.1.11.2. Harvesting stage

The data on Available Zn at harvesting stage are presented in the table 37a and 37b. From the data it is clear that none of the main effects or interaction effects are *significant.*

Table 35a. Effect of applied P, Zn and B on available Zn at harvest (mg kg^{-1})

Soils/sources	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	40.67	33.65	45.53	28.79	30.70	43.62	**37.16**
S_2	32.65	31.18	38.18	25.65	30.55	33.28	**31.92**
S_3	36.63	32.42	41.85	27.22	30.62	38.45	**34.53**
Mean	**36.65**	**32.42**	**41.85**	**27.22**	**30.62**	**38.45**	**34.54**

CD S NS **CD P NS** **CD S Zn NS** **CD S B NS**

Table 35b. Effect of applied Zn and B with applied P on available Zn at harvest (mg kg^{-1})

Sources	Zn_0	Zn_1	B_0	B_1	Mean
P_0	49.61	23.71	37.97	35.35	**36.65**
P_1	34.09	30.74	23.28	41.55	**32.42**
Mean	**41.85**	**27.22**	**30.62**	**38.45**	**34.54**

CD. P ×Zn NS **CD. P× B NS**

4.6.1.12. Available copper

The influence on main effects of P, Zn, B and interaction effects of zinc and boron with phosphorus on available copper at flowering and harvesting stage are presented in table 34 to 35.

4.6.1.12.1. Flowering stage

The data on the available Cu at flowering stage is given in the table 36a and 36b.The data showed that none of the main effects or interaction effects are significant.

Table 36a. Effect of applied P, Zn and B on available Cu at flowering (mg kg^{-1})

Soils/sources	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	6.70	6.53	6.39	6.82	6.55	6.66	**6.60**
S_2	6.78	6.82	6.60	7.10	6.71	6.90	**6.82**
S_3	6.76	6.85	6.59	7.03	6.69	6.93	**6.81**
Mean	**6.74**	**6.73**	**6.53**	**6.98**	**6.65**	**6.83**	**6.74**

CD S NS CD P NS CD Zn NS CD B NS

Table 36b. Effect of applied Zn and B with applied P on Cu at flowering(mg kg^{-1})

Sources	Zn_0	Zn_1	B_0	B_1	Mean
P_0	6.63	6.95	6.77	6.68	**6.74**
P_1	6.46	7.05	6.53	7.00	**6.73**
Mean	**6.53**	**6.98**	**6.65**	**6.83**	**6.74**

CD. P ×Zn NS CD. P ×B NS

4.6.1.12.2. Harvesting stage

The data on available Cu at harvesting stage are given in the Table 37a and 37b. The main effects of doses of P, Zn, B, types of soils and interaction effects were not significant.

Table 37a. Effect of applied P, Zn and B on available Cu at harvest (mg kg^{-1})

Soils/sources	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	5.2	8.57	6.89	6.88	8.38	5.39	**6.89**
S_2	5.46	10.67	7.10	9.04	9.01	7.12	**8.07**
S_3	5.33	9.62	6.99	7.96	8.69	6.26	**7.48**
MEAN	**5.33**	**9.62**	**6.99**	**7.96**	**8.69**	**6.26**	**7.48**

CD S NS CD P NS CD S Zn NS CD S B NS

Table 37b. Effect of applied Zn and B with applied P on Cu at harvest (mg kg^{-1})

Sources	Zn_0	Zn_1	B_0	B_1	Mean
P_0	5.52	5.13	5.24	5.42	5.33
P_1	8.45	10.79	12.14	7.10	9.62
Mean	6.99	7.96	8.69	6.26	7.48

CD. P ×Zn NS **CD. P ×B NS**

4.6.1.13. Available boron

The influence on main effects of P, Zn, B and interaction effects of zinc and boron with phosphorus on available zinc at flowering and harvesting stage are presented in Table 38 to 39.

4.6.1.13.1. Flowering stage

The available B estimated at the flowering stage is given in the Table 38a and 38b. The data revealed that the main effects of doses of, B and the types of soil were not significant. Application of P was found to decrease the available B (0.67 mg kg^{-1}) when compared to the treatment without P which has a value of 0.79 mg kg^{-1} which is significantly higher. However, the treatment with Zn has increased the available B (0.80 mg kg^{-1}) when compared to the treatment without Zn (0.67 mg kg^{-1}).

Table 38a. Effect of applied P, Zn and B on available B at flowering (mg kg^{-1})

Soils/sources	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	0.76	0.62	0.65	0.74	0.65	0.73	**0.69**
S_2	0.83	0.72	0.69	0.86	0.74	0.81	**0.77**
S_3	0.79	0.67	0.67	0.80	0.70	0.77	**0.73**
Mean	**0.79**	**0.67**	**0.67**	**0.80**	**0.70**	**0.77**	**0.73**

CD S NS CD P 0.11 CD Zn 0.11 CD B NS

Among the interaction effects, application of Zn without P (P_0Zn_1) recorded higher available B (0.97 $mgkg^{-1}$) than the treatment with the application of P with Zn (P_1Zn_1) (0.62 $mgKg^{-1}$). Application of B without P recorded the higher available B (0.91 $mgkg^{-1}$) than the treatment with both P and B (P_1B_1), which was significantly different and recorded a value of 0.63 mg kg^{-1}.

Table 38b. Effect of applied Zn and B with applied P on B at flowering (mg kg^{-1})

Sources	Zn_0	Zn_1	B_0	B_1	Mean
P_0	0.62	0.97	0.68	0.91	**0.79**
P_1	0.73	0.62	0.71	0.63	**0.67**
Mean	**0.67**	**0.80**	**0.70**	**0.77**	**0.73**

CD. P ×Zn 0.18 CD. P ×B 0.18

4.6.1.13.2. Harvesting stage

The available B estimated at the harvesting stage are given in the Table 39a and 39b. The data revealed that the treatment with P was found to decrease the available B (0.67 mg kg-1) in comparison with the treatment without P (0.58 mg kg^{-1}). Application of Zn had enhanced the available B content (0.66 mg kg-1) than the treatment without Zn which was significantly different also. Main effects of doses of B and the types of soil were not significant.

Table 39a. Effect of applied P, Zn and B on available B at harvest (mg kg^{-1})

Soils/sources	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	0.61	0.52	0.51	0.61	0.53	0.59	**0.57**
S_2	0.72	0.62	0.61	0.72	0.64	0.70	**0.67**
S_3	0.66	0.60	0.56	0.65	0.58	0.65	**0.62**
Mean	**0.67**	**0.58**	**0.56**	**0.66**	**0.58**	**0.65**	**0.62**

CD S NS CD P 0.09 CD S Zn 0.09 CD S B NS

Among the interaction effects, application of Zn without P (P_0Zn_1) had recorded higher available B (0.83 $mgKg^{-1}$) than the treatment with the application of P with Zn (P_1Zn_1) (0.51$mgKg^{-1}$). Application of B without P recorded higher available B (0.76 $mgKg^{-1}$) than the treatment with both P and B (P_1B_1) applied which was also significantly different (0.53 $mgKg^{-1}$).

Table 39b. Effect of applied Zn and B with applied P on B at harvest (mg kg^{-1})

Sources	Zn_0	Zn_1	B_0	B_1	Mean
P_0	0.51	0.83	0.56	0.76	**0.67**
P_1	0.62	0.51	0.60	0.53	**0.58**
Mean	**0.56**	**0.66**	**0.58**	**0.65**	**0.61**

CD. P ×Zn 0.17 **CD. P ×B 0.17**

4.6.2. Fractions of phosphorus at flowering and harvest

The data on inorganic fractions of phosphorus are presented below.

4.6.2.1. Soluble phosphorus

4.6.2.1.1. Flowering stage

Application P (P_1) was found to decrease the soluble P (11.32 mg kg^{-1}) in comparison to the treatment without P (14.09 mg kg^{-1}). Application of Zn and B also showed similar pattern and decreased the soluble phosphorous. The soil with high P (S_3) recorded the highest soluble P content at this stage (12.82 mg kg^{-1}) which was significantly different from that of other soils.

Table 40a. Effect of applied P, Zn and B on sol-P at flowering (mg kg^{-1})

Soils/sources	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	11.29	6.49	9.40	8.37	8.94	8.84	**8.88**
S_2	13.10	12.55	14.72	10.92	15.39	10.26	**12.82**
S_3	14.49	12.37	16.65	10.21	18.75	8.11	**13.43**
Mean	**12.96**	**10.47**	**13.59**	**9.83**	**14.36**	**9.07**	**11.71**

CD S 0.59 **CD P 0.59** **CD Zn 0.59** **CD B 0.59**

Among the interaction effects, the treatment without the application of P and Zn (P_0Zn_0) recorded the highest soluble P (15.56 mg kg^{-1}) when compared with other treatment combinations of P and Zn. Treatment with application of P and Zn (P_1Zn_1) recorded the lowest soluble P (9.32 mg kg^{-1}) at this stage. The treatment without application of P and B (P_0B_0) recorded significantly higher soluble P (17.25 mg kg^{-1}) than the treatment with P and B (P_1B_1).

Table 40b. Effect of applied Zn and B with applied P on sol -P at harvest (mg kg^{-1})

Sources	Zn_0	Zn_1	B_0	B_1	Mean
P_0	15.56	10.35	17.25	9.93	**13.27**
P_1	11.62	9.32	11.46	8.21	**10.15**
Mean	**13.59**	**9.84**	**14.36**	**9.07**	**11.71**

CD. P × Zn 0.84 **CD. P × B 0.84**

4.2.14.2. Harvesting stage

Application P (P_1) was found to increase the soluble P (17.37 mg kg^{-1}) in comparison with the treatment without P (12.66 mg kg^{-1}). Application of zinc and boron reduced the soluble P. The soil with the lowest P (S1) recorded the highest soluble P content at this stage (19.11 mg kg^{-1}) which was significantly different from that of other soil at harvesting stage.

Table 41a. Effect of applied P, Zn and B on sol-P at harvest (mg kg^{-1})

Soils/sources	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	16.97	20.69	19.67	19.66	18.00	19.66	**19.11**
S_2	12.25	13.91	15.50	12.70	13.46	12.70	**13.42**
S_3	8.74	17.52	14.94	12.14	14.12	12.14	**13.27**
Mean	**12.66**	**17.37**	**16.70**	**14.83**	**15.19**	**14.83**	**15.27**

CD S 1.09 CD P 0.90 CD Zn 0.90 CD B 0.90

Among the interactions, the treatment with application of P without Zn (P_1Zn_0) recorded the highest soluble P (19.66 mg kg^{-1}) when compared with other treatment combinations of P and Zn. Similarly the treatment without application of P and Zn (P_0Zn_0) recorded the lowest soluble P (11.56 mg kg^{-1}) at this stage. The treatment with the application of P without B (P_1B_0) recorded significantly high soluble P (17.97 mg kg^{-1}) than the treatment without P and B (P_0B_0) which recorded the lowest soluble P (12.42 mg kg^{-1}).

Table 41b. Effect of applied Zn and B with applied P on sol-P at harvest (mg kg^{-1})

Sources	Zn_0	Zn_1	B_0	B_1	Mean
P_0	14.60	13.74	12.42	12.88	**12.66**
P_1	19.66	15.08	17.97	16.78	**17.37**
Mean	**16.70**	**14.83**	**15.19**	**14.83**	**15.01**

CD. P × Zn 1.26 CD. P × B NS 1.26

4.6.2.2. Al-Phosphorus

4.6.2.2.1. Flowering stage

Treatment with P decreased the Al-P (39.66 mg kg^{-1}) content when compared to the treatment without P (46.27 mg kg^{-1}). It was observed that in treatment with zinc, the Al-P decreased (40.22 mg kg^{-1}) significantly in comparison to the treatment without Zn (45.72 mg kg^{-1}). Al-P content (44.07 mg kg^{-1}) increased with the application of B and decreased in the case without the application of B (41.85 mg kg^{-1}). The soil with low P (S1) recorded the highest Al- P content at this stage (50.43 mg kg^{-1}) which is significantly different from other soils.

Table 42a. Effect of applied P, Zn and B on Al-P at flowering (mg kg^{-1})

Soils/sources	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	54.67	46.17	56.08	44.79	52.33	48.51	**50.43**
S_2	48.85	44.97	47.79	46.03	41.63	52.19	**46.91**
S_3	35.28	27.84	33.28	29.84	31.60	31.52	**31.56**
Mean	**46.27**	**39.66**	**45.72**	**40.22**	**41.85**	**44.07**	**42.97**

CD S 1.52 CD P 1.24 CD Zn 1.24 CD B 1.24

When the interaction effects were considered, the treatment without P and Zn (P_0Zn_0) recorded significantly higher Al-P (52.35 mg kg^{-1}) in comparison with all the other treatments. The lowest Al-P was recorded in the treatment where both P and Zn (P_1Zn_1) were applied (39.06 mg kg^{-1}). Application of B without P (P_0B_1) showed the highest Al-P (48.03mg kg^{-1}) and the treatment B with P (P_1B_1) recorded the lowest Al-P (39.2 mg kg^{-1}) content.

Table 42b. Effect of applied Zn and B with applied P on Al-P at flowering (mg kg^{-1})

Sources	Zn_0	Zn_1	B_0	B_1	Mean
P_0	52.35	40.18	44.50	48.03	**46.27**
P_1	39.06	40.23	39.20	40.12	**39.66**
Mean	**45.72**	**40.22**	**41.85**	**44.07**	**42.96**

CD. P × Zn 1.74 **CD. P × B 1.74**

4.6.2.2.2. Harvesting stage

Thetreatment with P increased the Al-P (44.14 mg kg^{-1}) content when compared to the treatment without P (35.90 mg kg^{-1}). The soil with low P (S_1) recorded the highest Al- P content at this stage (47.80 mg kg^{-1}). Neither zinc nor boron influenced this quantity of phosphorus in Al-P fraction.

Table 43a. Effect of applied P, Zn and B on Al-P at harvest (mg kg^{-1})

Soils/sources	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	46.28	49.32	46.92	48.68	46.90	48.70	**47.80**
S_2	32.98	45.95	41.88	37.05	42.21	36.72	**39.47**
S_3	28.44	37.16	28.70	36.90	33.95	31.65	**32.80**
Mean	**35.90**	**44.14**	**39.17**	**40.88**	**41.02**	**39.02**	**40.02**

CD S 2.6 **CD P 2.1** **CD Zn NS** **CD B NS**

When the interaction effects were considered, the treatment without P and Zn (P_0Zn_0) recorded significantly lower Al-P (37.66 mg kg^{-1}) in comparison with all the other treatments combinations of P and Zn. The highest Al-P was recorded in the treatment where both P and Zn (P_1Zn_1) were applied (47.61 mg kg^{-1}). Application of B without P (P_0B_1) showed the lowest Al-P (34.39 mg kg^{-1}) and the application of P without B (P_1B_0) recorded the highest Al-P (44.63 mg kg^{-1}) content.

Table 43b. Effect of applied Zn and B with applied P on Al-P at harvest (mg kg^{-1})

Sources	Zn_0	Zn_1	B_0	B_1	Mean
P_0	37.66	34.14	37.41	34.39	**35.90**
P_1	40.68	47.61	44.63	43.66	**44.14**
Mean	**39.17**	**40.88**	**41.02**	**39.02**	**40.02**

CD. P × Zn 3.07 **CD. P × B 3.07**

4.6.2.3 Fe-*Phosphorus*

4.6.2.3.1. Flowering stage

The Fe-P content increased (163.07 mg kg^{-1}) in the treatment with the application of P and decreased in the treatment without P application (147.77 mg kg^{-1}). The treatment without Zn was significantly higher (162.84 mg kg^{-1}) than treatment with Zn (147.99 mg kg^{-1}). The soil with low P (S_1) recorded significantly high Fe- P content at this stage (209.27 mg kg^{-1}) from soil with high and medium P.

Table 44a. Effect of applied P, Zn and B on Fe-P at flowering (mg kg^{-1})

Soils/sources	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	195.98	222.56	225.23	193.31	204.50	214.05	**209.27**
S_2	133.75	139.95	147.08	126.63	140.35	133.36	**136.85**
S_3	113.57	126.71	116.20	124.02	125.65	114.58	**120.12**
Mean	**147.77**	**163.07**	**162.84**	**147.99**	**156.83**	**154.00**	**155.42**

CD S 7.05 CD P 5.9 CD Zn 5.9 CD B NS

The treatment P without Zn (P_1Zn_0) has recorded the highest Fe-P (163.30 mg kg^{-1}) content than the treatment Zn without P (P_0Zn_1) whose value was 133.42 mg kg^{-1}.Application of P without B (P_1B_0) was found to be significantly higher than the treatment B without P (P_0B_1) which has recorded a value of 149.27 mg kg^{-1}.

Table 44b. Effect of applied Zn and B with applied P on Fe-P at flowering (mg kg^{-1})

Sources	Zn_0	Zn_1	B_0	B_1	Mean
P_0	162.07	133.42	146.22	149.27	**147.77**
P_1	163.60	162.55	167.43	158.72	**163.07**
Mean	**162.84**	**147.99**	**156.83**	**154.00**	**155.41**

CD. P × Zn 8.18 CD. P × B 8.18

4.6.2.3.2. Harvesting stage

The Fe-P content was significantly higher (164.60 mg kg^{-1}) in the treatment with the application of P than that in the treatment without P (148.72 mg kg^{-1}). The soil with low P (S_1) recorded significantly higher Fe- P content at this stage (201.27

mg kg^{-1}). The quantity of Fe-P in all the three soils was slightly higher at harvesting stage than during that at flowering stage. Application of zinc and boron did not influence the Fe-P content at this stage.

Table 45a. Effect of applied P, Zn and B on Fe-P at harvest (mg kg^{-1})

Soils/sources	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	192.46	210.80	202.66	200.60	198.39	204.88	**201.63**
S_2	136.15	157.93	154.01	140.07	152.83	141.25	**147.04**
S_3	117.55	125.07	113.93	128.69	117.07	125.60	**121.32**
Mean	**148.72**	**164.60**	**156.87**	**156.45**	**156.10**	**157.24**	**156.66**

CD S 8.79 CD P 7.5 CD Zn NS CD B NS

The treatment with both P and Zn (P_1Zn_1) has recorded the highest Fe-P (*166.29 mg kg*$^{-1}$) *content* and the treatment without P and Zn (P_0Zn_1) recorded the lowest (146.62 mg kg^{-1}). Application of P without B (P_1B_0) recorded the highest Fe-P at this stage.

Table 45b. Effect of applied Zn and B with applied P on Fe-P at harvest(mg kg^{-1})

Sources	Zn_0	Zn_1	B_0	B_1	Mean
P_0	150.82	146.62	141.57	155.87	**148.72**
P_1	162.91	166.29	170.58	158.62	**164.60**
Mean	**156.87**	**156.45**	**156.10**	**157.24**	**156.66**

CD. P × Zn 10.15 CD. P × B 10.15

4.6.2.4 Occluded-phosphorus (Reductant-P)

4.6.2.4.1. Flowering stage

Occluded P fraction has decreased to a larger extent in treatment with P application (22.05 mg kg^{-1}) when compared to that of treatment without P (33.35 mg kg^{-1}). The treatment with Zn has recorded highest occluded P (31.34 mg kg^{-1}) and the treatment without Zn has recorded the lowest occluded P (24.26 mg kg^{-1}). Application of B was found to decrease the Oc-P (26.26 mg kg^{-1}) and the treatment without B has increased the Oc-P (30.34 mg kg^{-1}). The soil with high P (S3) recorded the highest Oc- P content at this stage (30.80 mg kg^{-1}) which is significantly different from other soil with medium and low P.

Table 46a. Effect of applied P, Zn and B on occluded -P at flowering (mg kg^{-1})

Soils/sources	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	28.19	23.08	21.75	29.51	28.41	22.85	**25.63**
S_2	32.62	22.31	21.52	33.41	28.19	26.75	**27.47**
S_3	39.85	20.75	29.52	31.09	34.42	29.19	**30.80**
Mean	**33.55**	**22.05**	**24.26**	**31.34**	**30.34**	**26.26**	**27.97**

CD S 2.48 CD P 2.03 CD Zn 2.03 CD B 2.03

Application of P without Zn (P_1Zn_0) has significantly reduced the Oc-P (20.56 mg kg^{-1}) in comparison with other treatments. The treatment Zn without P (P_0Zn_1) recorded the highest Oc-P (39.14 mg kg^{-1}). The treatment with the application of P and B (P_1B_1) recorded the lowest Oc- P (18.93 mg kg^{-1}) in comparison with the treatment B without P (P_0B_1) which has recorded the highest Oc-P (35.52 mg kg^{-1}).

Table 46b. Effect of applied Zn and B with applied P on occluded -P at flowering (mg kg^{-1})

Sources	Zn_0	Zn_1	B_0	B_1	Mean
P_0	27.97	39.14	35.52	31.59	**33.55**
P_1	20.56	23.53	25.13	18.93	**22.05**
Mean	**24.26**	**31.34**	**30.34**	**26.26**	**27.80**

CD. P × Zn 2.87 **CD. P × B 2.87**

4.6.2.4.2. Harvesting stage

Theoccluded P fraction was increased to a larger extent with the application of P (61.21 mg kg^{-1}) when compared to the treatment without P (40.33 mg kg^{-1}) during this stage. The treatment without Zn has recorded highest occluded P (53.11 mg kg^{-1}) and the treatment with Zn has recorded the lowest occluded P (48.43 mg kg^{-1}). The soil with the highest P (S_3) recorded the highest Oc- P content at this stage (61.07 mg kg^{-1}) which was significantly different from other soils with medium and low P (S_2 and S_1).

Table 47a. Effect of applied P, Zn and B on occluded-P at harvest (mg kg^{-1})

Soils/sources	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	35.07	40.96	45.17	30.86	39.30	36.74	**38.02**
S_2	41.51	67.27	55.41	53.37	58.06	50.72	**54.39**
S_3	44.40	75.40	58.74	61.07	58.63	68.18	**61.07**
Mean	**40.33**	**61.21**	**53.11**	**48.43**	**52.00**	**51.88**	**51.16**

CD S 3.3 **CD P 2.76** **CD Zn 2.76** **CD B NS**

Application of P without Zn (P_1Zn_0) has increased the Oc-P (68.41 mg kg^{-1}) in comparison with other treatments of P and Zn. The treatment without P and Zn (P_0Zn_0) recorded the lowest Oc-P (37.81 mg kg^{-1}). The treatment with the application of P and B (P_1B_1) recorded the highest Oc- P (64.24 mg kg^{-1}) in comparison with the application of boron without phosphorus (P_0B_1) which has recorded the lowest Oc-P (34.85 mg kg^{-1}) at this stage.

Table 47b. Effect of applied Zn and B with applied P on occluded-P at harvest (mg kg^{-1})

Sources	Zn_0	Zn_1	B_0	B_1	Mean
P_0	37.81	42.85	45.81	34.85	**40.33**
P_1	68.41	54.02	58.18	64.24	**61.21**
Mean	**53.11**	**48.43**	**52.00**	**51.88**	**50.77**

CD. P × Zn 3.9 **CD. P × B 3.9**

4.6.2.5 Calcium-Phosphorus (Ca-P)

4.6.2.5.1. Flowering stage

Application of P was found to decrease the Ca-P fraction (17.09 mg kg^{-1}) in comparison with treatment without P (18.87 mg kg^{-1}). The treatment with Zn recorded lowest Ca- P (16.78 mg kg^{-1}) in comparison to the treatment without Zn (19.17 mg kg^{-1}). Application of B was also found to decrease the Ca-P (16.69 mg kg^{-1}) in comparison to the treatment without B (19.27 mg kg^{-1}). The soil with medium P (S_2) recorded the highest Ca- P content at this stage (19.60 mg kg^{-1}) which is significantly different from that on other soil.

Table 48a. Effect of applied P, Zn and B on Ca-P at flowering (mg kg^{-1})

Soils/sources	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	17.3	14.72	17.00	15.01	16.40	15.61	**16.01**
S_2	20.33	18.86	19.99	19.20	21.63	17.56	**19.60**
S_3	18.97	17.69	20.52	16.14	19.77	16.89	**18.33**
Mean	**18.87**	**17.09**	**19.17**	**16.78**	**19.27**	**16.69**	**17.98**

CD S 1.32 CD P 1.09 CD Zn 1.09 CD B 1.09

Application of P with Zn (P_1Zn_1) was found to reduce the Ca-P (16.65 mg kg^{-1}) in comparison with other treatments. The treatment without the application of P and Zn (P_0Zn_0) recorded the highest Ca-P (20.81 mg kg^{-1}). The treatment with the application of P and B (P_1B_1) recorded the lowest Ca-P (15.67 mg kg^{-1}) when compared to the treatment without P and B (P_0B_0) which has recorded the highest Ca-P (20.03 mg kg^{-1}).

Table 48b. Effect of applied Zn and B with applied P on Ca-P at flowering (mg kg^{-1})

Sources	Zn_0	Zn_1	B_0	B_1	Mean
P_0	20.81	16.92	20.03	17.7	**18.87**
P_1	17.53	16.65	18.51	15.67	**17.09**
Mean	**19.17**	**16.78**	**19.27**	**16.69**	**17.98**

CD. P × Zn 1.55 CD. P × B 1.55

4.6.2.5.2. Harvesting stage

Application of P was found to increase the Ca-P fraction (19.12 mg kg^{-1}) in comparison to the treatment without P (17.32 mg kg^{-1}). The treatment with Zn recorded the lowest Ca- P (17.83 mg kg^{-1}) in comparison with the treatment without Zn (18.61 mg kg^{-1}) which recorded the highest Ca-P fraction. Application of B was found to decrease the Ca-P (17.83 mg kg^{-1}) in comparison to the treatment without B (18.61mg kg^{-1}). The soil with the lowest P (S_1) recorded the highest Ca- P content at this stage (19.67 mg kg^{-1}) which is significantly different from that of the other soils.

Table 49a. Effect of applied P, Zn and B on Ca-P at harvest (mg kg^{-1})

Soils/sources	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	19.40	19.93	19.85	19.48	19.83	19.50	**19.67**
S_2	15.00	16.91	16.28	15.62	16.76	15.15	**15.95**
S_3	17.57	20.52	19.70	18.40	19.25	18.85	**19.05**
Mean	**17.32**	**19.12**	**18.61**	**17.83**	**18.61**	**17.83**	**18.22**

CD S 1.07 CD P 0.87 CD Zn 0.87 CD B 0.87

Application of P with Zn (P_1Zn_1) has increased the Ca-P (19.45 mg kg^{-1}) in comparison with other treatment combinations of P and Zn. The treatment without the application of P and with the application of Zn (P_0Zn_1) recorded the lowest Ca-P (16.21 mg kg^{-1}). The treatment with the application of P without B (P_1B_0) recorded the highest Ca-P (20.45 mg kg^{-1}) when compared to the treatment without P and B (P_0B_0) which has recorded the lowest Ca-P (16.78 mg kg^{-1}).

Table 49b. Effect of applied Zn and B with applied P on Ca-P at harvest(mg kg^{-1})

Sources	Zn_0	Zn_1	B_0	B_1	Mean
P_0	18.43	16.21	16.78	17.86	**17.32**
P_1	18.79	19.45	20.45	17.80	**19.12**
Mean	**18.61**	**17.83**	**18.61**	**17.83**	**18.22**

CD. P × Zn 1.24 CD. P × B 1.2

4.6.3. Fractions of zinc at flowering and harvesting

The details of fractions of zinc at flowering and harvesting are presented below.

4.6.3.1. Water soluble +exchangeable zinc (Ws+Exch-Zn)

4.6.3.1.1. Flowering

Application of P (P_1) was found to decrease the Ws+Exch-zinc (0.04 mg kg^{-1}) in comparison to the treatment without P (0.08 mg kg^{-1}). Application of zinc increased the Ws+Exch-zinc (0.07 mg kg^{-1}) content in the soil in comparison to the treatment without Zn (0.05 mg kg^{-1}). The treatment with boron and without boron showed similar effect as that of zinc. The soil with medium P (S_2) recorded the highest Ws+Exch-zinc at this stage (0.10 mg kg^{-1}) which is significantly different from that of other soils.

Table 50a. Effect of applied P, Zn and B on Ws+Exch-Zn at flowering (mg kg^{-1})

Soils/sources	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	0.03	0.03	0.03	0.03	0.02	0.04	**0.03**
S_2	0.14	0.06	0.08	0.12	0.09	0.11	**0.10**
S_3	0.06	0.03	0.03	0.06	0.04	0.05	**0.05**
Mean	**0.08**	**0.04**	**0.05**	**0.07**	**0.05**	**0.07**	**0.06**

CD S 0.01 CD P 0.007 CD Zn 0.007 CD B 0.007

Among the interactions, the treatment without the application of P and with the application of Zn (P_0Zn_1) recorded the highest Ws+Exch-zinc (0.11 mg kg^{-1}) when compared with othertreatment combinations of P and Zn. Treatment with application of P and Zn (P_1Zn_1) and with application of P and without the application of Zn (P_1Zn_0)recorded the lowest Ws+Exch-zinc (0.04 mg kg^{-1}) at this stage. The treatment without application of P and with the application of B (P_0B_1) recorded significantly high Ws+Exch-zinc (0.09 mg kg^{-1}) when compared with other treatment combinations of P and B. The treatments P_1B_0 and P_1B_1 recorded the lowest values (0.04 mg kg^{-1}).

Table 50b. Effect of applied Zn and B with applied P on Ws+Exch-Zn at flowering (mg kg^{-1})

Sources	Zn_0	Zn_1	B_0	B_1	Mean
P_0	0.05	0.11	0.07	0.09	**0.08**
P_1	0.04	0.04	0.04	0.04	**0.04**
Mean	**0.05**	**0.07**	**0.05**	**0.07**	**0.06**

CD. P × Zn 0.014 **CD. P × B NS 0.014**

4.6.3.1.2. Harvesting

Application P (P_1) was found to decrease the Ws+Exch-zinc (0.05 mg kg^{-1}) in comparison to the treatment without P (0.14 mg kg^{-1}). Application of zinc increased the Ws+Exch-zinc (0.12 mg kg^{-1}) content in the soil in comparison to the treatment without Zn (0.07 mg kg^{-1}). The treatment with B and without B showed similar effect as that of Zn. The soil with medium P (S_2) recorded the highest Ws+Exch-zinc content at this stage (0.17 mg kg^{-1}) which is significantly different from that of other soils.

Table 51a. Effect of applied P, Zn and B on Ws+Exch-Zn at harvest (mg kg^{-1})

	P_0	P_1	Zn_0	ZN_1	B_0	B_1	Mean
S_1	0.05	0.04	0.04	0.06	0.04	0.06	**0.05**
S_2	0.26	0.08	0.13	0.21	0.14	0.21	**0.17**
S_3	0.10	0.04	0.04	0.09	0.05	0.08	**0.07**
Mean	**0.14**	**0.05**	**0.07**	**0.12**	**0.08**	**0.12**	**0.10**

CD S 0.02 CD P 0.016 CD Zn 0.016 CD B 0.016

Among the interactions, the treatment without the application of P and with the application of Zn (P_0Zn_1) recorded the highest Ws+Exch-zinc (0.20 mg kg^{-1}) when compared with othertreatment combinations of P and Zn. Treatment with application of P and Zn (P_1Zn_1) and with application of P and without the application of Zn (P_1Zn_0)recorded the lowest Ws+Exch-zinc (0.04 mg kg^{-1}) at this stage. The treatment without application of P and with the application of B (P_0B_1) recorded significantly higher Ws+Exch-zinc (0.17 mg kg^{-1}) when compared with other treatment combinations of P and B.

Table 51b. Effect of applied Zn and B with applied P on Ws+Exch-Zn at harvest (mg kg^{-1})

	Zn_0	Zn_1	B_0	B_1	Mean
P_0	0.08	0.20	0.11	0.17	**0.14**
P_1	0.06	0.04	0.04	0.06	**0.05**
Mean	**0.07**	**0.12**	**0.08**	**0.12**	**0.10**

CD. P ×Zn 0.02 CD. P × B NS 0.02

4.6.3.2. Specifically adsorbed zinc (Sp.Ad-Zn)

4.6.3.2.1. Flowering

Treatment with P increased the Sp.Ad- Zn(1.68 mg kg^{-1}) content when compared to the treatment without P (1.32 mg kg^{-1}). The contentofSp.Ad-Zndecreased (1.38 mg kg^{-1}) with the application of B and increased in the case without the application of B (1.61 mg kg^{-1}). The soil with medium (S2) recorded the highest Sp.Ad- Zncontent at this stage (3.62 mg kg^{-1}) which is significantly different from that on other soils.

Table 52a. Effect of applied P, Zn and B on Sp.Ad-Zn at flowering(mg kg^{-1})

Soils/sources	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	0.46	0.46	0.23	0.70	0.75	0.18	**0.46**
S_2	2.95	4.29	4.03	3.21	3.53	3.71	**3.62**
S_3	0.54	0.28	0.29	0.53	0.55	0.27	**0.41**
Mean	**1.32**	**1.68**	**1.52**	**1.48**	**1.61**	**1.38**	**1.50**

CD S 0.3 CD P 0.23 CD Zn NS CD B 0.23

When the interaction effects were considered, the treatment with P and Zn (P_1Zn_1) recorded significantly higher Sp.Ad-Zn(2.12 mg kg^{-1}) in comparison with all the other treatment combinations of P and Zn. The lowest Sp.Ad-Zn(0.84 mg kg^{-1}) was recorded in the treatment with Zn and without P (P_0Zn_1). Application of both B and P (P_1B_1) showed the highest Sp.Ad- Zn(1.75mg kg^{-1}) and the treatment B without P (P_0B_1) has recorded the lowest Sp.Ad- Zn(1.02 mg kg^{-1}) concentration.

Table 52b. Effect of applied Zn and B with applied P on Sp.Ad-Zn at flowering ($mg\ kg^{-1}$)

Sources	Zn_0	Zn_1	B_0	B_1	Mean
P_0	1.80	0.84	1.62	1.02	**1.32**
P_1	1.23	2.12	1.61	1.75	**1.68**
Mean	**1.52**	**1.48**	**1.61**	**1.38**	**1.50**

CD. P × Zn 0.34 **CD. P × B 0.34**

4.6.3.2.2. Harvesting

Treatment with P increased the Sp.Ad-Zn(2.37 mg kg^{-1}) content when compared to the treatment without P (1.66 mg kg^{-1}). During the treatment with Zn, the Sp.Ad-Znincreased (2.37 mg kg^{-1}) in comparison to the treatment without Zn (1.66 mg kg^{-1}). Sp.Ad-Zncontentdecreased (1.11 mg kg^{-1}) with the application of B and increased in the case without the application of B (2.93 mg kg^{-1}). The Sp.Ad-Zncontent increased in the harvesting stage when compared with the flowering stage during the treatment with B.The soil with mediumP (S_2) recorded significantly higher Sp.Ad-Zncontent at this stage (4.96 mg kg^{-1}) which is significantly different from that on other soils and even higher than the content during flowering stage.

Table 53a. Effect of applied P, Zn and B on Sp.Ad-Zn at harvest ($mg\ kg^{-1}$)

	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	0.46	1.04	0.16	1.34	0.54	0.97	**0.75**
S_2	4.34	5.58	4.56	5.36	7.97	1.95	**4.96**
S_3	0.176	0.50	0.26	0.41	0.28	0.40	**0.34**
Mean	**1.66**	**2.37**	**1.66**	**2.37**	**2.93**	**1.11**	**2.02**

CD S 0.2 CD P 0.15 CD Zn 0.15 CD B 0.15

When the interaction effects were considered, the treatment with P and Zn (P_1Zn_1) recorded significantly higher Sp.Ad-Zn(2.94 mg kg^{-1}) in comparison with all the other treatments. The lowest Sp.Ad-Zn(1.52 mg kg^{-1}) was recorded in the treatment without Zn and P (P_0Zn_0). Application of P without B (P_1B_0) resulted in significantly higher Sp.Ad-Zn(3.23 mg kg^{-1}) and the treatment B without P (P_0B_1) has recorded the lowest Sp.Ad-Zn(0.69 mg kg^{-1}) concentration.

Table 53b. Effect of applied Zn and B with applied P on Sp.Ad-Zn at harvest (mg kg^{-1})

	Zn_0	**Zn_1**	**B_0**	**B_1**	**Mean**
P_0	1.52	1.80	2.63	0.69	**1.66**
P_1	1.81	2.94	3.23	1.52	**2.37**
Mean	**1.66**	**2.37**	**2.93**	**1.11**	**2.02**

CD. P × Zn 0.25 **CD. P × B 0.25**

4.6.3.3. Acid soluble zinc (Acid sol-Zn)

4.6.3.3.1. Flowering

The acid soluble Zn content increased (3.63 mg kg^{-1}) in the treatment with the application of P and decreased in the case without P (1.96 mg kg^{-1}). The treatment with Zn showed significantly higher (3.19 mg kg^{-1}) concentration of acid soluble Zn than treatment without Zn (2.40 mg kg^{-1}). Application of B was found to slightly increase the acid soluble Zn (2.83 mg kg^{-1}) in comparison to treatment without B (2.76 mg kg^{-1}). The soil with medium P (S_2) recorded significantly high acid soluble Zn content at this stage (7.40 mg kg^{-1}) from soil with low and high P.

Table 54a. Effect of applied P, Zn and B on Acid sol-Zn at flowering (mg kg^{-1})

	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	0.41	0.31	0.47	0.25	0.37	0.35	**0.36**
S_2	4.54	10.25	5.76	9.03	7.47	7.32	**7.40**
S_3	0.94	0.32	0.97	0.29	0.44	0.83	**0.63**
Mean	**1.96**	**3.63**	**2.40**	**3.19**	**2.76**	**2.83**	**2.80**

CD S 0.5 CD P 0.42 CD Zn 0.42 CD B NS

Among the interaction effects, the treatment with P and Zn (P_1Zn_1) has recorded the highest acid soluble Zn content (4.84 mg kg^{-1}) and the treatment Zn without P (P_0Zn1) recorded the lowest acid soluble Zn content (1.54 mg kg^{-1}). Application of P without B (P_1B_0) was found to be significantly higher than the treatment without P and B (P_0B_0) which has recorded the lowest value of 1.60 mg kg^{-1}.

Table 54b. Effect of applied Zn and B with applied P on Acid sol-Zn at flowering (mg kg^{-1})

	Zn_0	Zn_1	B_0	B_1	Mean
P_0	2.38	1.54	1.60	2.33	**1.96**
P_1	2.42	4.84	3.92	3.34	**3.63**
Mean	**2.40**	**3.19**	**2.76**	**2.83**	**2.80**

CD. P × Zn 0.6 CD. P × B 0.6

4.6.3.3.2. Harvesting

The acid soluble Zn content increased slightly (3.38 mg kg^{-1}) in the treatment with the application of P and decreased in the case without P (3.34 mg kg^{-1}). The treatment with Zn showed significantly higher (4.05 mg kg^{-1}) concentration of acid soluble Zn than treatment without Zn (2.68 mg kg^{-1}). Application of B was found to slightly increase the acid soluble Zn (3.45mg kg^{-1}) in comparison to treatment without B 3.27 mg kg^{-1}). The soil with medium P (S_2) recorded significantly high acid soluble Zn content at this stage (8.85 mg kg^{-1}) from soil with low and high P at this stage. Similar results were recorded at the flowering stage.

Table 55a. Effect of applied P, Zn and B on Acid sol-Zn at harvest (mg kg^{-1})

	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	0.19	0.12	0.07	0.24	0.17	0.15	**0.16**
S_2	8.037	9.66	6.71	10.99	8.64	9.06	**8.85**
S_3	1.805	0.37	1.25	0.93	1.02	1.16	**1.09**
Mean	**3.34**	**3.38**	**2.68**	**4.05**	**3.27**	**3.45**	**3.36**

CD S 0.41 CD P 0.32 CD Zn 0.32 CD B NS

Among the interaction effects, the treatment with P and Zn (P_1Zn_1) has recorded the highest acid soluble Zn content (4.73 mg kg^{-1}) and the treatment P without Zn (P_1Zn_0) recorded the lowest acid soluble Zn content (2.04 mg kg^{-1}). Application of B without P (P_0B_1) was found to be significantly higher than the treatment without P and B (P_0B_0) which has recorded the lowest value of 1.60 mg kg^{-1} at this stage. The interaction effects were different from that of flowering stage.

Table 55b. Effect of applied Zn and B with applied P on Acid sol-Zn at harvest (mg kg^{-1})

	Zn_0	Zn_1	B_0	B_1	Mean
P0	3.32	3.37	1.98	4.70	**3.34**
P1	2.04	4.73	4.57	2.21	**3.38**
Mean	**2.68**	**4.05**	**3.27**	**3.45**	**3.36**

CD. P × Zn 0.5 CD. P × B 0.5

4.6.3.4. Mn oxide occluded zinc (MnO-Zn)

4.6.3.4.1. Flowering

MnO-Znfraction has increased with the application of P (2.56 mg kg^{-1}) when compared to the treatment without P (2.36 mg kg^{-1}). The treatment with Zn has recorded higher MnO-Zn (2.61 mg kg^{-1}) and the treatment without Zn has recorded lower MnO-Zn (2.31 mg kg^{-1}). But the treatments with and without Zn were found to be non significant. Similar pattern was observed with B. The soil with medium P (S2) recorded the highest MnO-Zncontent at this stage (5.86 mg kg^{-1}) which is significantly different from other soil with high and low P.

Table 56a. Effect of applied P, Zn and B on MnO-Zn at flowering (mg kg^{-1})

	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	0.68	1.01	0.78	0.91	0.72	0.97	**0.84**
S_2	5.76	5.95	5.62	6.10	6.09	5.62	**5.86**
S_3	0.65	0.70	0.53	0.82	0.94	0.41	**0.68**
Mean	**2.36**	**2.56**	**2.31**	**2.61**	**2.58**	**2.34**	**2.46**

CD S 0.34 CD P NS CD Zn NS CD B NS

Among the interaction effects, application of treatment with P and Zn (P_1Zn_1) has significantly increased the MnO-Zn(2.80 mg kg^{-1}) in comparison with other treatments. The treatment with the application of P without B (P_1B_0) recorded the highest MnO-Zn(2.70 mg kg^{-1}) in comparison to the treatment B without P (P_0B_1) which has recorded the lowest MnO-Zn(2.26 mg kg^{-1}).

Table 56b. Effect of applied Zn and B with applied P on MnO-Zn at flowering ($mg\ kg^{-1}$)

	Zn_0	Zn_1	B_0	B_1	Mean
P_0	2.31	2.42	2.47	2.26	**2.36**
P_1	2.31	2.80	2.70	2.41	**2.56**
Mean	**2.31**	**2.61**	**2.58**	**2.34**	**2.46**

CD. P × Zn 0.41 **CD. P × B 0.41**

4.6.3.4.2. Harvesting

MnO-Znfraction increased with the application of P (2.91 $mg\ kg^{-1}$) when compared to the treatment without P (2.37 $mg\ kg^{-1}$). The treatment with Zn has recorded higher MnO-Zn (3.17 $mg\ kg^{-1}$) and the treatment without Zn recorded lower MnO-Zn (2.11 $mg\ kg^{-1}$). In the case of treatment with B MnO-Znfraction decreased (2.52 $mg\ kg^{-1}$) and treatment without B MnO-Znfraction has increased (2.77 $mg\ kg^{-1}$). The soil with medium P (S_2) recorded the highest MnO-Zncontent at this stage (5.91 $mg\ kg^{-1}$) which is significantly different from other soil with high and low P.

Table 57a. Effect of applied P, Zn and B on MnO-Zn at harvest ($mg\ kg^{-1}$)

	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	0.327	2.78	0.48	2.62	2.75	0.35	**1.55**
S_2	6.352	5.46	5.51	6.31	5.18	6.64	**5.91**
S_3	0.444	0.49	0.36	0.58	0.38	0.56	**0.47**
Mean	**2.37**	**2.91**	**2.11**	**3.17**	**2.77**	**2.52**	**2.64**

CD S 0.32 CD P 0 .228 CD Zn 0 .228 CD B NS

Among the interaction effects, application of treatment with P and Zn (P_1Zn_1) has significantly increased the MnO-Zn(3.84 mg kg^{-1}) in comparison with other treatments. The treatment with the application of P without B (P_1B_0) recorded the highest MnO-Zn(3.74 mg kg^{-1}) in comparison to the treatment without P and B (P_0B_0) which has recorded the lowest MnO-Zn(1.80 mg kg^{-1}).

Table 57b. Effect of applied Zn and B with applied P on MnO-Zn at harvest (mg kg^{-1})

	Zn_0	Zn_1	B_0	B_1	Mean
P_0	2.255	2.494	1.80	2.95	**2.37**
P_1	1.972	3.848	3.74	2.08	**2.91**
Mean	**2.11**	**3.17**	**2.77**	**2.52**	**2.64**

CD. P × Zn 0.32 **CD. P × B 0.21**

4.6.3.5. Organic matter occluded zinc (OM-Zn)

4.6.3.5.1. Flowering

Application of P was found to increase the OM occluded Zn fraction (2.06 mg kg^{-1}) in comparison to the treatment without P (1.65 mg kg^{-1}). The treatment without Zn recorded lowest OM occluded Zn (1.64 mg kg^{-1}) in comparison with the treatment with Zn (2.06 mg kg^{-1}). Application of B was found to decrease the OM occluded Zn (1.49 mg kg^{-1}) in comparison to the treatment without B (2.21 mg kg^{-1}). The soil with medium P (S_2) recorded the highest OM occluded Zn content at this stage (4.90 mg kg^{-1}) which is significantly different from that of other soil.

Table 58a. Effect of applied P, Zn and B on OM-Zn at flowering (mg kg^{-1})

	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	0.293	0.21	0.17	0.34	0.20	0.30	**0.25**
S_2	4.19	5.61	4.43	5.37	6.14	3.66	**4.90**
S_3	0.459	0.35	0.33	0.47	0.30	0.51	**0.40**
Mean	**1.65**	**2.06**	**1.64**	**2.06**	**2.21**	**1.49**	**1.85**

CD S 0.36 CD P 0.30 CD Zn 0.30 CD B 0.30

When the interaction effects are considered application of P with Zn (P_1Zn_1) was found to increase the OM occluded Zn (2.73 mg kg^{-1}) in comparison with other treatments. The treatment with P and without Zn (P_1Zn_0) recorded the lowest OM occluded Zn (1.38 mg kg^{-1}). The treatment with P and without B (P_1B_0) recorded the highest OM occluded Zn (2.88 mg kg^{-1}) and the treatment with P and B (P_1B_1) recorded the lowest OM occluded Zn (1.23 mg kg^{-1}).

Table 58b. Effect of applied Zn and B with applied P on OM-Zn at flowering (mg kg^{-1})

	Zn_0	Zn_1	B_0	B_1	Mean
P_0	1.90	1.39	1.55	1.75	**1.65**
P_1	1.38	2.73	2.88	1.23	**2.05**
Mean	**1.64**	**2.06**	**2.21**	**1.49**	**1.85**

CD. P × Zn 0.41 CD. P × B 0.41

4.6.3.5.2. Harvesting

Application of P was found to decrease the OM occluded Zn fraction (1.63 mg kg^{-1}) in comparison to the treatment without P (2.25 mg kg^{-1}). The treatment without Zn recorded lowest OM occluded Zn (1.67 mg kg^{-1}) in comparison with the treatment with Zn (2.21 mg kg^{-1}). Application of B was found to increase the OM occluded Zn (2.04 mg kg^{-1}) in comparison to the treatment without B (1.83 mg kg^{-1}). The soil with medium P (S_2) recorded the highest OM occluded Zn content at this stage (4.75 mg kg^{-1}) which is significantly different from that of other soil. During flowering stage also the soil with medium P (S_2) recorded the highest OM occluded Zn content.

Table 59a. Effect of applied P, Zn and B on OM-Zn at harvest (mg kg^{-1})

	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	0.367	0.58	0.29	0.66	0.38	0.57	**0.47**
S_2	5.269	4.22	4.58	4.91	4.62	4.87	**4.75**
S_3	1.105	0.09	0.14	1.06	0.50	0.69	**0.60**
Mean	**2.25**	**1.63**	**1.67**	**2.21**	**1.83**	**2.04**	**1.94**

CD S 0.25 CD P 0.22 CD Zn 0.22 CD B NS

When the interaction effects are considered application of Zn without P (P_0Zn_1) was found to increase the OM occluded Zn (2.32 mg kg^{-1}) in comparison with other treatments. The treatment with P and without Zn (P_1Zn_0) recorded the lowest OM occluded Zn (1.16 mg kg^{-1}). The treatment with B and without P (P_0B_1) recorded the highest OM occluded Zn (2.59 mg kg^{-1}) and the treatment with P and B (P_1B_1) recorded the lowest OM occluded Zn (1.49 mg kg^{-1}).

Table 59b. Effect of applied Zn and B with applied P on OM-Zn at harvest (mg kg^{-1})

	Zn_0	Zn_1	B_0	B_1	Mean
P_0	2.18	2.32	1.90	2.59	**2.25**
P_1	1.16	2.10	1.77	1.49	**1.63**
Mean	**1.67**	**2.21**	**1.83**	**2.04**	**1.94**

CD. P × Zn 0.32 CD. P × B 0.32

4.6.3.6. Amorphous iron occluded zinc (AmFeO-Zn)

4.6.3.6.1. Flowering

Treatment with P increased the Am Fe ocld Zn (1.51 mg kg^{-1}) when compared to the treatment without P (1.23 mg kg^{-1}). It was observed that in the treatment were Zn was applied, AmFeO-Zn increased (1.30 mg kg^{-1}). But in the case of treatment without Zn, the AmFeO-Zn was 1.23 mg kg^{-1}. Application of B also was found to decrease the AmFeO-Zn (1.24 mg kg^{-1}) in comparison to the treatment without B (1.50 mg kg^{-1}). The soil with medium P (S_2) recorded the highest AmFeO-Zn content at this stage (1.71 mg kg^{-1}) which is significantly different from soil with high and low P.

Table 60a. Effect of applied P, Zn and B on AmFeO-Zn at flowering (mg kg^{-1})

	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	0.91	1.65	1.43	1.38	1.44	1.12	**1.32**
S_2	2.05	1.66	1.60	1.25	2.30	1.42	**1.71**
S_3	0.72	1.23	0.68	1.28	0.77	1.18	**0.98**
Mean	**1.23**	**1.51**	**1.23**	**1.30**	**1.50**	**1.24**	**1.34**

CD S 0.2 CD P .15 CD Zn .15 CD B .15

Among the interaction effects, the treatment with P and Zn (P_1Zn_1) recorded significantly higher AmFeO-Zn (2.18 mg kg^{-1}). The lowest AmFeO-Zn was recorded in the treatment Zn without P (P_0Zn_1) i.e., 0.85 mg kg^{-1}. Application of treatments B and P (P_1B_1) recorded the highest AmFeO-Zn (1.53 kg^{-1}) and the treatment with B and without P (P_0B_1) recorded the lowest total AmFeO-Zn (0.96 mg kg^{-1}).

Table 60b. Effect of applied Zn and B with applied P on Am FeO-Zn at flowering(mg kg^{-1})

	Zn_0	Zn_1	B_0	B_1	Mean
P_0	1.61	0.85	1.50	0.96	**1.23**
P_1	0.86	2.18	1.51	1.53	**1.52**
Mean	**1.23**	**1.51**	**1.50**	**1.24**	**1.37**

CD. P × Zn 0 .25 **CD. P × B 0 .25**

4.6.3.6.2. Harvesting

Treatment with P decreased the AmFeO-Zn (0.56 mg kg^{-1}) when compared to the treatment without P (0.99 mg kg^{-1}). It was observed that in the treatment were Zn was applied, the AmFeO-Zn decreased (0.74 mg kg^{-1}). But in the case of treatment without Zn, the AmFeO-Zn was 0.81 mg kg^{-1}. Application of B also was also found to decrease the AmFeO-Zn (0.71 mg kg^{-1}) in comparison to the treatment without B (0.84 mg kg^{-1}). The soil with medium P (S_2) recorded the highest Am Fe ocld Zn content at this stage (0.93 mg kg^{-1}) which is significantly different from soil with high and low P.

Table 61a. Effect of applied P, Zn and B on AmFeO-Zn at flowering (mg kg^{-1})

	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	0.733	0.54	0.72	0.55	0.74	0.54	**0.64**
S_2	1.11	0.76	0.73	1.13	1.01	0.86	**0.93**
S_3	1.14	0.38	0.98	0.54	0.78	0.74	**0.76**
Mean	**0.99**	**0.56**	**0.81**	**0.74**	**0.84**	**0.71**	**0.78**

CD S 0.09 CD P 0.08 CD Zn NS CD B NS

Among the interaction effects, the treatment without P and Zn (P_0Zn_0) recorded significantly higher AmFeO-Zn (1.18 mg kg^{-1}). The lowest AmFeO-Zn was recorded in the treatment P without Zn (P_1Zn_0) i.e., 0.44 mg kg^{-1}. Application of treatments without B and P (P_0B_0) recorded the highest AmFeO-Zn (1.13 kg^{-1}) and the treatment with P and without B (P_1B_0) recorded the lowest total AmFeO-Zn (0.96 mg kg^{-1}). The interaction effects were different in the flowering stage when compared with the harvesting stage.

Table 61b. Effect of applied Zn and B with applied P on AmFeO-Zn at harvest (mg kg^{-1})

	Zn_0	Zn_1	B_0	B_1	Mean
P_0	1.18	0.81	1.13	0.86	**0.99**
P_1	0.44	0.67	0.55	0.57	**0.56**
Mean	**0.81**	**0.74**	**0.84**	**0.71**	**0.78**

CD. P × Zn 0 .09 **CD. P × B 0 .09**

4.6.3.7. Crystalline iron occluded zinc (CryFeO-Zn)

4.6.3.7.1. Flowering

Application P (P_1) was found to decrease the Cry FeO-Zn(1.18 mg kg^{-1}) in comparison to the treatment without P (1.47 mg kg^{-1}). Application of zinc and boron also showed the similar pattern. The soil with medium P (S_2) recorded the highest content of Cry FeO-Znat this stage (2.13 mg kg^{-1}) which is significantly different from that of other soils.

Table 62a. Effect of applied P, Zn and B on CryFeO-Znat flowering (mg kg^{-1})

	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	1.28	1.02	1.17	1.12	1.31	1.00	**1.15**
S_2	2.27	1.98	2.32	1.94	2.30	1.96	**2.13**
S_3	0.85	0.55	0.78	0.62	0.87	0.54	**0.70**
Mean	**1.47**	**1.18**	**1.42**	**1.23**	**1.49**	**1.17**	**1.33**

CD S 0.15 CD P 0.13 CD Zn 0.13 CD B 0.13

Among the interaction effects, the treatment without the application of P and Zn (P_0Zn_0) recorded the highest Cry FeO-Zn(1.64 mg kg^{-1}) when compared with othertreatment combinations. Treatment with application of P and Zn (P_1Zn_1) recorded the lowest Cry FeO-Zn(1.16 mg kg^{-1}) at this stage. The treatment without application of P and B (P_0B_0) recorded significantly high Cry FeO-Zn(1.72 mg kg^{-1}) when compared with other treatment combinations. The treatment with P and B (P_1B_1)*recorded the lowest values* (1.11 mg kg^{-1}).

Table 62b. Effect of applied Zn and B with applied P on CryFeO -Zn at flowering (mg kg^{-1})

	Zn_0	Zn_1	B_0	B_1	Mean
P_0	1.64	1.30	1.72	1.22	**1.47**
P_1	1.21	1.16	1.26	1.11	**1.19**
Mean	**1.43**	**1.23**	**1.49**	**1.16**	**1.33**

CD. P × Zn 0.2 CD. P × B 0.2

4.6.3.7.2. Harvesting

Application P (P_1) was found to increase the Cry FeO-Zn(1.02 mg kg^{-1}) in comparison to the treatment without P (0.91 mg kg^{-1}). Application of zinc showed the similar pattern. But in the treatment with B the Cry FeO-Zndecreased (0.93 mg kg^{-1}) slightly from the treatment without B (1.00 mg kg^{-1}). The soil with medium P (S_2) recorded the highest content of Cry FeO-Znat this stage (1.39 mg kg^{-1}) which is significantly different from that of other soils.

Table 63a. Effect of applied P, Zn and B on CryFeO-Znat harvest (mg kg^{-1})

	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	0.81	0.62	0.68	0.75	0.75	0.68	**0.72**
S_2	1.16	1.61	1.06	1.71	1.73	1.04	**1.39**
S_3	0.78	0.82	0.79	0.80	0.52	1.07	**0.79**
Mean	**0.91**	**1.02**	**0.84**	**1.09**	**1.00**	**0.93**	**0.97**

CD S 0.12 CD P 0.10 CD Zn 0.11 CD B NS

Among the interaction effects, the treatment with the application of P and Zn (P_1Zn_1) recorded the highest Cry FeO-Zn(1.22 mg kg^{-1}) when compared with othertreatment combinations. Treatment with application of P without Zn (P_1Zn_0) recorded the lowest Cry FeO-Zn(0.82 mg kg^{-1}) at this stage. The treatment with application of P without B (P_1B_0) recorded significantly high Cry FeO-Zn(1.04 mg kg^{-1}) when compared with other treatment combinations. The treatment with B without P (P_0B_1)recorded the lowest values (0.86 mg kg^{-1}) during this stage.

Table 63b. Effect of applied Zn and B with applied P on CryFeO-Zn at harvest (mg kg^{-1})

	Zn_0	Zn_1	B_0	B_1	Mean
P_0	0.87	0.95	0.97	0.86	**0.91**
P_1	0.82	1.22	1.04	1.00	**1.02**
Mean	**0.84**	**1.09**	**1.00**	**0.93**	**0.97**

CD. P × Zn 0.16 CD. P × B NS

4.6.3.8. Residual zinc (Resd-Zn)

4.6.3.8. 1. Flowering

Treatment with P decreased the residual Zn(49.80 mg kg^{-1}) content when compared to the treatment without P (52.43 mg kg^{-1}). But it was observed that in treatment with zinc, the residual Zn increased (52.76 mg kg^{-1}) in comparison to the treatment without Zn (49.48 mg kg^{-1}). Residual Zncontentincreased (52.76 mg kg^{-1}) with the application of B and decreased in the case without the application of B (50.04 mg kg^{-1}). The soil with high P (S_3) recorded the highest residual Zncontent at this stage (55.07 mg kg^{-1}) which is significantly different from that on other soils.

Table 64a. Effect of applied P, Zn and B on Resd-Zn at flowering(mg kg^{-1})

	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	45.44	45.02	43.34	47.13	44.78	45.69	**45.23**
S_2	57.44	48.65	53.63	52.48	50.59	55.51	**53.05**
S_3	54.41	55.73	51.48	58.67	54.74	55.40	**55.07**
Mean	**52.43**	**49.80**	**49.48**	**52.76**	**50.04**	**52.20**	**51.12**

CD S 1.00 CD P 0.15 CD Zn 0.15 CD B 0.15

When the interaction effects were considered, the treatment Zn without P (P_0Zn_1) recorded significantly higher residual Zn(56.74 mg kg^{-1}) in comparison with all the other treatments. The lowest residual Zn(48.12 mg kg^{-1}) was recorded in the treatment without Zn and P (P_0Zn_0). Application of both B and P (P_1B_1) showed the highest residual Zn(52.99 mg kg^{-1}) and the treatment P without B (P_1B_0) has recorded the lowest residual Zn(48.20 mg kg^{-1}) concentration.

Table 64b. Effect of applied Zn and B with applied P on Resd-Zn at flowering ($mg\ kg^{-1}$)

	Zn_0	Zn_1	B_0	B_1	Mean
P_0	48.12	56.74	51.88	52.99	**52.43**
P_1	50.84	48.77	48.20	51.41	**49.81**
Mean	**49.48**	**52.76**	**50.04**	**52.20**	**51.12**

CD. P × Zn 0.25 **CD. P × B 0.25**

4.6.3.8. 2. Harvesting

Treatment with P slightly increased the residual Zn(45.59 $mg\ kg^{-1}$) content when compared to the treatment without P (45.36 $mg\ kg^{-1}$). In treatment with zinc also, the residual Zn increased slightly (45.69 $mg\ kg^{-1}$) in comparison to the treatment without Zn (45.26 $mg\ kg^{-1}$). Residual Zncontentincreased (46.74 $mg\ kg^{-1}$) with the application of B and decreased in the case without the application of B (44.22 $mg\ kg^{-1}$). The soil with high P (S3) recorded the highest residual Zncontent at this stage (53.85 $mg\ kg^{-1}$) which is significantly different from that on other soils.

Table 65a. Effect of applied P, Zn and B on Resd-Zn at harvest ($mg\ kg^{-1}$)

	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	40.85	40.69	40.62	40.93	38.84	42.70	**40.77**
S_2	41.98	41.63	43.59	40.03	39.58	44.04	**41.81**
S_3	53.25	54.46	51.58	56.13	54.23	53.48	**53.85**
Mean	**45.36**	**45.59**	**45.26**	**45.69**	**44.22**	**46.74**	**45.48**

CD S 0.79 CD P NS CD Zn NS CD B 0.65

When the interaction effects were considered, the treatment Zn without P (P_0Zn_1) recorded significantly higher residual Zn(46.98 $mg\ kg^{-1}$) in comparison with all the other treatments. The lowest residual Zn(43.74 mg kg^{-1}) was recorded in the treatment without Zn and P (P_0Zn_0). Application of both B and P (P_1B_1) showed the highest residual Zn(48.63 mg kg^{-1}) and the treatment P without B (P_1B_0) has recorded the lowest residual Zn(42.56 mg kg^{-1}) concentration at this stage. For interaction effects similar results were obtained during flowering stage.

Table 65b. Effect of applied Zn and B with applied P on Resd-Zn at harvest (mg kg^{-1})

	Zn_0	Zn_1	B_0	B_1	Mean
P_0	43.74	46.98	45.87	44.85	45.36
P_1	46.79	44.41	42.56	48.63	45.59
Mean	45.26	45.69	44.22	46.74	45.48

CD. P × Zn 0.91 **CD. P × B 0.91**

4.6.4. Fractions of boron at flowering and harvest

The details of fractions of boron at flowering and harvest are presented below.

4.6.4.1 Readily soluble boron (RS-B)

4.6.4.1.1. Flowering stage

Application of P (P_1) was found to decrease the readily soluble B (0.07 mg kg^{-1}) in comparison with the treatment without P (0.15 mg kg^{-1}). Application of Zn and B also showed similar pattern and showed a reduction in soluble B. Readily soluble B was more in the treatment with application of B (0.12 mg kg^{-1}). The soil with highest P (S_3) recorded the highest soluble B content (0.18 mg kg^{-1}) and soil with the lowest P recorded the lowest B content (0.01 mg kg^{-1}) at this stage.

Table 66a. Effect of applied P,Zn and B on RS-B at flowering (mg kg^{-1})

Soil/source	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	0.01	0.01	0.01	0.01	0.01	0.01	**0.01**
S_2	0.19	0.08	0.13	0.13	0.12	0.14	**0.13**
S_3	0.25	0.11	0.19	0.17	0.16	0.21	**0.18**
Mean	**0.15**	**0.07**	**0.11**	**0.10**	**0.10**	**0.12**	**0.11**

CD S 0.01 CD P 0.009 CD Zn 0.009 CD B 0.009

Among the interaction effects, the treatment without the application of P and with the application Zn (P_0Zn_1) recorded the highest soluble B (0.16 mg kg^{-1}) and the treatment with application of P with Zn (P_1Zn_1) recorded the lowest soluble B (0.05 mg kg^{-1}) at this stage. In the case of P-B interaction, application of B without P (P_0B_1) recorded highest value of readily soluble B (0.17 mg kg^{-1}) and the treatments(P_1B_0)and (P_1B_1) were on par and recorded the lowest soluble B (0.07 mg kg^{-1}).

Table 66b.Effect of applied Zn and B with applied P on RS-B at flowering (mg kg^{-1})

Sources	Zn_0	Zn_1	B_0	B_1	Mean
P_0	0.14	0.16	0.13	0.17	**0.15**
P_1	0.08	0.05	0.07	0.07	**0.07**
Mean	**0.11**	**0.10**	**0.10**	**0.12**	**0.11**

CD. P × Zn 0.01 CD. P × B 0.01

4.6.4.1.2. Harvesting stage

Application of P (P_1) was found to decrease the soluble B (0.08 mg kg^{-1}) in comparison with the treatment without P (0.16 mg kg^{-1}). The treatment with and without the application of Zn showed equal content of readily soluble B. Readily soluble B was more in the treatment with application of B (0.13 mg kg^{-1}). The soil with highest P (S_3) recorded the highest soluble B content (0.19 mg kg^{-1}) and soil with lowest P recorded lowest B content (0.02 mg kg^{-1}) during this stage.

Table 67a. Effect of applied P,Zn and B on RS-B at harvest(mg kg^{-1})

Soil/source	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	0.02	0.02	0.02	0.02	0.02	0.02	**0.02**
S_2	0.19	0.09	0.15	0.15	0.14	0.16	**0.15**
S_3	0.26	0.12	0.21	0.18	0.17	0.22	**0.19**
Mean	**0.16**	**0.08**	**0.12**	**0.12**	**0.11**	**0.13**	**0.12**

CD S 0.01 CD P 0.01 CD Zn NS CD B 0.01

Among the interaction effects, the treatment without the application of P and with the application Zn (P_0Zn_1) recorded the highest soluble B (0.17 mg kg^{-1}) and the treatment with application of P with Zn (P_1Zn_1) recorded the lowest soluble B (0.06 mg kg^{-1}) at this stage. In the case of P-B interaction, the treatment without P and with B (P_0B_1) recorded highest value of available B (0.19 mg kg^{-1}) and the treatments P_1B_0 and P_1B_1 were on par and recorded the lowest soluble B (0.08 mg kg^{-1}).

Table 67b. Effect of applied Zn and B with applied P on RS-B at harvest(mg kg^{-1})

Sources	Zn_0	Zn_1	B_0	B_1	Mean
P_0	0.15	0.17	0.14	0.19	**0.16**
P_1	0.10	0.06	0.08	0.08	**0.08**
Mean	**0.12**	**0.12**	**0.11**	**0.13**	**0.12**

CD. P × Zn 0.012 **CD. P × B 0.012**

4.6.4.2 Specifically adsorbed boron (Sp.Ad-B)

4.6.4.2.1. Flowering stage

The highest value of specifically adsorbed B (0.18 mg kg^{-1}) was recorded in the case of treatment with the application of P (P_1) and the lowest value (0.09 mg kg^{-1}) was recorded in the treatment without application of P (P_0). But, the treatment without Zn has showed the highest value and the treatment with Zn has showed the lowest value for specifically adsorbed B. Similarly, in the case of treatment without the application of B, the specifically adsorbed Bcontent was higher (0.14 mg kg^{-1}) than the treatment with the application of B. The highest value for specifically adsorbed B(0.21 mg kg^{-1}) was recorded in the soil with medium P.

Table 68a. Effect of applied P,Zn and B on Sp.Ad-B at flowering (mg kg^{-1})

Soil/source	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	0.02	0.02	0.02	0.02	0.02	0.02	**0.02**
S_2	0.30	0.12	0.23	0.20	0.22	0.20	**0.21**
S_3	0.23	0.12	0.21	0.13	0.17	0.18	**0.17**
Mean	**0.18**	**0.09**	**0.15**	**0.12**	**0.14**	**0.13**	**0.14**

CD S 0.009 CD P 0.008 CD Zn 0.008 CD B 0.008

When the interaction effect was considered the treatment without P and with B (P_0B_1)and treatment without P and Zn (P_0Zn_0) and (P_0Zn_1) was on par and showed equal quantity of specifically adsorbed B(0.18 mg kg^{-1}). The treatment without application of P and Zn (P_1Zn_1) recorded highest value (0.05 mg kg^{-1}) for specifically adsorbed B.

Table 68b. .Effect of applied Zn and B with applied P on Sp.Ad-B at flowering (mg kg^{-1})

Sources	Zn_0	Zn_1	B_0	B_1	Mean
P_0	0.18	0.18	0.17	0.20	**0.18**
P_1	0.13	0.05	0.10	0.07	**0.09**
Mean	**0.15**	**0.12**	**0.14**	**0.13**	**0.13**

CD. P × Zn 0.01 **CD. P × B 0.01**

4.6.4.2.2.Harvesting stage

The highest value of specifically adsorbed B (0.19 mg kg^{-1}) was recorded in the case of treatment without the application of P (P_0) and the lowest value (0.09 mg kg^{-1}) was recorded in the treatment with application of P (P_1). But, the treatment without Zn has showed the highest value and the treatment with Zn has showed the lowest value for specifically adsorbed B. Similarly, in the case of treatment without the application of B, the specifically adsorbed B content was lower (0.13 mg kg^{-1}) than the treatment with the application of B. The highest value for specifically adsorbed B (0.20 mg kg^{-1}) was recorded in the soil with the highest P.

Table 69a. Effect of applied P,Zn and B on Sp.Ad-B at harvest (mg kg^{-1})

Soil/source	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	0.03	0.03	0.03	0.03	0.03	0.03	**0.03**
S_2	0.25	0.12	0.19	0.19	0.19	0.19	**0.19**
S_3	0.27	0.13	0.22	0.19	0.18	0.22	**0.20**
Mean	**0.19**	**0.09**	**0.15**	**0.13**	**0.13**	**0.15**	**0.14**

CD S 0.02 CD P 0.01 CD Zn 0.01 CD B 0.01

When the interaction effect was considered the treatment without P and with B and treatment without P and Zn (P_0Zn_0 and P_0Zn_1 respectively) was on par and showed equal quantity of specifically adsorbed B(0.18 mg kg^{-1}). The treatment with application of P and without application of Zn (P_1Zn_0) recorded highest value (0.13 mg kg^{-1}) for specifically adsorbed B.

Table 69b. Effect of applied Zn and B with applied P on Sp.Ad-B at harvest(mg kg^{-1})

Sources	Zn_0	Zn_1	B_0	B_1	Mean
P_0	0.18	0.20	0.17	0.21	**0.19**
P_1	0.11	0.07	0.10	0.09	**0.09**
Mean	**0.15**	**0.13**	**0.13**	**0.15**	**0.14**

CD. P Zn × 0.03 CD. P × B 0.03

4.6.4.3 Oxide bound boron (OX-B)

4.6.4.3.1. Flowering stage

Treatment without P decreased the oxide bound B (1.30mg kg^{-1}) content when compared to the treatment with P (1.92 mg kg^{-1}). It was observed that in treatment with zinc, the oxide bound B decreased (1.61 mg kg^{-1}) in comparison to the treatment without Zn (1.62 mg kg^{-1}). Oxide bound B content (44.07 mg kg^{-1}) decreased without the application of B and increased in the case with the application of B (1.69 mg kg^{-1}). The soil with low P (S_1) recorded the highest oxide bound B content at this stage (1.41mg kg^{-1}) and the soil with highest P recorded the highest oxide bound B (1.87 mg kg^{-1}) content.

Table 70a. Effect of applied P,Zn and B on OX-B at flowering (mg kg^{-1})

Soil/source	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	1.17	1.64	1.50	1.33	1.28	1.54	**1.41**
S_2	1.13	2.00	1.46	1.68	1.48	1.66	**1.57**
S_3	1.60	2.13	1.90	1.83	1.87	1.86	**1.87**
Mean	**1.30**	**1.92**	**1.62**	**1.61**	**1.54**	**1.69**	**1.61**

CD S 0.05 CD P 0.02 CD Zn 0.02 CD B 0.02

When the interaction effects were considered, the treatment with P and Zn (P_1Zn_1) recorded significantly higher oxide bound B (2.00 mg kg^{-1}) in comparison with other treatments. The lowest (1.23 mg kg^{-1}) oxide bound B was recorded in the treatment without P and with Zn (P_0Zn_1). Application of B with P (P_1B_1) showed the highest oxide bound B (2.02 mg kg^{-1}) and the treatment without B and P (P_0B_0) recorded the lowest oxide bound B (1.25 mg kg^{-1}) fraction at flowering stage.

Table 70b. Effect of applied Zn and B with applied P on OX-B at flowering(mg kg^{-1})

Sources	Zn_0	Zn_1	B_0	B_1	Mean
P_0	1.37	1.23	1.25	1.35	**1.30**
P_1	1.85	2.00	1.80	2.02	**1.92**
Mean	**1.62**	**1.61**	**1.54**	**1.69**	**1.61**

CD. P × Zn 0.05 **CD. P × B 0.05**

4.6.4.3.2. Harvesting stage

Treatment with P increased the oxide bound B (1.94 mg kg^{-1}) content when compared to the treatment without P (1.32 mg kg^{-1}). Oxide bound B content (1.56 mg kg^{-1}) decreased in the case without the application of B and increased in the case with the application of B (1.70 mg kg^{-1}). The soil with the highest P (S_3) recorded the highest oxide bound B content at this stage (1.88mg kg^{-1}) and the soil with lowest P recorded the lowest oxide bound B (1.87 mg kg^{-1}) content.

Table 71a. Effect of applied P,Zn and B on OX-B at harvest (mg kg^{-1})

Soil/source	P_0	P_1	Zn_0	ZN_1	B_0	B_1	Mean
S_1	1.19	1.66	1.50	1.34	1.29	1.55	**1.42**
S_2	1.15	2.02	1.47	1.69	1.50	1.67	**1.58**
S_3	1.61	2.15	1.91	1.85	1.89	1.88	**1.88**
Mean	**1.32**	**1.94**	**1.63**	**1.63**	**1.56**	**1.70**	**1.63**

CD S 0.06 **CD P 0.04** **CD Zn NS** **CD B 0.04**

When the interaction effects were considered, the treatment with P and Zn (P_1Zn_1) recorded significantly higher oxide bound B (2.01 mg kg^{-1}) in comparison with other treatments. The lowest (1.25 mg kg^{-1}) oxide bound B was recorded in the treatment without P and with Zn (P_0Zn_1).*Application of* B with P (P_1B_1) showed the highest oxide bound B (2.04 mg kg^{-1}) and the treatment without B and P (P_0B_0) recorded the lowest oxide bound B (1.27 mg kg^{-1}) fraction at harvesting stage.

Table 71b. Effect of applied Zn and B with applied P on OX-B at harvest(mg kg^{-1})

Source	Zn_0	Zn_1	B_0	B_1	Mean
P_0	1.39	1.25	1.27	1.37	**1.32**
P_1	1.87	2.01	1.85	2.04	**1.94**
Mean	**1.63**	**1.63**	**1.56**	**1.70**	**1.63**

CD. P × Zn 0.06 **CD. P × B 0.06**

4.6.4.4. *Organic matter bound boron* (OM-B)

4.6.4.4.1. Flowering stage

The organic matter bound B content increased in the treatment with the application of P (1.57 mg kg^{-1}) and decreased in the case without P (1.15 mg kg^{-1}). The treatment with Zn was having higher organic matter bound B (1.39 mg kg^{-1}) than treatment without Zn (1.32 mg kg^{-1}). Application of B was found to increase the organic matter bound B (1.40 mg kg^{-1}) in comparison to treatment without B (1.31 mg kg^{-1}). The soil with the highest P (S_1) recorded the highest organic matter bound B *content at this stage* (1.63^{-1}) which is significantly different from soil with the lowest and medium P.

Table 72a. Effect of applied P,Zn and B on OM-B at flowering(mg kg^{-1})

Soil/source	P_0	P_1	Zn_0	ZN_1	B_0	B_1	Mean
S_1	1.03	1.25	1.10	1.15	1.01	1.27	**1.14**
S_2	1.07	1.54	1.23	1.37	1.26	1.34	**1.30**
S_3	1.35	1.91	1.62	1.64	1.66	1.60	**1.63**
Mean	**1.15**	**1.57**	**1.32**	**1.39**	**1.31**	**1.40**	**1.36**

CD S 0.02 CD P 0.02 CD Zn 0.02 CD B 0.02

The treatment P with Zn (P_1Zn_1) recorded the highest organic matter bound B (1.62 mg kg^{-1}) content. Treatment with and without Zn and without P (P_0Zn_1 and P_0Zn_0) were on par and recorded the lowest value of (1.15 mg kg^{-1}) organic matter bound B. Application of treatment with P and B (P_1B_1) was found to be significantly higher than the treatment without P and B (P_0B_0) which has recorded a value of 1.10 mg kg^{-1}.

Table 72b. Effect of applied Zn and B with applied P on OM-B at flowering (mg kg^{-1})

Source	Zn_0	Zn_1	B_0	B_1	Mean
P_0	1.15	1.15	1.10	1.20	**1.15**
P_1	1.51	1.62	1.52	1.62	**1.57**
Mean	**1.32**	**1.39**	**1.31**	**1.40**	**1.36**

CD. P × Zn 0.022 CD. P ×B 0.022

4.6.4.4.1. Harvesting stage

The organic matter bound B content increased in the treatment with the application of P (1.58 mg kg^{-1}) and decreased in the case without P (1.16 mg kg^{-1}). The treatment with Zn was higher (1.40 mg kg^{-1}) than the treatment without Zn (1.34 mg kg^{-1}). Application of B was found to increase the organic matter bound B (1.42 mg kg^{-1}) in comparison to treatment without B (1.32 mg kg^{-1}). The soil with the highest P (S_1) recorded the highest organic matter bound B content at this stage (1.64 mg kg^{-1}) which is significantly different from soil with the lowest and medium P.

Table 73a. Effect of applied P,Zn and B on OM-B at harvest (mg kg^{-1})

Soil/source	P_0	P_1	Zn_0	ZN_1	B_0	B_1	Mean
S_1	1.04	1.26	1.14	1.16	1.02	1.28	**1.15**
S_2	1.08	1.55	1.24	1.39	1.28	1.35	**1.31**
S_3	1.36	1.92	1.63	1.65	1.67	1.61	**1.64**
Mean	**1.16**	**1.58**	**1.34**	**1.40**	**1.32**	**1.42**	**1.37**

CD S 0.03 CD P 0.03 CD Zn 0.03 CD B 0.03

The treatment P with Zn (P_1Zn_1) has recorded the highest organic matter bound B (1.64 mg kg^{-1}) content. Treatments with and without Zn and without P (P_0Zn_1 and P_0Zn_0) were on par and recorded the lowest value of 1.16 mg kg^{-1}. Application of treatment with P and B (P_1B_1) was found to be significantly higher than the treatment without P and B (P_0B_0) which has recorded a value of 1.10 mg kg^{-1}.

Table 73b. Effect of applied Zn and B with applied P OM-B at harvest (mg kg^{-1})

Source	Zn_0	Zn_1	B_0	B_1	Mean
P_0	1.16	1.16	1.12	1.21	**1.16**
P_1	1.52	1.64	1.53	1.63	**1.58**
Mean	**1.34**	**1.40**	**1.32**	**1.42**	**1.37**

CD. P ×Zn 0.04 **CD. P ×B 0.04**

4.6.4.5. Residual boron (Resd-B)

4.6.4.5.1. Flowering stage

The treatment effect was significantly higher with P (29.44 mg kg^{-1}) than without P (26.53 mg kg^{-1}) on the of residual B. Application of Zn increased the residual B when compared to the treatment without Zn. Residual B was highest (28.10 mg kg^{-1}) without the application of B and lowest (27.81 mg kg^{-1}) with the application of B. The soil with the highest P (29.20 mg kg^{-1}) recorded significantly higher amount of residual B compared with other soil at this stage.

Table 74a. Effect of applied P,Zn and B on Resd-B at flowering (mg kg^{-1})

Soil/source	P_0	P_1	Zn_0	ZN_1	B_0	B_1	Mean
S_1	26.57	27.87	27.08	27.27	28.64	25.71	**27.19**
S_2	26.01	29.00	26.51	28.50	26.62	28.39	**27.51**
S_3	27.00	31.44	29.55	28.82	29.05	29.33	**29.20**

Mean	26.53	29.44	27.71	28.20	28.10	27.81	27.96

CD S 0.50 CD P 0.42 CD Zn 0.42 CD B NS

In the case of interaction effect, treatment with P and Zn (P_1Zn_1) resulted in higher (29.61 mg kg^{-1}) residual B compared to the other treatments. The effect of treatment without P and with B resulted in the lowest (26.46 mg kg^{-1}) residual B and the treatment with P and without B (P_1B_0) recorded the highest (29.66 mg kg^{-1}) the highest residual B.

Table 74b. Effect of applied Zn and B with applied P on Resd-B at flowering(mg kg^{-1})

Source	Zn_0	Zn_1	B_0	B_1	Mean
P_0	26.23	26.78	26.54	26.46	**26.53**
P_1	29.20	29.61	29.66	29.15	**29.44**
Mean	**27.71**	**28.20**	**28.10**	**27.81**	**27.95**

CD. P × Zn 0.60 CD. P × B 0.60

4.6.4.5.1. Harvesting stage

The treatment effect was significantly higher with P (27.04 mg kg^{-1}) than without P (24.60 mg kg^{-1}). The soil with the highest P (26.71 mg kg^{-1}) recorded significantly higher amount of residual B compared with other soil at this stage.

Table 75a. Effect of applied P,Zn and B on Resd-B at harvest (mg kg^{-1})

Soil/source	P_0	P_1	Zn_0	ZN_1	B_0	B_1	Mean
S_1	25.19	25.68	25.44	25.43	27.03	23.83	**25.43**
S_2	24.03	26.59	24.38	26.24	24.48	26.14	**25.31**

S_3	24.56	28.85	27.07	26.34	26.58	26.83	**26.71**
Mean	**24.60**	**27.04**	**25.63**	**26.00**	**26.03**	**25.60**	**25.82**

CD S 1.5 CD P 0.95 CD Zn NS CD B NS

In the case of interaction effect, treatment with P and Zn (27.20 mg kg^{-1}) increased the residual B compared to the other treatments. The effect of treatment without P and with B was the lowest (24.48 mg kg^{-1}) and the treatment with P and without B was the highest (27.34 mg kg^{-1}) at this satge.

Table 75b. Effect of applied Zn and B with applied P on Resd-B at harvest (mg kg^{-1})

Source	**Zn_0**	**Zn_1**	**B_0**	**B_1**	**Mean**
P_0	24.40	24.80	24.72	24.48	**24.60**
P_1	26.86	27.20	27.34	26.73	**27.04**
Mean	**25.63**	**26.00**	**26.03**	**25.60**	**25.82**

CD. P × Zn 1.09 CD. P × B 1.09

4.6.5. Nutrient content in plant at flowering and harvest

The details of nutrient concentration in plant at flowering are presented below.

4.6.5.1. Nitrogen

4.6.5.1.1. Flowering

Application of phosphorus was found to reduce the nitrogen content in plant (3.06%) as compared to that without application of P (3.18%). Plant nitrogen content was significantly higher in the treatment with application of zinc (3.27%) than that without zinc application. Boron application was found to reduce the plant nitrogen content (2.91%) in comparison to that of the treatment without B (3.33%). The P rich soil (S_3) recorded the highest plant nitrogen content (3.38%).

Table 76a.Effect of applied P,Zn and B on N content in plant at flowering (%)

	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	2.91	3.06	2.80	3.17	2.98	3.00	**2.99**
S_2	3.01	2.97	3.03	2.97	3.36	2.64	**3.00**
S_3	3.62	3.14	3.10	3.66	3.67	3.10	**3.38**
Mean	**3.18**	**3.06**	**2.98**	**3.27**	**3.33**	**2.91**	**3.12**

CD S .04 **CD P 0.02** **CD Zn 0.02** **CD B0.02**

Among the interaction the treatment with application of zinc without phosphorus (P_0Zn_1) recorded significantly higher plant nitrogen content (3.43%) than all other treatment combinations of P and Zn. Application of phosphorus without boron (P_1B_0) recorded the highest plant nitrogen content (3.35%) compared with that of all other treatment combinations of P and B.

Table 76b . Effect of Zn and B with applied P on N content in plant at flowering (%)

	Zn_0	Zn_1	B_0	B_1	Mean
P_0	2.94	3.43	3.32	3.05	**3.18**
P_1	3.02	3.10	3.35	2.77	**3.06**
Mean	**2.98**	**3.27**	**3.33**	**2.91**	**3.12**

CD P Zn 0.04 **CD P B 0.04**

4.6.5.1.2. Harvesting

Application of phosphorus wasfound to reduce the nitrogen content in plant (2.52%) compared to that of the treatment without application of P (2.79%). Plant nitrogen content was significantly higher in the treatment with application of zinc (2.87%) than that without zinc application. Boron application was found to reduce the plant nitrogen content (2.44%) in comparison to that the treatment without B (2.87%). The P rich soil (S_3) recorded the highest plant nitrogen content (2.86%).

Table 77a. Effect of applied P,Zn and B on N content in plant at harvest (%)

	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	2.68	2.52	2.35	2.85	2.48	2.72	**2.60**
S_2	2.58	2.45	2.47	2.56	2.96	2.07	**2.51**
S_3	3.11	2.60	2.50	3.21	3.16	2.55	**2.86**
Mean	**2.79**	**2.52**	**2.44**	**2.87**	**2.87**	**2.44**	**2.66**

CD S 0.023 CD P 0.022 CD Zn 0.022 CD B 0.022

Among the interaction, the treatment with application of zinc without phosphorus (P_0Zn_1) recorded significantly higher plant nitrogen content (3.14%) than all other treatment combinations of P and Zn. Treatment without the application of both phosphorus and boron (P_0B_0) recorded the highest plant nitrogen content (2.91%) compared to all other treatment combinations of P and B.

Table 77b. Effect of Zn and B with applied P on N content in plant at harvest (%)

	Zn_0	Zn_1	B_0	B_1	Mean
P_0	2.44	3.14	2.91	2.67	**2.79**
P_1	2.44	2.61	2.82	2.22	**2.52**

Mean	2.44	2.87	2.87	2.44	2.66

CD P × Zn 0.04 **CD P × B 0.04**

4.6.5.2. Phosphorus

4.6.5.2.1. Flowering

Application of P (P_1) was found to increase the plant P content (0.29%) in comparison to the treatment without P (0.19%). The treatment with boron significantly reduced the plant P content at this stage. The soil with the highest P (S_3) recorded the highest plant P content (0.27%).

Table 78a. Effect of applied P,Zn and B on Pcontent in plant at flowering (%)

	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	0.14	0.26	0.23	0.17	0.19	0.21	**0.20**
S_2	0.22	0.28	0.26	0.24	0.28	0.23	**0.25**
S_3	0.21	0.32	0.24	0.29	0.29	0.24	**0.27**
Mean	**0.19**	**0.29**	**0.24**	**0.24**	**0.25**	**0.23**	**0.24**

CD S 0.01 CD P 0.009 CD Zn NS CD B 0.009

Among the interaction effects, the treatment with application of P without Zn recorded the highest plant P content (0.29%). The same trend was followed in phosphorus-boron interaction.

Table 78b.Effect of Zn and B with applied P on P content in plant at flowering (%)

	Zn_0	Zn_1	B_0	B_1	Mean
P_0	0.20	0.19	0.18	0.20	**0.19**
P_1	0.29	0.27	0.32	0.25	**0.29**
Mean	**0.24**	**0.24**	**0.25**	**0.23**	**0.24**

CD. P × Zn 0.01 CD. P × B 0.01

4.6.5.2.2. Harvesting

The P content in plant was significantly higher (0.33%) in treatment with phosphorus (P_1) in comparison with the treatment without P (0.26%). Application of zinc and boron was found to slightly reduce the P content in cowpea plant. Highest P content (0.34%) was recorded in plant grown in high P soil (S_3).

Table 79a. Effect of applied P,Zn and B on P content in plant at harvest (%)

	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	0.19	0.32	0.27	0.24	0.25	0.27	**0.26**
S_2	0.29	0.28	0.32	0.26	0.28	0.29	**0.29**
S_3	0.29	0.39	0.30	0.38	0.36	0.32	**0.34**
Mean	**0.26**	**0.33**	**0.30**	**0.29**	**0.30**	**0.29**	**0.29**

CD S .01 CD P 0.009 CD Zn 0.009 CD B 0.009

Among the interaction effects, application of phosphorus without zinc recorded the highest plant P (0.34%) and the treatment without P and Zn recorded the lowest plant P (0.26%). Similar was the effect of boron on plant P content.

Table 79b.Effect of Zn and B with applied P on P content in plant at harvest (%)

	Zn_0	Zn_1	B_0	B_1	Mean
P_0	0.26	0.27	0.25	0.27	**0.26**
P_1	0.34	0.32	0.35	0.31	**0.33**
Mean	**0.30**	**0.29**	**0.30**	**0.29**	**0.29**

CD. P × Zn 0.01 **CD. P × B NS 0.01**

4.6.5.3. Potassium

4.6.5.3.1. Flowering

Treatment with P increased the plant K (2.58 %) content when compared to the treatment without P (2.23 %). The potassium content in plant was significantly higher (2.54%) in treatment with zinc than that of the treatment without zinc (2.35%); however plant K content decreased (2.32 %) with the application of boron and increased in the treatment without the application of boron (2.57 %). The soil with low P (S_1) and medium P (S_2) recorded the highest plant K content at this stage (2.53 % and 2.52%) which is significantly different from that of other soils.

Table 80a. Effect of applied P,Zn and B on K content in plant at flowering (%)

	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	2.29	2.58	2.63	2.51	2.81	2.33	**2.53**
S_2	2.50	2.53	2.20	2.83	2.49	2.54	**2.52**
S_3	1.89	2.62	2.21	2.29	2.41	2.10	**2.25**
Mean	**2.23**	**2.58**	**2.35**	**2.54**	**2.57**	**2.32**	**2.43**

CD S 0.06 **CD P 0.06** **CD Zn 0.06** **CD B 0.06**

When the interaction effects were considered, the treatment with P and Zn (P_1Zn_1) recorded significantly higher plant K content (2.72%) in comparison with all the other treatment combinations of P and Zn. The lowest plant K content (2.08 %) was recorded in the treatment without Zn and P (P_0Zn_0). Application of P without B (P_1B_0) showed the highest plant K (2.75%) and the treatment B without P (P_0B_1) has recorded the lowest plant K (2.07 %) concentration.

Table 80b. Effect of Zn and B with applied P on K content in plant at flowering (%)

	Zn_0	**Zn_1**	**B_0**	**B_1**	**Mean**
P_0	2.08	2.37	2.34	2.07	**2.22**
P_1	2.61	2.72	2.75	2.58	**2.67**
Mean	**2.35**	**2.55**	**2.55**	**2.33**	**2.44**

CD. P × Zn 0.10 **CD. P × B 0.10**

4.6.5.3.2. Harvesting

The content in plant was significantly higher (2.73%) in treatment with P than that the treatment without P (2.60%). Application of zinc was found to increase the potassium content in plant significantly (2.75%); however application of boron decreased the plant K content (2.61%) significantly in comparison to the treatment without application of boron which has recorded a value of 2.71%. The soil with low P (S_1) recorded the highest K (2.78%) content which is significantly different from the other two soils.

Table 81a.Effect of applied P,Zn and B on K content in plant at harvest (%)

	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	2.55	3.00	3.03	2.53	2.91	2.64	**2.78**
S_2	2.71	2.53	2.28	2.96	2.67	2.58	**2.62**
S_3	2.51	2.67	2.42	2.76	2.56	2.62	**2.59**
Mean	**2.60**	**2.73**	**2.58**	**2.75**	**2.71**	**2.61**	**2.66**

CD S 0.02 CD P 0.017 CD Zn 0.017 CD B 0.017

When the interaction effects were considered, the treatment with P and Zn (P_1Zn_1) recorded significantly higher plant K (2.85%) in comparison with all the other treatment combinations of P and Zn. The lowest plant K (2.53%) was recorded in the treatment without Zn and P (P_0Zn_0). The treatment with application of phosphorus and boron recorded highest potassium content (2.89%) in plant and the treatment with application of boron without phosphorus has recorded the lowest K content (2.34%).

Table 81b. Effect of Zn and B with applied P on K content in plant at harvest (%)

	Zn_0	Zn_1	B_0	B_1	Mean
P_0	2.53	2.65	2.85	2.34	**2.60**
P_1	2.62	2.85	2.58	2.89	**2.73**
Mean	**2.58**	**2.75**	**2.71**	**2.61**	**2.66**

CD. P × Zn 0.02 CD. P × B 0.02

4.6.5.4. Calcium

4.6.5.4.1. Flowering

Both the treatment and interaction effects were non-significant with respect to available plant Ca content.

Table 82a. Effect of applied P,Zn and B on Ca content in plant at flowering (%)

	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	1.11	1.20	1.29	1.19	1.24	1.28	**1.22**
S_2	1.15	1.30	1.12	1.12	1.22	1.22	**1.19**
S_3	1.21	1.05	1.31	1.50	1.17	1.22	**1.24**
Mean	**1.16**	**1.18**	**1.24**	**1.27**	**1.21**	**1.24**	**1.22**

CD S NS CD P NS CD Zn NS CD B NS

Table 82b. Effect of Zn and B with applied P on Ca content in plant at flowering (%)

	Zn_0	Zn_1	B_0	B_1	Mean
P_0	1.12	1.13	1.00	1.10	**1.16**
P_1	1.14	1.14	1.10	1.21	**1.18**
Mean	**1.24**	**1.27**	**1.21**	**1.24**	**1.24**

CD. P × Zn NS CD. P × B NS

4.6.5.4.2. Harvesting

The main effects as well as the interaction effects of P, Zn, and B were not significant with respect to calcium content in plant.

Table 83a. Effect of applied P,Zn and B on Ca content in plant at harvest (%)

	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	1.24	1.54	1.45	1.33	1.34	1.44	**1.39**
S_2	1.19	1.42	1.05	1.57	1.28	1.34	**1.31**
S_3	1.06	1.14	1.01	1.20	1.27	0.94	**1.10**
Mean	**1.17**	**1.37**	**1.17**	**1.37**	**1.30**	**1.24**	**1.27**

CD S NS CD P NS CD Zn NS CD B NS

Table 83b. Effect of Zn and B with applied P on Ca content in plant at harvest (%)

	Zn_0	Zn_1	B_0	B_1	Mean
P_0	1.10	1.23	1.13	1.20	**1.17**
P_1	1.23	1.50	1.46	1.27	**1.37**
Mean	**1.17**	**1.37**	**1.30**	**1.24**	**1.27**

CD. P × Zn NS **CD. P × B NS**

4.6.5.5. Magnesium

4.6.5.5.1. Flowering

Mg content in plant increased with the application of P (0.34 %) when compared to the treatment without P (0.28 %). The treatment with Zn recorded the lowest Mg content in plant (0.30 %) comparedto the treatment without Zn (0.32 %). Treatment with B also showed similar effects like that of Zn. The soil with medium P (S_2) recorded the highest Mg content in plant at this stage (0.34%) which is significantly different from theother two soils.

Table 84a. Effect of applied P,Zn and B on Mg content in plant at flowering (%)

	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	0.31	0.30	0.32	0.29	0.34	0.27	**0.30**
S_2	0.27	0.42	0.34	0.34	0.38	0.31	**0.34**
S_3	0.26	0.31	0.30	0.28	0.26	0.32	**0.29**
Mean	**0.28**	**0.34**	**0.32**	**0.30**	**0.33**	**0.30**	**0.31**

CD S 0.02 **CD P 0.01** **CD Zn 0.01** **CD B 0.01**

Among the interaction effects, the treatment with application of both phosphorus and zinc (P_1Zn_1) and the treatment with application of phosphorus without zinc (P_1Zn_0) have significantly increased the plant Mg (0.34 %) in comparison with other two treatment combinations. The treatment with application of both P and B (P_1B_1) and treatment with P and without B (P_1B_0) has significantly increased the Mg content in plant (0.34 %). Interaction effect of B without P (P_0B_1) recorded the lowest Mg content in plant (0.26 %).

Table 84b.Effect of Zn and B with applied P on Mg content in plant at flowering (%)

	Zn_0	Zn_1	B_0	B_1	Mean
P_0	0.30	0.26	0.29	0.26	**0.28**
P_1	0.34	0.34	0.34	0.34	**0.34**
Mean	**0.32**	**0.30**	**0.32**	**0.30**	**0.31**

CD. P × Zn 0.02 **CD. P × B 0.02**

4.6.5.5.2. Harvesting

The magnesium content in plant has increased (0.44%) with application of phosphorus when compared with the treatment without P application (0.37%). Application of zinc has decreased plant magnesium content (0.39%), while the treatment without zinc increased the plant magnesium content (0.42%) significantly. The treatment without application of boron recorded significantly higher (0.43%) magnesium content than the treatment with boron (0.38%).

Table 85a.Effect of applied P,Zn and B on Mg content in plant at harvest (%)

	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	0.40	0.41	0.44	0.38	0.44	0.38	**0.41**
S_2	0.33	0.52	0.43	0.42	0.48	0.38	**0.43**
S_3	0.36	0.39	0.39	0.36	0.35	0.40	**0.38**
Mean	**0.37**	**0.44**	**0.42**	**0.39**	**0.43**	**0.38**	**0.40**

CD S 0.009 CD P 0.008 CD Zn 0.008 CD B 0.008

Among the interaction effects, application of with P without Zn (P_1Zn_0) has significantly increased the Mg content in plant (0.46%) in comparison with other treatment combinations of P and Zn. Application of boron without phosphorus (P_0B_1) recorded the lowest Mg content (0.35%), while application of P without boron (P_1B_0) recorded the highest plant magnesium content (0.47%).

Table 85b. Effect of Zn and B with applied P on Mg content in plant at harvest (%)

	Zn_0	Zn_1	B_0	B_1	Mean
P_0	0.38	0.34	0.38	0.35	**0.37**
P_1	0.46	0.43	0.47	0.42	**0.44**
Mean	**0.42**	**0.39**	**0.43**	**0.38**	**0.40**

CD. P × Zn 0.01 CD. P × B 0.01

4.6.5.6. Sulphur

4.6.5.6.1. Flowering

The sulphur content in plant did not differ significantly with and without application of phosphorus where as application of zinc and boron increased the sulphur content (0.30% and 0.29% respectively) significantly when compared with treatments without zinc and boron (0.26% and 0.27% respectively). The soil with low P (S_1) recorded the lowest sulphur content in plant (0.25%).

Table 86a. Effect of applied P,Zn and B on S content in plant at flowering (%)

	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	0.24	0.26	0.24	0.27	0.24	0.27	**0.25**
S_2	0.30	0.28	0.26	0.32	0.32	0.26	**0.29**
S_3	0.28	0.30	0.28	0.30	0.25	0.33	**0.29**
Mean	**0.28**	**0.28**	**0.26**	**0.30**	**0.27**	**0.29**	**0.28**

CD S 0.006 CD P NS CD Zn 0.005 CD B 0.005

Comparison of interaction effects between P and Zn revealed that zinc application without P (P_0Zn_1) recorded the highest plant sulphur content (0.31%) whereas the treatment without P and Zn (P_0Zn_0) recorded the lowest S content (0.24%). Similarly application of boron without phosphorus (P_0B_1) did increase the sulphur content (0.30%) while the treatment without P and B recorded the lowest sulphur content (0.25%) in plant.

Table 86b. Effect of Zn and B with applied P on S content in plant at flowering (%)

	Zn_0	Zn_1	B_0	B_1	Mean
P_0	0.24	0.31	0.26	0.30	**0.28**
P_1	0.28	0.28	0.28	0.28	**0.28**
Mean	**0.26**	**0.30**	**0.27**	**0.29**	**0.28**

CD P × Zn 0.007 CD P × B 0.007

4.6.5.6.2. Harvesting

The sulphur content in plant did not differ significantly with and without application, of phosphorus where as application of zinc and boron increased the sulphur content (0.31% and 0.30% respectively) significantly when compared with treatments without zinc and boron (0.28% and 0.29% respectively). The soil with low P (S_1) recorded the lowest sulphur content in plant (0.73%).

Table 87a.Effect of applied P,Zn and B on S content in plant at harvest (%)

	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	0.26	0.28	0.26	0.29	0.26	0.29	**0.27**
S_2	0.32	0.30	0.28	0.34	0.34	0.28	**0.31**
S_3	0.29	0.30	0.29	0.30	0.27	0.33	**0.30**
Mean	**0.29**	**0.29**	**0.28**	**0.31**	**0.29**	**0.30**	**0.29**

CD S .01 CD P NS CD Zn 0.008 CD B 0.008

Comparison of interaction effects between P and Zn revealed that zinc application without P (P_0Zn_1) recorded the highest plant sulphur content (0.33%) where as the treatment without P and Zn (P_0Zn_0) recorded the lowest S content (0.26%). Similarly application of boron without phosphorus (P_0B_1) did increase the sulphur content (0.31%) while the treatment without P and B recorded the lowest sulphur content (0.28%) in plant.

Table 87b. Effect of Zn and B with applied P on S content in plant at harvest (%)

	Zn_0	Zn_1	B_0	B_1	Mean
P_0	0.26	0.33	0.28	0.31	**0.29**
P_1	0.29	0.30	0.30	0.29	**0.29**
Mean	**0.28**	**0.31**	**0.29**	**0.30**	**0.29**

CD P × Zn .02 CD P × B 0.02

4.6.5.7. Iron

4.6.5.7.1. Flowering

Treatment with P significantly increased the plant Fe content (594.20 mg kg^{-1}) when compared to the treatment without application of phosphorus (540.25 mg kg^{-1}). It was observed that in the treatment where Zn was applied, plant Fe content decreased (565.60 mg kg^{-1}). Application of B also was found to increase the plant Fe content (590.30 mg kg^{-1}) in comparison to the treatment without B (544.27 mg kg^{-1}). The soil with low P (S_1) recorded the highest plant Fe content at this stage (579.36 mg kg^{-1}) which is significantly different from that of theother two soils.

Table 88a. Effect of applied P,Zn and B on Fe content in plant at flowering (mg kg^{-1})

	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	561.83	596.91	596.20	562.50	550.91	607.83	**579.36**
S_2	506.00	586.10	508.50	583.90	516.08	576.33	**546.15**
S_3	552.91	599.60	602.10	550.41	565.83	586.75	**576.27**
Mean	**540.25**	**594.20**	**568.93**	**565.60**	**544.27**	**590.30**	**567.26**

CD S 11.60 CD P 9.80 CD Zn 9.80 CD B 9.80

Among the interaction effects, the treatment with application of both P and Zn (P_1Zn_1) recorded significantly higher plant Fe content (599.83mg kg^{-1}). The lowest plant Fe was recorded in the treatment with application of zinc without phosphorus (P_0Zn_1) i.e., 531.38 mg kg^{-1}. Application of treatments with P and without B (P_1B_0) recorded the highest plant Fe (599.90 kg^{-1}) content and the treatment without P and B (P_0B_0) recorded the lowest plant Fe content (488.61 mg kg^{-1}) at this stage.

Table 88b. Effect of Zn and B with applied P on Fe content in plant at flowering (mg kg^{-1})

	Zn_0	Zn_1	B_0	B_1	Mean
P_0	549.16	531.38	488.61	591.40	**540.14**
P_1	588.77	599.83	599.90	588.66	**594.29**
Mean	**568.97**	**565.61**	**544.26**	**590.03**	**567.21**

CD. P × Zn 13.68 CD. P × B 13.68

4.6.5.7.2. *Harvesting*

Treatment with P significantly increased the plant Fe (584.50 mg kg^{-1}) when compared to the treatment without P (525.33 mg kg^{-1}). The treatment with and without Zn did not have any significant influence on iron content in plant. Application of B increased the iron content in plant (578.08 mg kg^{-1}) in comparison with the treatment without B (531.75 mg kg^{-1}). The soil with high P (S_3) recorded the highest plant iron content at this stage (573.88 mg kg^{-1}) which is significantly different from that of the other two soils.

Table 89a. Effect of applied P,Zn and B on Fe content in plant at harvest (mg kg^{-1})

	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	514.62	581.00	574.00	521.63	536.25	559.38	**547.81**
S_2	499.87	586.25	499.25	586.88	500.13	586.00	**543.06**
S_3	561.50	586.25	592.00	555.75	558.88	588.88	**573.88**
Mean	**525.33**	**584.50**	**555.08**	**554.75**	**531.75**	**578.08**	**554.92**

CD S 12.6 CD P 10.3 CD Zn NS CD B 10.3

Among the interaction effects, the treatment with P and Zn (P_1Zn_1) and P without Zn (P_1Zn_0) has recorded almost similar and significantly higher plant Fe (584.33 and 584.67 mg kg^{-1} respectively) content in comparison with the other two combinations of P and B (P_0Zn_0 and P_0Zn_1). The lowest plant Fe was recorded in the treatment with application of zinc without phosphorus (P_0Zn_1) i.e., 525.16 mg kg^{-1}. Application of phosphorus and boron (P_1B_1) recorded the highest plant Fe content (586.00 kg^{-1}) and the treatment without P and B (P_0B_0) recorded the lowest plant Fe content (480.50 mg kg^{-1}) at this stage.

Table 89b. Effect of Zn and B with applied P on Fe content in plant at harvest (mg kg^{-1})

	Zn_0	Zn_1	B_0	B_1	Mean
P_0	525.50	525.16	480.50	570.17	**525.33**
P_1	584.67	584.33	583.00	586.00	**584.50**
Mean	**555.08**	**554.75**	**531.75**	**578.08**	**554.92**

CD. P × Zn 14.2 CD. P × B 14.2

4.6.5.8. Manganese

4.6.5.8.1. Flowering

Application P (P_1) was found to increase the Mn content in plant (243.26 mg kg^{-1}) in comparison to the treatment without P (206.49mg kg^{-1}). Application of zinc decreased the plant Mn (203.33 mg kg^{-1}) compared to that of treatment without Zn (246.39 mg kg^{-1}). But the application of B increased the plant Mn content(232.45 mg kg^{-1}) significantly in comparison with that of the treatment without B (217.29 mg kg^{-1}). The soil with high P (S_3) recorded the highest content of plant Mn at this stage (279.88 mg kg^{-1}) which is significantly different from that of other soils.

Table 90a. Effect of applied P,Zn and B on Mn content in plant at flowering (mg kg^{-1})

	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	194.39	248.56	186.9	256.00	240.33	202.62	**221.47**
S_2	150.49	196.05	220.25	126.28	178.00	168.50	**173.26**
S_3	274.59	285.16	332.03	227.72	233.53	326.22	**279.88**
Mean	**206.49**	**243.26**	**246.39**	**203.33**	**217.29**	**232.45**	**224.87**

CD S 18.80 CD P 15.41 CD Zn 15.41 CD B 15.41

Among the interaction effects, the treatment with application of phosphorus without zinc (P_1Zn_0) recorded the highest Mn content in plant(254.63 mg kg^{-1}) in comparison with other treatment combinations of P and Zn. The treatment with application of P without B (P_1B_0) recorded significantly higher Mn content in plant(259.62 mg kg^{-1}) in comparison with other treatment combinations of P and B. The treatment without application both P and B (P_0B_0) recorded the lowest manganese content in plant (174.95 mg kg^{-1}).

Table 90b. Effect of Zn and B with applied P on Mn content in plant at flowering (mg kg^{-1})

	Zn_0	Zn_1	B_0	B_1	Mean
P_0	238.16	174.82	174.95	238.02	**206.49**
P_1	254.63	231.88	259.62	226.89	**243.26**
Mean	**246.40**	**203.35**	**217.29**	**232.46**	**224.87**

CD. P × Zn 21.79 CD. P × B 21.79

4.6.5.8.2. Harvesting

Application P (P_1) significantly increased the plant manganese content (224.88 mg kg^{-1}) content in comparison to the treatment without P (167.75 mg kg^{-1}). Application of zinc decreased the plant Mn (164.98 mg kg^{-1}) significantly when compared to that of treatment without Zn (227.65 mg kg^{-1}). But the application of B increased the plant Mn (206.60 mg kg^{-1}) in comparison with the treatment without B (186.03 mg kg^{-1}). The soil with high P (S_3) recorded the highest content of plant Mn at this stage (254.15 mg kg^{-1}) which is significantly different from that of other two soils.

Table 91a. Effect of applied P,Zn and B on Mn content in plant at harvest(mg kg^{-1})

	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	136.13	221.60	175.14	182.60	179.50	178.24	**178.87**
S_2	133.01	178.85	203.51	108.35	160.79	151.08	**155.93**
S_3	234.10	274.20	304.31	203.99	217.80	290.50	**254.15**
Mean	**167.75**	**224.88**	**227.65**	**164.98**	**186.03**	**206.60**	**196.32**

CD S 15.41 CD P 14.8 CD Zn 14.8 CD B 14.8

Among the interaction effects, application of phosphorus without Zn (P_1Zn_0) recorded the highest plant Mn (239.98 mg kg^{-1}) when compared with othertreatment combinations of P and Zn. Application of Zn without P (P_0Zn_1) recorded the lowest plant Mn content(120.16 mg kg^{-1}) at this stage. The treatment P without the application of B (P_1B_0) recorded significantly high plant Mn (237.60 mg kg^{-1}) when compared with other treatment combinations of P and B. The treatment without P and B (P_0B_0)recorded the lowest value (134.46 mg kg^{-1}) for plant manganese content.

Table 91b.Effect of Zn and B with applied P on Mn content in plant at harvest (mg kg^{-1})

	Zn_0	Zn_1	B_0	B_1	**Mean**
P_0	215.33	120.16	134.46	201.04	**167.75**
P_1	239.98	209.79	237.60	212.17	**224.88**
Mean	**227.65**	**164.98**	**186.03**	**206.60**	**196.32**

CD. P × Zn 20.79 CD. P × B 20.79

4.6.5.9. Zinc

4.6.5.9.1. Flowering

The Zn content decreased substantially (47.15 mg kg^{-1}) with the application of P when compared to the treatment without P (75.01 mg kg^{-1}). The treatment with application of zinc showed significantly higher (67.77 mg kg^{-1}) concentration of Zn than treatment without Zn (54.40 mg kg^{-1}). Application of B was also found to increase the Zn content in plant (66.39 mg kg^{-1}) in comparison with the treatment without B (56.14mg kg^{-1}). The soil with medium P (S_2) recorded significantly high Zn content at this stage (69.82 mg kg^{-1}) when compared to the soil with low and high P.

Table 92a. Effect of applied P,Zn and B on Zn content in plant at flowering(mg kg^{-1})

	P_0	P_1	Zn_0	Zn_1	B_0	B_1	**Mean**
S_1	94.63	41.47	61.03	75.07	68.10	69.10	**68.23**
S_2	80.33	59.31	66.46	73.18	58.97	80.67	**69.82**
S_3	50.07	40.68	35.71	55.05	41.35	49.41	**45.38**
Mean	**75.01**	**47.15**	**54.40**	**67.77**	**56.14**	**66.39**	**61.14**

CD S 1.01 CD P 0.82 CD Zn 0.82 CD B 0.82

Among the interaction effects, the treatment with application of zinc without phosphorus (P_0Zn_1) has recorded the highest Zn content (82.54 mg kg^{-1}) and the treatment P without Zn (P_1Zn_0) recorded the lowest Zn content (41.31 mg kg^{-1}). Application of B without P (P_0B_1) increased (82.12 mg kg^{-1}) the plant Zn when compared with other treatment combinations of P and B.

Table 92b. Effect of Zn and B with applied P on Zn content in plant at flowering (mg kg^{-1})

	Zn_0	Zn_1	B_0	B_1	Mean
P_0	67.40	82.54	67.90	82.12	**74.99**
P_1	41.31	53.00	44.37	49.94	**47.16**
Mean	**54.36**	**67.77**	**56.14**	**66.03**	**61.07**

CD. P × Zn 1.16 **CD. P × B 1.16**

4.6.5.9.2. Harvesting

The Zn content decreased drastically (42.38 mg kg^{-1}) with the application of P when compared to the treatment without P (69.11 mg kg^{-1}). The treatment with Zn showed significantly higher (61.67 mg kg^{-1}) concentration of Zn than that of treatment without Zn (49.83 mg kg^{-1}). Application of B was also found to increase the Zn content (60.24 mg kg^{-1}) in comparison to treatment without B (51.26 mg kg^{-1}). The soil with medium P (S_2) recorded significantly higher zinc content at this stage (68.61 mg kg^{-1}) and the soil with highest P(S_3) recorded the lowest zinc content at this stage.

Table 93a.Effect of applied P,Zn and B on Zn content in plant at harvest(mg kg^{-1})

	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean

S_1	86.4	35.33	55.60	66.13	61.64	60.09	**60.86**
S_2	77.17	60.05	64.34	72.89	56.94	80.29	**68.61**
S_3	43.76	31.78	29.55	45.99	35.20	40.34	**37.77**
Mean	**69.11**	**42.38**	**49.83**	**61.67**	**51.26**	**60.24**	**55.75**

CD S 1.2 CD P 1.02 CD Zn 1.02 CD B 1.02

Among the interaction effects, application of zinc without phosphorus (P_0Zn_1) has recorded the highest Zn content (75.92 mg kg^{-1}) and the treatment with P without Zn (P_1Zn0) recorded the lowest Zn content (37.36 mg kg^{-1}). Application of B without P (P_0B_1) increased (74.66 mg kg^{-1}) the plant Zn when compared with other treatment combinations.

Table 93b. Effect of Zn and B with applied P on Zn content in plant at harvest (mg kg^{-1})

	Zn_0	Zn_1	B_0	B_1	Mean
P_0	62.30	75.92	63.57	74.66	**69.11**
P_1	37.36	47.41	38.95	45.82	**42.38**
Mean	**49.83**	**61.67**	**51.26**	**60.24**	**55.75**

CD. P × Zn 1.4 CD. P × B 1.4

4.6.5.10. Copper

4.6.5.10.1. Flowering

Application of P was found to P decrease the plant copper content (12.78 mg kg^{-1}) content when compared with the treatment without P (21.75 mg kg^{-1}). It was observed that in treatment with zinc, the Cu content in plantincreased (21.76 mg kg^{-1}) in comparison to the treatment without Zn (12.77mg kg^{-1}). Cu content in plantwas significantly lower (14.03 mg kg^{-1}) with application of boron than that in treatment without boron(20.47 mg kg^{-1}).

Table 94a. Effect of applied P,Zn and B on Cu content in plant at flowering (mg kg^{-1})

	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	22.84	11.05	12.6	21.29	23.80	10.09	**16.95**
S_2	34.94	12.02	17.02	29.95	27.80	19.15	**23.48**
S_3	7.46	15.27	8.69	14.05	9.80	12.86	**11.36**
Mean	**21.75**	**12.78**	**12.77**	**21.76**	**20.47**	**14.03**	**17.26**

CD S 1.27 CD P 1.02 CD Zn 1.02 CD B 1.02

When the interaction effects were considered, the treatment Zn without P (P_0Zn_1) recorded significantly higher plant Cu (29.01mg kg^{-1}) in comparison with all the other treatments combinations of P and Zn. The lowest plant Cu (11.05 mg kg^{-1}) was recorded in the treatment P without Zn (P_1Zn_0). Treatment without B and P (P_0B_0) showed the highest plant Cu (29.65 mg kg^{-1}) and the treatment P without B (P_1B_0) has recorded the lowest plant Cu (11.33 mg kg^{-1}) content in plant.

Table 94b. Effect of Zn and B with applied P on Cu content in plant at flowering (mg kg^{-1})

	Zn_0	Zn_1	B_0	B_1	Mean
P_0	14.40	29.01	29.65	13.84	**21.73**
P_1	11.05	14.51	11.33	14.23	**12.78**
Mean	**12.73**	**21.76**	**20.49**	**14.04**	**17.25**

CD. P × Zn 1.45 CD. P × B 1.45

4.6.5.9.2. Harvesting

Application of P was found to decrease the plant copper content (12.46 mg kg^{-1}) when compared with the treatment without P (25.41 mg kg^{-1}). It was observed that in treatment with zinc, the Cu content in plantincreased (21.18 mg kg^{-1}) in comparison to the treatment without Zn (16.69 mg kg^{-1}). Cu content in plantwas significantly higher (19.88 mg kg^{-1}) without application of boron than that in treatment with boron(17.99 mg kg^{-1}).

Table 95a. Effect of applied P,Zn and B on Cu content in plant at harvest (mg kg^{-1})

	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	20.45	10.73	11.71	19.46	21.29	9.89	**15.59**
S_2	34.94	10.91	16.55	29.30	27.68	18.18	**22.93**
S_3	20.82	15.76	21.81	14.78	10.69	25.89	**18.29**
Mean	**25.41**	**12.46**	**16.69**	**21.18**	**19.88**	**17.99**	**18.93**

CD S NS CD P 3.7 CD Zn 3.7 CD B NS

When the interaction effects were considered, the treatment Zn without P (P_0Zn_1) recorded significantly higher plant Cu (27.89 mg kg^{-1}) in comparison with all the other treatments combinations of P and Zn. The lowest Cu content in plant(10.46 mg kg^{-1}) was recorded in the treatment P without Zn (P_1Zn_0). Treatment without B and P (P_0B_0) showed the highest plant Cu (28.93 mg kg^{-1}) and the treatment P without B (P_1B_0) has recorded the lowest plant Cu (10.83 mg kg^{-1}) content.

Table 95b. Effect of Zn and B with applied P on Cu content in plant at harvest (mg kg^{-1})

	Zn_0	Zn_1	B_0	B_1	Mean
P_0	22.91	27.89	28.93	21.88	**25.41**

P_1	10.46	14.47	10.83	14.10	**12.46**
Mean	**16.69**	**21.18**	**19.88**	**17.99**	**18.93**

CD. P × Zn 5.3 **CD. P × B 5.3**

4.6.5.11. Boron

4.6.5.11.1. Flowering

The boron content decreased (25.82 mg kg^{-1}) with the application of P when compared to the treatment without P (35.67 mg kg^{-1}); however, the treatment with Zn decreased (28.58 mg kg^{-1}) concentration of B than treatment without Zn (32.92 mg kg^{-1}). Application of B was found to increase the B content (33.36 mg kg^{-1}) in comparison to treatment without B (28.12 mg kg^{-1}). The soil with high P (S_3) recorded significantly high B content at this stage (59.57 mg kg^{-1}) from that of other two soils (S_1 and S_2).

Table 96a. Effect of applied P,Zn and B on B content in plant at flowering (mg kg^{-1})

	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	6.52	5.37	6.85	5.05	4.02	7.87	**5.95**
S_2	31.67	21.76	32.96	20.47	25.73	27.70	**26.72**
S_3	68.82	50.32	58.95	60.23	54.60	64.50	**59.57**
Mean	**35.67**	**25.82**	**32.92**	**28.58**	**28.12**	**33.36**	**30.74**

CD S 0.76 CD P 0.61 CD Zn 0.61 CD B 0.61

Among the interaction effects, the treatment without P and Zn (P_0Zn_0) has recorded the highest B content (39.02 mg kg^{-1}) and the treatment with P and Zn (P_1Zn_1) recorded the lowest B content (24.85 mg kg^{-1}). Application of B without P (P_0B_1) increased (38.56 mg kg^{-1}) the plant B when compared with other treatment combinations. Application of P without B (P_1B_0) recorded the lowest B content (23.45 mg kg^{-1}) at this stage.

Table 96b.Effect of Zn and B with applied P on B content in plant at flowering (mg kg^{-1})

	Zn_0	Zn_1	B_0	B_1	Mean
P_0	39.02	32.32	32.78	38.56	35.67
P_1	26.81	24.85	23.45	28.20	25.83
Mean	32.92	28.59	28.12	33.38	30.75

CD. P × Zn 0.912 **CD. P × B 0.912**

4.6.5.11.2. Harvesting

The B content decreased (31.60 mg kg^{-1}) with the application of P when compared to the treatment without P (40.54 mg kg^{-1}). The treatment with Zn decreased (34.27 mg kg^{-1}) concentration of B than treatment without Zn (37.87 mg kg^{-1}). Application of B was found to increase the B content (38.54 mg kg^{-1}) significantly in comparison to treatment without B (33.60 mg kg^{-1}). The soil with high P (S_3) recorded significantly high B content at this stage (68.83 mg kg^{-1})in comparison with thatof other two soils.

Table 97a.Effect of applied P,Zn and B on B content in plant at harvest(mg kg^{-1})

	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	8.47	6.84	8.41	6.90	5.89	9.43	7.66
S_2	36.91	26.54	37.98	25.48	31.18	32.28	31.73

S_3	76.23	61.41	67.21	70.44	63.74	73.91	**68.83**
Mean	**40.54**	**31.60**	**37.87**	**34.27**	**33.60**	**38.54**	**36.07**

CD S 0.94 CD P 0.80 CD Zn 0.80 CD B 0.80

Among the interaction effects, the treatment without P and Zn (P_0Zn_0) has recorded the highest B content (42.65 mg kg^{-1}) and the treatment with P and Zn (P_1Zn_1) recorded the lowest B content (30.11 mg kg^{-1}). Application of B without P (P_0B_1) increased (43.53 mg kg^{-1}) the plant B when compared with other treatment combinations of P and B. Application of P without B (P_1B_0) recorded the lowest B content (29.64 mg kg^{-1}).

Table 97b. Effect of Zn and B with applied P on B content in plant at harvest (mg kg^{-1})

	Zn_0	Zn_1	B_0	B_1	Mean
P_0	42.65	38.43	37.56	43.53	**40.54**
P_1	33.08	30.11	29.64	33.55	**31.60**
Mean	**37.87**	**34.27**	**33.60**	**38.54**	**36.07**

CD. P × Zn 1.14 CD. P × B 1.14

4.6.6. Pearson correlation of available P, Zn and B with plant P, Zn and B content

Table 98. Correlation of available P with plant content

	Av. P	Av. Zn	Av. B	Plant P	Plant Zn	PlantB
Av. P	1					
Av. Zn	**-0.18***	**1**				

Av. B	-.071*	0.331**	1			
Plant P	0.161*	-0.145**	-0.060*	1		
Plant Zn	-0.239*	0.348**	0.279*	-.554**	1	
Plant B	-0.313**	-0.072*	0.053*	-.410**	-.352**	1

4.6.7. Biometric observations

4.6.7.1. Plant height

Application P (P_1) was found to increase the plant height (55.29 cm) in comparison to the treatment without P (53.55 cm). The treatment with B and without B did not have any significant influence on plant height. The soil with highest P(S_3) recorded the highest plant height (58.46 cm) and the soil with low P(S_1) recorded the lowest plant height (52.20cm)

Table 99a.Effect of applied P,Zn and B on plant height (cm)

	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	51.77	52.63	51.70	52.70	52.21	52.19	52.20
S_2	51.67	53.54	52.88	52.34	52.81	52.40	52.61
S_3	57.20	59.71	59.10	57.81	59.41	57.50	58.46
Mean	53.55	55.29	55.41	54.95	54.26	54.03	54.42

CD S 0.64 CD P 0.5 CD Zn NS CD B NS

None of the interaction effects were found significant with regard to plant height.

Table 99b. Effect of Zn and B with applied P on plant height(cm)

	Zn_0	Zn_1	B_0	B_1	Mean

P_0	55.20	55.31	54.00	54.01	54.63
P_1	55.61	55.59	54.52	54.05	54.69
Mean	55.41	54.95	54.26	54.03	54.66

CD. P × Zn NS CD. P × B NS

4.6.7.2. Number of leaves

The soil with medium P(S_3) recorded the highest number of leaves (31.29) and the soil with low P(S_1) recorded the lowest number of leaves (25.38). None of the other treatment effects were found significant regarding the number of leaves

Table 100a. Effect of applied P,Zn and B on number of leaves

	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	27.58	27.83	26.92	28.50	28.17	27.25	**27.71**
S_2	29.83	32.75	31.00	31.58	31.75	30.83	**31.29**
S_3	26.00	24.75	25.25	25.50	25.42	25.33	**25.38**
Mean	**27.81**	**28.44**	**27.72**	**28.53**	**28.44**	**27.81**	**28.12**

CD S 1.8 CD P NS CD Zn NS CD B NS

Application of Zn without P (P_0Zn_1) recorded highest number of leaves (29.22) when compared to the other treatment combinations of P and Zn. Treatment without P and Zn (P_0Zn_o) recorded the lowest leaf number (26.39). The interaction effect of P and B were found to be non-significant with respect to number of leaves.

Table 100b. Effect of Zn and B with applied P on Number of leaves

	Zn_0	Zn_1	B_0	B_1	Mean
P_0	26.39	29.22	27.33	28.28	**27.81**
P_1	29.06	27.83	29.56	27.33	**28.44**
Mean	**27.72**	**28.53**	**28.44**	**27.81**	**28.13**

CD. P × Zn 2.05 **CD. P × B NS**

4.6.7.3. Hundred grain weight

None of the treatment effects were found to be significant with respect to 100 grain weight.

Table 101a. Effect of applied P,Zn and B on 100 grain weight (g)

	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	19.88	20.34	20.10	20.13	20.11	20.11	**20.11**
S_2	19.78	19.58	19.21	20.15	19.80	19.56	**19.68**
S_3	19.93	19.91	19.79	20.06	19.78	20.07	**19.92**
Mean	**19.87**	**19.94**	**19.70**	**20.11**	**19.90**	**19.91**	**19.91**

CD S NS CD P NS CD Zn NS CD B NS

Interaction effects were also found to be non-significant and hence did not influence the 100 grain weight.

Table 101 b. Effect of Zn and B with applied P on 100 grain weight (g)

	Zn_0	Zn_1	B_0	B_1	Mean

P_0	19.74	20.00	19.61	20.13	**19.87**
P_1	19.66	20.22	20.19	19.70	**19.94**
Mean	**19.70**	**20.11**	**19.90**	**19.92**	**19.91**

CD. P × Zn NS **CD. P × B NS**

4.6.7.4. Pod length

The highest pod length (17.26 cm) was recorded in the soil with medium P (S_2) and the lowest pod length (16.36 cm) was recorded in the soil with low P (S_1). The treatment effects and interaction effects were not found to influence the pod length.

Table 102 a. Effect of applied P,Zn and B on pod length (cm)

	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	16.46	16.26	16.31	16.41	16.56	16.16	**16.36**
S_2	17.15	17.36	16.96	17.55	17.53	16.99	**17.26**
S_3	17.21	16.98	17.11	17.08	16.99	17.20	**17.09**
Mean	**16.94**	**16.87**	**16.80**	**17.01**	**17.03**	**16.78**	**16.90**

CD S 0.26 CD P NS CD Zn NS CD B NS

Table 102 b. Effect of Zn and B with applied P on pod length (cm)

	Zn_0	Zn_1	B_0	B_1	Mean
P_0	16.87	17.02	16.88	17.00	**16.94**
P_1	16.73	17.01	17.17	16.57	**16.87**
Mean	**16.80**	**17.01**	**17.03**	**16.78**	**16.90**

CD. P × Zn NS CD. P × B NS

4.6.7.5. Grain yield/plant

The soil with medium P (S_2) recorded the highest grain yield per plant (22.58 g) and the soil with low P(S_1) recorded the lowest grain yield per plant (17.82). Among the treatment effects application of P (P_1) reduced the grain yield per plant (20.37) when compared to the treatment without P (P_0) which recorded a grain yield of 20.83g.

Table 103 a. Effect of applied P,Zn and B on grain yield per plant (g)

	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	17.66	17.99	17.25	18.40	18.53	17.13	**17.82**
S_2	23.81	21.34	21.59	23.56	22.71	22.44	**22.58**
S_3	21.02	21.79	21.00	21.81	21.04	21.78	**21.41**
Mean	**20.83**	**20.37**	**19.95**	**21.26**	**20.76**	**20.45**	**20.60**

CD S 0.57 CD P 0.48 CD Zn NS CD B NS

Regarding the grain yield per plant, interaction of Zn without P (P_0Zn_1) recorded highest value (21.38 g) when compared to other treatment combinations. Application of P without Zn (P_1Zn_0) recorded the lowest value (19.61 g). Treatment without P and B (P_0B_o) recorded the highest grain yield per plant (21.17) compared to other treatment combinations of P and B.

Table 103 b. Effect of Zn and B with applied P on grain yield per plant (g)

	Zn_0	Zn_1	B_0	B_1	Mean
P_0	20.28	21.38	21.17	20.50	20.83
P_1	19.61	21.13	20.35	20.39	20.37
Mean	19.95	21.26	20.76	20.45	20.60

CD. P × Zn 0.68 **CD. P × B 0.68**

4.6.7.6. Number of grain/pod

None of the treatment effects or interaction effects were found to be significant with regard to number of grains per pod.

Table 104 a. Effect of applied P,Zn and B on number of grain per pod

	P_0	P_1	Zn_0	Zn_1	B_0	B_1	Mean
S_1	7.41	6.83	7.17	7.08	6.83	7.42	7.13
S_2	6.91	6.67	7.00	6.58	6.75	6.83	6.79
S_3	6.66	6.83	6.58	6.92	6.50	7.00	6.75
Mean	7.00	6.78	6.92	6.86	6.69	7.08	6.89

CD S NS CD P NS CD Zn NS CD B NS

Table 104b.Effect of Zn and B with applied P on Number of grain per pod

	Zn_0	Zn_1	B_0	B_1	Mean
P_0	6.83	7.16	6.67	7.33	7.00
P_1	7.00	6.56	6.72	6.83	6.78
Mean	6.92	6.86	6.69	7.08	6.89

CD. P × Zn NS CD. P × B NS

Discussion

5. DISCUSSION

The results of the present study presented in Section 4 are discussed critically with supporting evidences as well as the related studies from the literature. Eighteen soils under Ultisol, have been characterized initially. This was carried out with the objective of understanding the relationship, if any, of the electrochemical properties and fractions of phosphorus, zinc and boron of these soils.

5.1. Electrochemical properties and available nutrient status

As shown in the table 4, out of 18 soil samples collected, four soils were extremely acidic (pH 3.5 to 4.5), five were very strongly acidic (pH 4.5 to 5), five were strongly acidic (pH 5 to 5.5) and remaining four were moderately acidic (pH 5.5 to 6.0). In general, the electrical conductivity was normal (0.06 to 0.21dSm^{-1}). The organic carbon status ranged from as low as 0.09% (sample 11) to the highest value of 1.96% (sample 16).

Among 18 soil samples collected, the first 6 samples recorded very low available P to the tune of <5kg ha^{-1}, while the second set of six samples recorded medium available P status with a range of 17-20 kg ha^{-1} .The remaining six samples contained very high levels of available P in the range of 52.7-225.4 kg ha^{-1}. With respect to available potassium, 13 samples were medium in status (115-275 kg ha^{-1}) and three samples were low available potassium (<115 kg ha^{-1}).

Among the secondary nutrients, 17 samples were deficient in available Ca (<300 mg kg^{-1}). *Deficiency of available magnesium* (<120 mg kg^{-1}) *was observed in* 16 samples. Deficiency of available sulphur was observed only in 5 soils (<5 mg kg^{-1}).

All the 18 selected soil samples were sufficient in available Fe (>5 mg kg^{-1}), Mn (>5 mg kg^{-1}), and Cu (>1mg kg^{-1}). The available Zn (<1 mg kg^{-1}) was deficient in 3 soils, remaining 15 samples are sufficient in available Zn (<1 mg kg^{-1}). With respect to available boron, 8 soils were deficient (<0.5 mg kg^{-1}). The highest available zinc (14.43 mg kg^{-1}) wasrecorded in soil with medium P soil (S_2) and lowest was recorded (1.32 mg kg^{-1}) in soil with low P (S_1)

5.2. Exchangeable cations and Cation Exchange Capacity

The data on exchangeable cations in table 5 revealed that the most dominant cation on exchange sites in all the 18 soils was Ca^{2+} contributing more than 50% of CEC [range 1.17 to 6.15 cmol (p+)kg^{-1}] followed by Na^+ and K^+. Exchangeable Al^{3+} and Mg^{2+} showed similar range in these soils with Al often exceeding the values of exchangeable Mg^{2+}. The contribution of Cu^{2+}, Fe^{2+} Zn^{2+} and Mn^{2+}, were negligible at the exchange surface.

The CEC of these soils were very low ranging from 2.37 to 10.09 cmol (p+)kg^{-1} . The low CEC in lateritic soils were also reported by Seena *et al.* (2002) and was attributed to dominance of low activity 1:1 kaolinite type of clay.

5.3. Distribution of fractions of phosphorus in soil

The data on inorganic fractions of P *viz.* soluble P, Al-P, Fe-P, sesquioxide occluded P (reductant soluble P), and Ca-P which were extracted sequentially indicated that among the soils with low, medium and high available phosphorus, Fe-P was the dominant fraction with a distribution of almost 55 to 62 per cent. The occluded P was the second dominant fraction in soils with low and medium available P, and ranged from 12 to15 per cent respectively. The Al-P was the second dominant fraction in soils with high available P (16%). In all the three types of soils, distribution of soluble P remained almost same (about 6%) (Table 6, fig 4a, 5a, 6a)

The Fe-P, Al-P and occluded P had significant correlations with available P. Same results were also reported by Gupta and Srivastava (1998). Soluble P failed to have significant correlation with available P probably because of its lower concentration in comparison with that of other fractions (Table 7)

5.4. Soil boron fractions

Irrespective of available P content, all the soils had same pattern in distribution of different fractions of boron. The residual fraction of B showed highest percentage in distribution (>90%) while the readily soluble B recorded the lowest (0.18-1.75%) (Table 8 fig 10a, 11a, 12a).

The significant positive correlation of all the fractions with available boron as well as mutual significant correlation among the fractions themselves point to the fact that, there exists a dynamic equilibrium among these fractions (table 9). However path coefficients (table10) indicated that RS-B and OX-B were directly contributing to available pool. The other fractions were contributing to the available pool indirectly through these two fractions.

The direct effect of RS-B was very high and positive, indicating its direct contribution to the available pool. The direct effects OM B as well as the indirect effects of RS, SP, and OX B, through OM B were very high and negative. This showed the influence of organic matter in binding boron and making it unavailable. These results were in line with the observation of Santhosh (2013).

5.5. Distribution of fractions of zinc in soil

The data on different fractions of Zn *viz.* water soluble + exchangeable, specifically adsorbed, acid soluble, MnO-Zn, OM-Zn, Am FeO-Zn, Cr FeO-Zn and residual Zn, which were extracted sequentially indicated that the dominant fraction was residual in all soils. Studies by Verma and Subema (2005) and Joshi *et al.* (2014)also reported that in acid soils, residual zinc was the predominant fraction among the different zinc fractions. Water soluble + exchangeable fraction showed least dominance in all the soils (Table 11).

The significant positive correlations of available zinc with different fractions except Am FeO–Zn at initial stage (Table 12) clearly indicated that these fractions were in equilibrium with one another and once they get solubilized, became available.

This is substantiated by the data on path coefficients (Table13, Fig 7a,8a and 9a) indicating the direct and indirect effects of fractions of Zn with available zinc. The data revealed that Ws+Exch-Zn as well as OM occluded zinc directly contributed to the available pool. The other fractions *viz.* specifically adsorbed, acid soluble, MnO-Zn, Am FeO-Zn ,CrFeO-Zn and total zinc were contributing to available pool through Ws+Exch zinc fraction as indicated by the path coefficients. This would mean that zinc in soil is existing in different fractions due to various chemical transformation and finally comes to ionic form (Zn^{+2}), which exist either in soil solution or on the negative sites of the exchange phase of inorganic as well as organic colloids.

5.6. Pot culture experiment

5.6.1. Electrochemical properties and available nutrient status at flowering and at harvest

5.6.1.1. Soil pH

At both stages of sampling (flowering and harvest), there was no significant effects for the fertilizers of P, Zn and B on soil pH. However, the soil pH was increased from initial status at flowering and at harvest due to basal incorporation of lime (Table 14 to 15).

5.6.1.2. EC

There was a slight increase in EC from the initial status in all the three soils (S_1, S_2 and S_3) at harvest because of applied soluble sources of P, Zn and B, which has increased the total electrolyte concentration (Table 16 to 17).

5.6.1.3. Organic carbon

At both stages of sampling (flowering and harvest), there was no significant effects for the fertilizers of P, Zn and B on organic carbon status (Table 18 to 19).The increase in organic carbon due to application of phosphorus is to be further investigated.

5.6.1.4. Available phosphorus

Available phosphorus status increased substantially in soils with low P (S_1) and medium P (S_2) . This was attributed to the increase in pH from 4.8 to 6.12 in S_1 and 4.9 to 6.12 in S_2. This would mean that, even though there is enough quantity of total P in these soils it existed in the insoluble forms. In acid soils, the main P fraction contributing to the available pool is iron and aluminium phosphate. Tandon (1987) also made similar observations and reported that Fe-P and Al-P were more abundant in acid soils. The significant positive correlation of these fractions with available P also supports this fact. At flowering Fe-P and Al-P fraction increased substantially (as indicated by data on the fraction of P without addition of P fertilizers (P_0). (Table 20a and 20b).

The available P status in the P rich soil (S_3) decreased to almost half of the initial value at flowering. In soils, with high available phosphorus, iron and aluminium bound P fractions were decreased, which might have reduced the available phosphorus. The increased available P status without application of P not only substantiated the contribution of native insoluble P to available pool, which solubilized when the pH is enhanced. Further, applied soluble P along with native available P leads to fixation, even though there exist in native available phosphorus. Vance *et al.*, (2003) also reported that high rate of P fixation and formation of insoluble complexes with aluminum and iron under acid conditions are recognized as the important factor contributing to the low P availability. This is clearly indicated by the substantial decrease in available P status due to the application of P in all the three soils.

At harvest, the available P decreased in all the three soils probably due to plant absorption. Application of P increased the available phosphorus at harvest due to added phosphate in soil solution. (Table 21a and 21b). The available P status increased due to applied P at harvest which was in contrast to the trend at flowering. This would mean that the applied P initially got fixed which was slowly being coming to the soluble form as and when solution P got depleted due to plant absorption.

Application of zinc significantly reduces the available P status due to conversion of soluble phosphorus to insoluble zinc phosphate. Haldar and Mandal (1981) also made similar observations. The decrease in available P due to boron application might be due to anionic competition at both the stages of sampling. Gunes and Alpaslan (2000) reported significant antagonistic relationship between the effects of the application B and P.

5.6.1.5. Available potassium

Available K in all the three soils gradually decreased from initial status towards flowering and harvest mainly because of the plant absorption. Further application of boron as well as zinc either separately or together did reduce available K status significantly. These can be related to the enhanced uptake of potassium due to the application of P and Zn which in turn must have enhanced the growth at both the stages. (Table 22 to 23).

5.6.1.6. Available calcium

The available calcium status enhanced in all the three soils as well as in all the treatment combination of P, Zn and B at flowering. The increase of available calcium was due to the application of lime in all the experimental pots. But at harvesting the level of calcium decreased compared to flowering due to increased plant absorption of calcium at later stages of crop growth (Table 24 to 25).

5.6.1.7. Available Magnesium

Available Mg decreased drastically from flowering till harvest of the crop due to plant absorption. At flowering there was no significant influence of P, Zn, B and interaction effect on available Mg.

At harvest application of zinc was found to reduce the available Mg status probably due to restriction of solubility of magnesium due to increased concentration of zinc in soil solution (Table 26 to 27).

5.6.1.8. Available sulphur

The notable increase in available sulphurat flowering and at harvest in all the three soils was due to the sulphur added from zinc sulphate . The significant main effect on increase in the available sulphur content due to the application zinc clearly indicated the above fact. The available sulphur status decreased at harvest compared to flowering due to plant absorption (Table 28 to 29).

5.6.1.9. Available iron

The available iron status increased from the initial value till harvest of the crop in all the three soils. It was already noted that available P increased in low and medium P soils which was attributed to increase in Fe-P. Increase in available iron also points to the fact that the Fe bound P is becoming available.

Application of zinc was found to reduce the available Fe content while application of boron enhanced the available Fe content. Increase in zinc concentration in soil solution due to application of zinc sulphate might have reduced the soluble iron content (Table 30 to 31).

5.6.1.10. Available manganese

The available manganese content increased substantially from initial status towards harvest of the crop in all the three soils. It is clear from the data that the increase was significantly higher in treatment devoid of addition of P. Application of P reduced the available manganese status probably due to the formation insoluble Mn- phosphate. Application of P along with zinc reduced the manganese content (Table 32 to 33).

5.6.1.11. Available zinc

None of the main effects and interaction effects has any effect on available zinc at both the stages of sampling. Howeverin soils with low and high P (S_1 and S_3), available zinc increased substantially than that at the initial stage. While in soil with medium P (S_2) the available zinc decreased. The corresponding increase in MnO –Zn and Om- zinc was noted in this soil during flowering stage which was substantial when compared to other two soils. The available zinc increased at harvest compared to that at flowering as well as initial stages (Table 34 to 35).

5.6.1.12. Available copper

The available copper status increased in all the three soils at flowering and at harvest compared to that at initial status. The main effects and interaction effects were not found to have any influence an available copper content at both stages (Table 36 to 37).

5.6.1.13. Available boron

The available boron increased in all the treatments at flowering stage when compared to the initial values and then decreased at harvesting due to increased plant absorption of boron at reproductive phase after flowering.

The significant positive decrease of available boron status in phosphorus applied treatments clearly indicated the antagonistic effect of P on boron solubility, which might be due to anionic competition. Bingham and Garber (1960) and Bingham *et al.*, (1958) also reported that excessive phosphorous additions reduced uptake of boron. On the other hand, application of zinc was found to improve the available boron status probably because of the indirect effect of zinc on phosphorus. This fact was supported by the data on P-Zn interaction on available boron *viz* when zinc was applied without P, maximum available boron was recorded. Further boron application without P recorded the highest available boron while boron application with P gave the lowest available boron. The treatment with and without boron did not increase the boron content significantly at both the stages (Table 38 to 39).

5.6.2. Fractions of phosphorus at flowering and at harvest

5.6.2.1. Soluble phosphorus

In general, in all the three soils, the soluble P fraction decreased at flowering in treatments with and without phosphorus. Further at harvest, this fraction showed an increasing trend from that of initial and flowering stages. However, the rate of increase was higher in P applied treatments in both the stages.

The decrease in soluble P at flowering might be due to the combined effect of fixation of applied P and also the increased P absorption by the plant at vegetative phase in P applied treatments. In treatment with application of P, the reduction in soluble P might be due to plant absorption only. Further at harvest, the fixed P in both the treatments might have transformed to soluble form.due to increase in pH.

Application of zinc was found to reduce the soluble P at both the stages due to immobilization of soluble P as insoluble zinc phosphate. The effect of boron might be in reducing the solubility since boron is more soluble and this might have reduced the soluble P content in soil solution (Table 40 to 41, Fig 4 to 6).

5.6.2.2. Al-Phosphorus

The Al bound P showed an increasing trend from initial status at flowering. Further at harvest, this fraction decreased in comparison with that at flowering. This might be due to transformation of applied P to Al bound P by fixation at flowering. At harvest, this fixed P might have solubilized and contributed to available P as indicated by the decrease in Al-P at harvest with increase in pH.Application of zinc did reduce Al bound P probably because of precipitation of phosphorus as zinc phosphate at both flowering and harvest. The soil with low P (S_1) recorded the higher Al-P both at flowering and at harvesting stage (Table 42 to 43, Fig 4 to 6).

5.6.2.3. Fe-Phosphorus

The soil with low P (S_1) recorded higher Fe-P concentration both at flowering and at harvest due to the highest exchangeable iron content in this soil. At both flowering and at harvest, the increase in Fe-P fraction with application of P indicated that a portion of the applied P might have transformed to Fe bound P which was later contributing to the available pool with increase in pH. Application of zinc did reduce Fe bound P probably because of precipitation of P as zinc phosphate at flowering. But at harvest, the application of zinc did not influence the iron bound P content (Table 44 to 45, Fig 4 to 6).

5.6.2.4. Occluded-phosphorus (Reductent- P)

The data on occluded P at harvest indicated that it increased than that at flowering stage. This would mean that the applied P got transformed to occluded P with time. Increase in soluble phosphorus at harvesting stage might be the after effect of solubilization from Al-P and Fe-P due to increase in pH. Application of soluble form of P fertilizer has directly contributed to the available pool, at the same time the occluded P fraction before the experiment might have solubilized due to consequent increase in pH. Thus applied P during flowering stage was not transformed to occluded pool. It is because of this simultaneous effect, application of soluble P recorded significantly lower levels of occluded P in comparison to the treatment without P. On the contrary, application of zinc has contributed to the transformation of P into occluded pool. The reason for decreasing occluded P due to boron application is to be further investigated (Table 46 to 47, Fig 4 to 6).

5.6.2.5. Calcium-phosphorus

The increase in Ca-P at harvest might be due to the transformation of part of Al-P to Ca-P with consequent increase in pH. Zinc and boron reduced the quantity of this fraction due to possibility of formation of insoluble zinc phosphate and calcium

Fig. 4a. Initial distribution of fractions of P in soil with low available P (S_1)

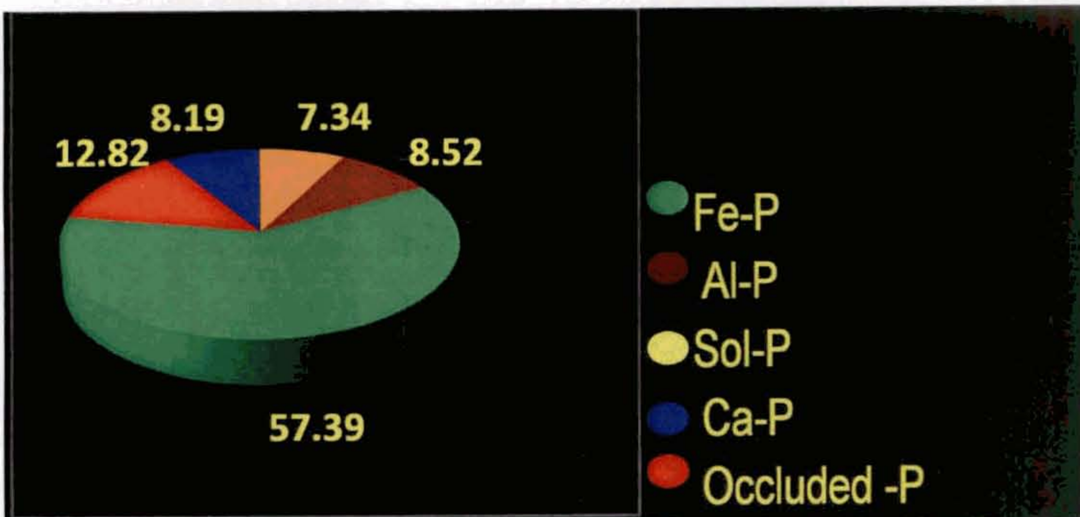


Fig.4b.Changes in fractions of P in P-Zn interaction

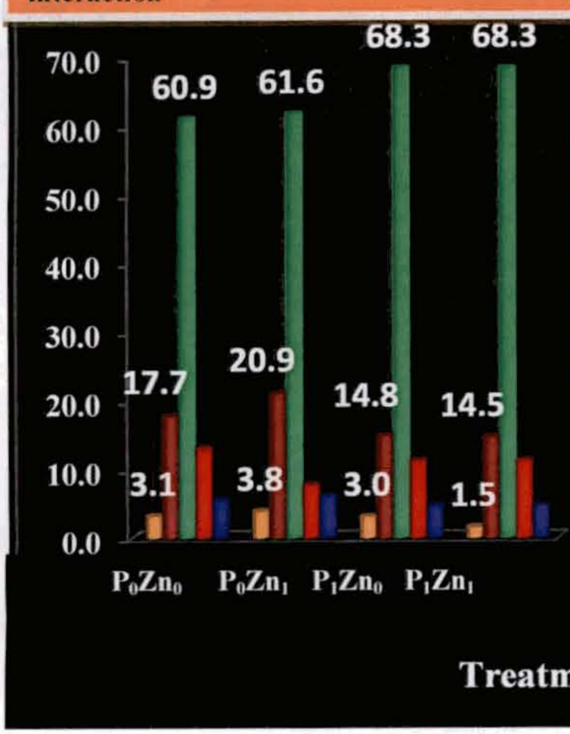


Fig.4 c. Changes in fractions of P in P-Zn interaction

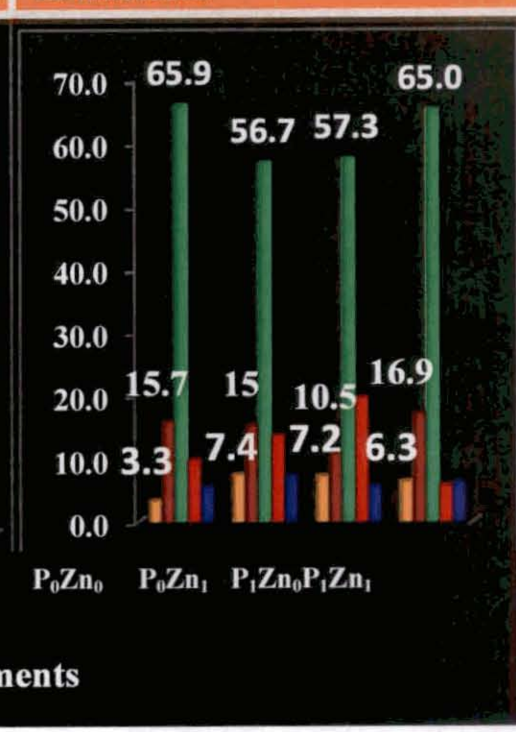


Fig. 4a. Initial distribution of fractions of P in soil with low available P (S_1)

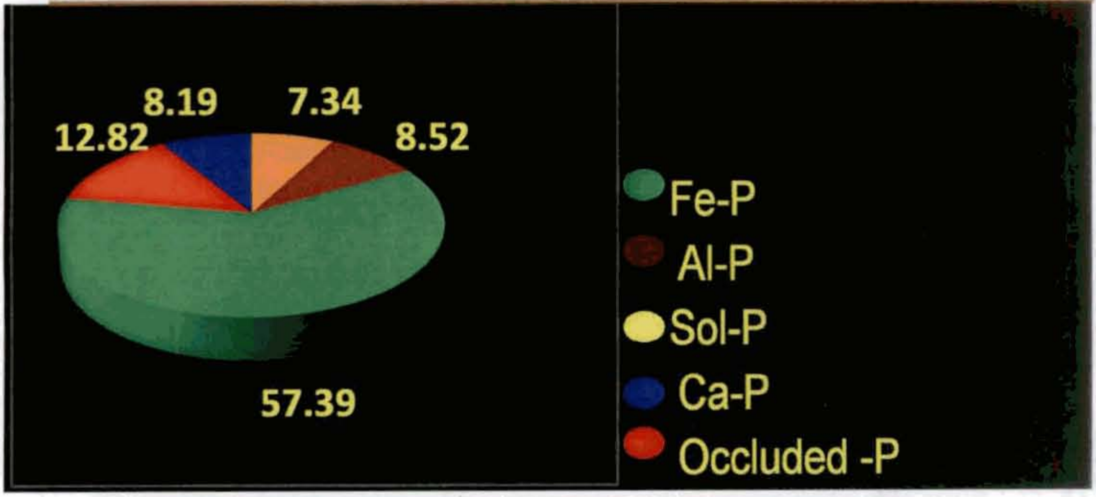
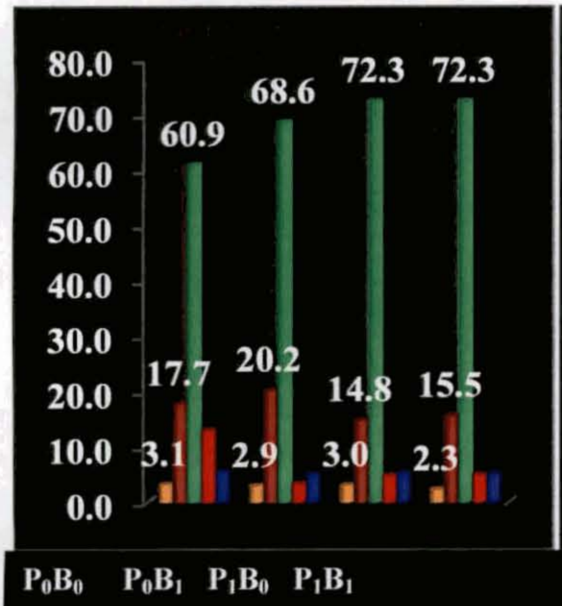
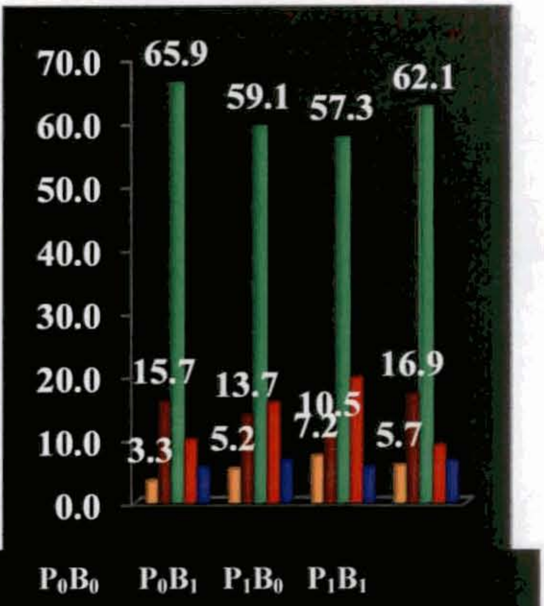


Fig.4d. Changes in fractions of P in P-B interaction

Fig.4 e. Changes in fractions of P in P-B interaction





Treatments

Fig. 5a. Initial distribution of fractions of P in soil with medium availableP (S_2)

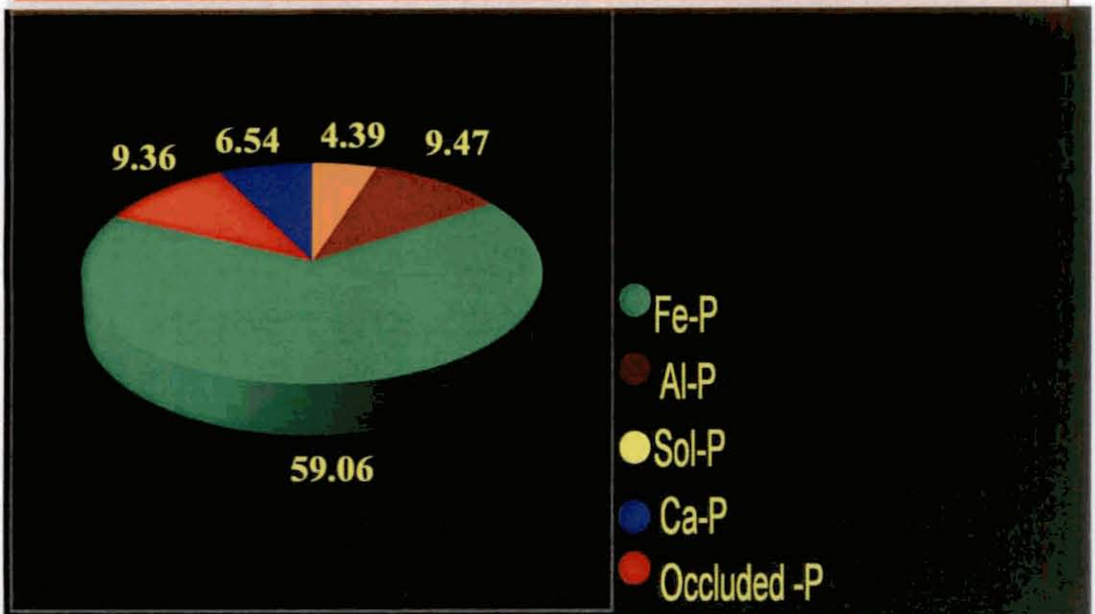


Fig. 5b.Changes in fractions of P in P-Zn interaction at flowering

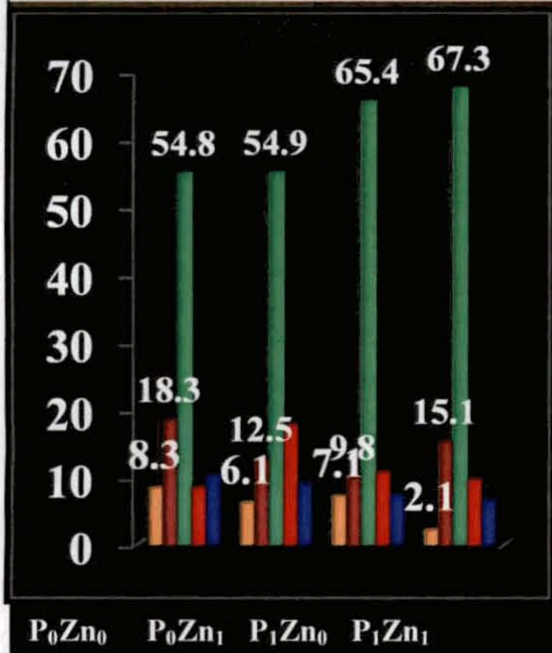


Fig. 5c.Changes in fractions of P in P-Zn interaction at harvest

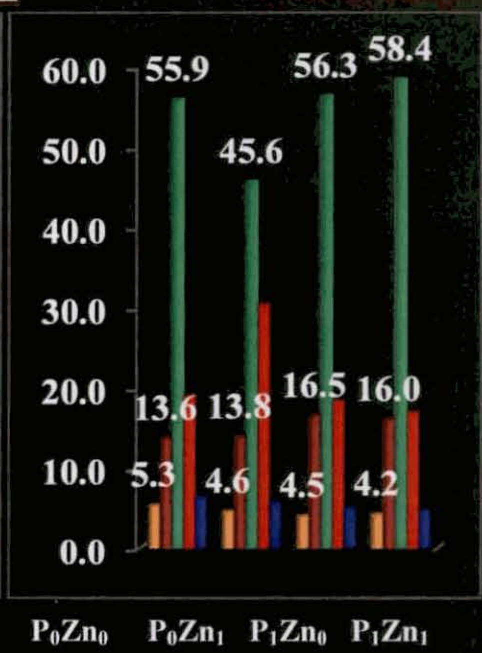


Fig. 5a. Initial distribution of fractions of P in soil with medium availableP (S_2)

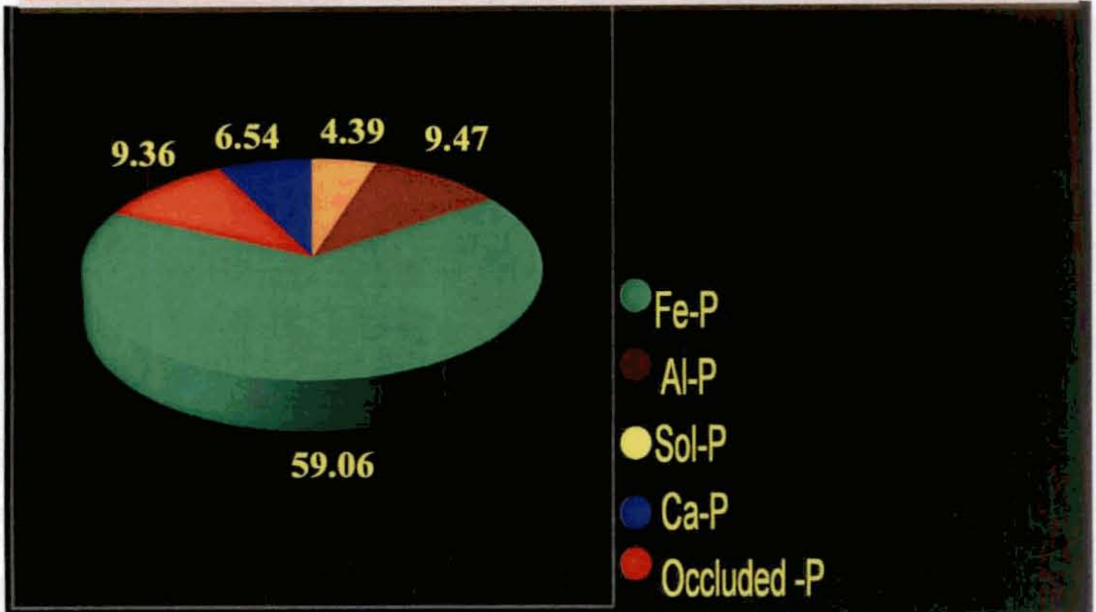


Fig. 5d.Changes in fractions of P in P-B interaction at flowering

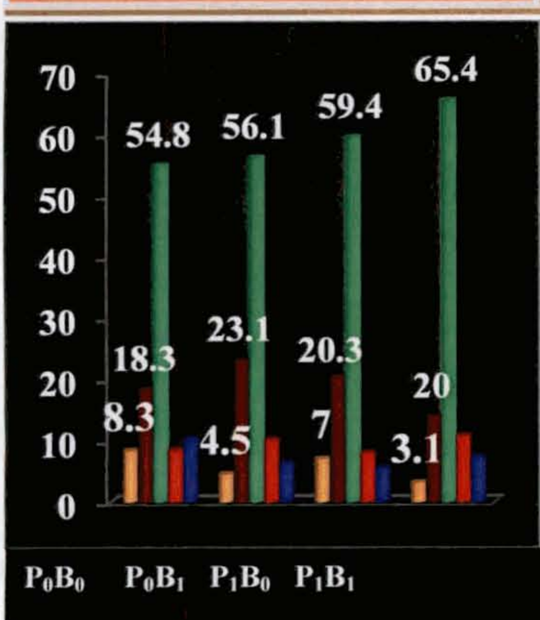


Fig. 5e.Changes in fractions of P in P-B interaction at harvest

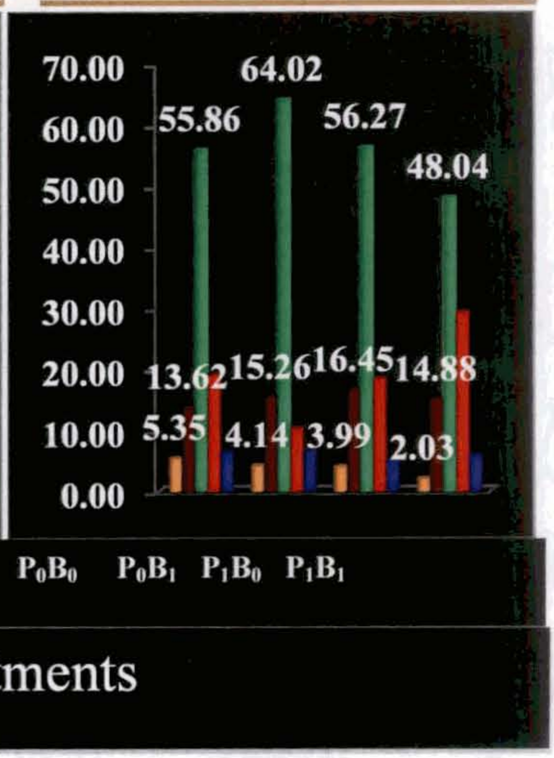


Fig. 6a. Initial distribution of fractions of P in soil with high availableP (S_3)

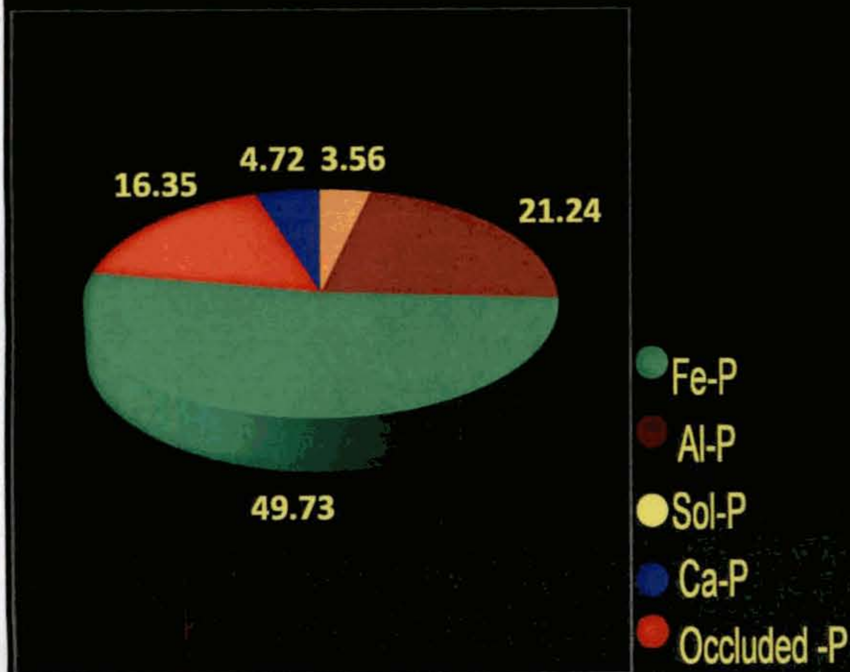


Fig. 6b.Changes in fractions of P in P-Zn interaction at flowering

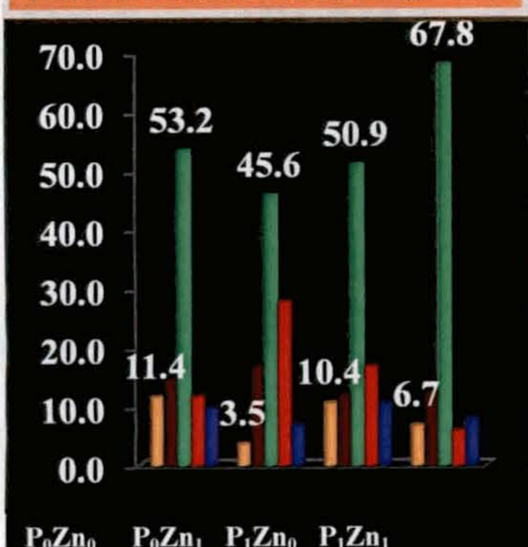
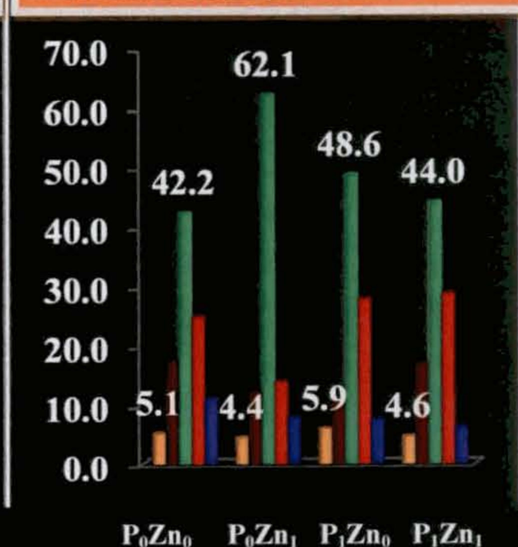


Fig .6c.Changes in fractions of P in P-Zn interaction at harvest



Treatments

Fig. 6a. Initial distribution of fractions of P in soil with high availableP (S_3)

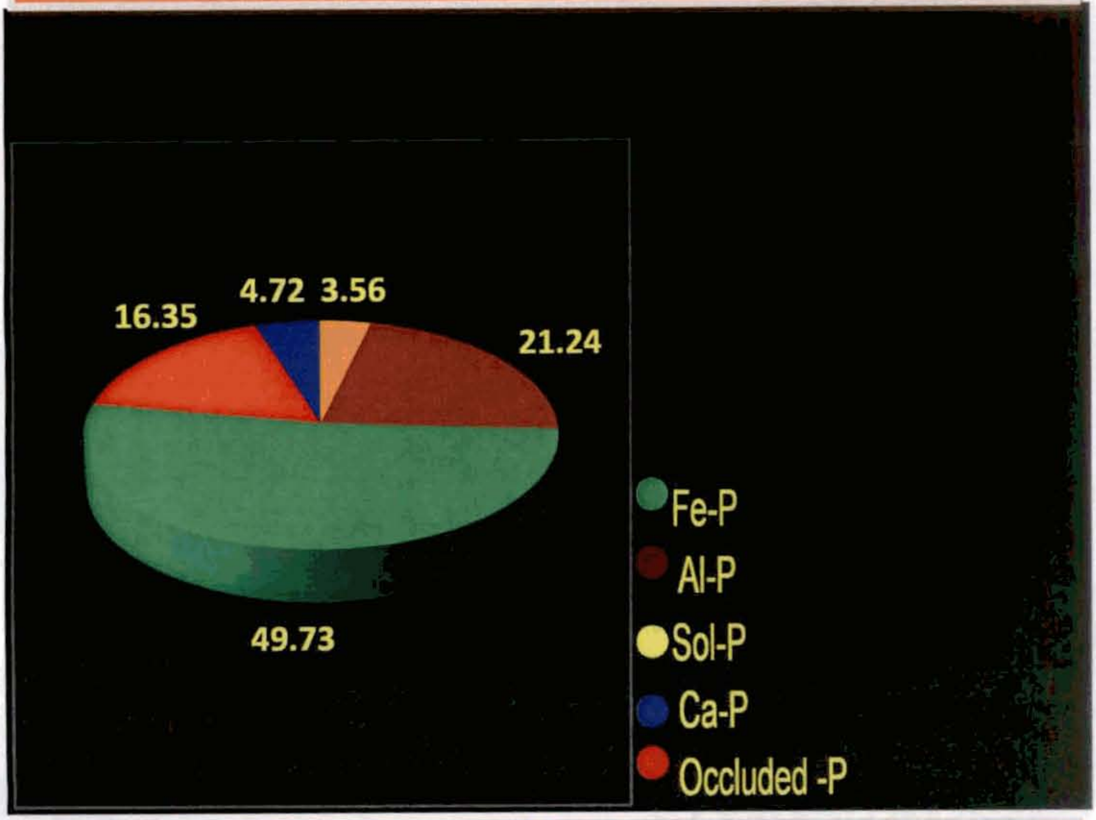


Fig .6d.Changes in fractions of P in P-B interaction at flowering

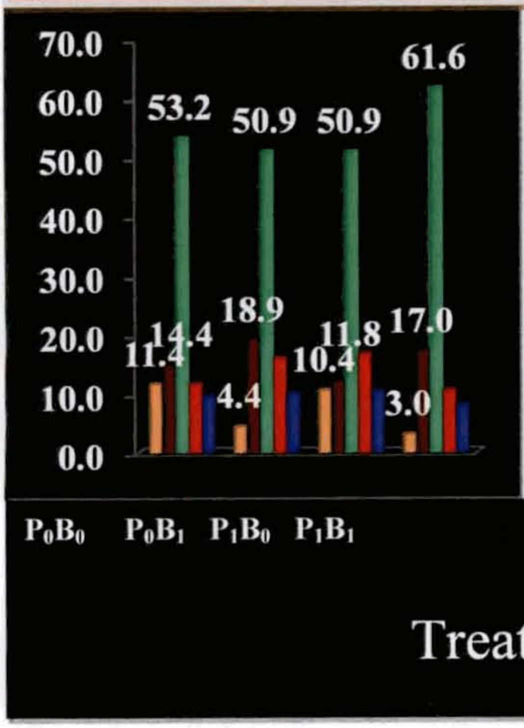
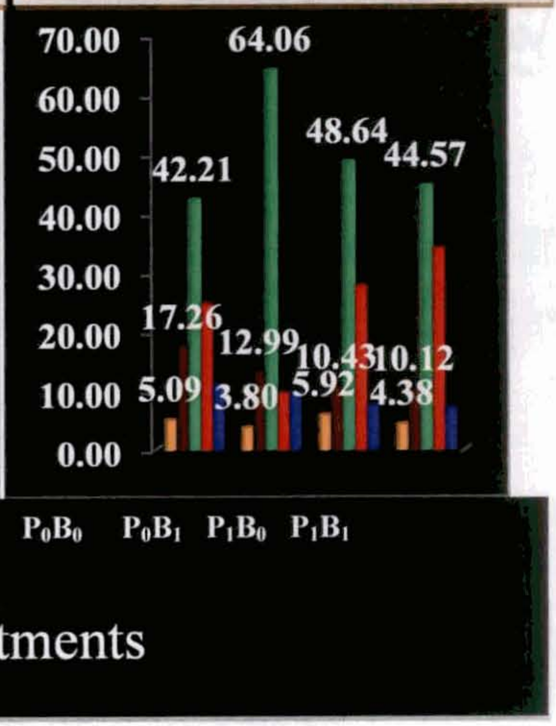


Fig. 6e.Changes in fractions of P in P-B interaction at harvest



borate respectively; however this effect of zinc and boron when applied without phosphorus could be partially nullified when P was applied in soluble form.

The absorption of applied P by plant decreased phosphorus in soil solution which in turn might have reduced the possibility of binding P with calcium. However, the native Ca-P must have still existed which maintained Ca-P level when P was not applied. Zinc and boron application recorded lower Ca-P levels which is an indirect effect of depleted P concentration in soil solution. The significant positive correlation of Ca-P with available P as well as with soluble P also supports this fact as the Ca-P status was very similar to that of soluble P (Table *48* to *49*, *Fig 4 to 6*).

5.6.3. Fractions of zinc at flowering and harvesting

5.6.3.1. Water soluble + exchangeable Zinc

The general trend with respect to Ws+Exch zinc status at various stages of crop growth showed that, this fraction was gradually getting depleted even with application of zinc due to absorption by the crop. The significant positive correlations of Ws+Exch-zinc with available as well as with plant content also support this fact. Sureshkumar *et al.* (2004) also made similar reports with respect to available Zn fraction. The soil with medium P (S_2) recorded the highest Ws+Exch-zinc content both at flowering and at harvest (0.10 mg kg^{-1},and 0.17 and respectively), which was significantly different from that of other soils probably because of highest initial available zinc content in this soil

At both the stages, application of P was found to decrease the water soluble + exchangeable zinc fraction substantially. Even in soil with medium P (S_2), there was a reduction in P content from the initial value of 2.6 mg kg^{-1} to 0.1 mg kg^{-1} at flowering and to 0.17 mg kg^{-1} at harvest. This indicated the negative interaction of high P levels on zinc solubility due to precipitation of zinc as zinc phosphate. Application of boron was found to enhance the Ws+Exch zinc fraction. It was also observed that zinc content in this fraction was more, when boron was applied without

P. This might be due to the lesser effect of boron on zinc solubility in comparison to that of phosphorus (Table 50 to 51, Fig 7 to 9).

5.6.3.2. Specifically adsorbed Zn

In general, Sp.Ad zinc decreased throughout the growth stages of the crop, irrespective of the treatment with or without zinc. This was because of the contribution of this fraction through Ws+Exch-zinc. The soil with medium P (S_2) recorded the highest Sp.Ad zinc both at flowering and at harvest. (3.62 mg kg^{-1} and 4.96 mg kg^{-1} respectively). This was significantly different from that of other soils probably because of highest initial available zinc in the soil (Table 4).

At both the stages of sampling, application of P recorded significantly higher amount of Sp.ad zinc. Application of zinc increased the quantity of this fraction at harvest, while a slight decrease was observed at flowering. Application of P along with zinc was found to enhance the amount of zinc in this fraction at both the stages.This might be due to formation of zinc phosphate as well as due to adsorption of zinc on negative sites of sorbed P on oxides and hydrous oxides.

The treatment with boron recorded significantly lower content of Sp.ad zinc than that in the treatment without boron. The decrease in the amount of this fraction due to boron application also should be viewed in relation to reduction in number of sites for zinc adsorption, especially because of the lowest amount of Sp.Ad zinc being recorded, when B was applied without P at both the stages (Table 52 to 53, Fig 7 to 9).

5.6.3.3. Acid soluble Zn

The acid soluble zinc fraction showed an increasing trend in all the three soils from initial stageto harvest.

Application of P, Zn, as well as boron increased the zinc content in acid soluble pool at both the stages in soil with medium P (S_2). It is clear from the data that, part of the applied as well as native zinc was transformed to this fraction and made available to the crop for absorption. Such a transformation was practically not observed in soil with low and high P (S_1 and S_3) where available zinc was very low (Table 54 to 55, Fig 7 to 9).

5.6.3.4. Manganese Oxide occluded Zn

MnO-zinc fraction substantially increased at flowering in soil with highest available zinc (S2) and the level was maintained at harvest. In the other two soils there was no clear trend with respect to MnO-zinc during the crop growth stages.

No significant effect on this fraction was observed to influence the quantity of MnO-zinc with respect to application P, Zn and boron at flowering. But at harvest, application of P and Zn increased the MnO-zinc. The interaction effects at both the stages indicated that application of zinc along with P was responsible for the highest zinc content in this fraction. Application of P without boron recorded the highest MnO-zinc content. These data revealed that as in case of acid soluble zinc, phosphorus bound to oxides and hydrous oxides of manganese contributed to the occlusion of zinc in this amorphous material and boron showed a competitive effect with P in occlusion of zinc in this fraction (Table 56 to 57, Fig 7 to 9).

5.6.3.5. Organic matter occluded Zn

Similar to the trend with respect to MnO-zinc, the OM-zinc in soil with medium available zinc (S_2) increased substantially at flowering and almost same level was maintained at harvest.

At flowering, application of P enhanced the quantity of OM-zinc fraction whereas application of B decreased this fraction. At harvest application of P decreased the OM-zinc fraction, while application of Zn showed an increase in this fraction. Thus the interaction effect of P with Zn was positive at flowering. At both stages, application of boron along with P recorded the lowest quantity OM-zinc fraction (Table 58 to 59, Fig 7 to 9).

5.6.3.6. Amorphous iron oxide occluded Zn

The Am-FeO-zinc showed a declining trend from the initial level till harvest. At harvest, Am-FeO-zinc declined with application of phosphorus. Neither application of zinc nor boron was found to have any significant effect at harvest. However the interaction effect showed that application of zinc and boron along with P did reduce AmFeO-zinc at this stage. The soil with highest available zinc recorded highest value of this fraction.

At flowering application of P and Zn increased the Am-FeO-zinc but application of boron was found to reduce it. The interaction effects revealed that application of zinc and boron with P increased the quantity of this fraction. The data indicated that there was release from this fraction to the available pool. At the same time, the soluble zinc reverted back to this pool. This dynamic transformation must have resulted in getting no significant correlation for this fraction with available zinc. It is also clear from the data that part of applied zinc was getting occluded in oxides and hydrous oxides of iron (Table 60 to 61, Fig 7 to 9).

5.6.3.7. Crystalline iron oxide occluded Zn

The soil with highest available zinc (S_2) as well as total zinc recorded the highest quantity of Cry-FeO- zinc.

At flowering application of P was found to decrease Cry-FeO-zinc while at harvest this treatment resulted in an increase of this fraction. Zinc application resulted in decrease of this fraction at flowering while at harvest the same fraction got increased with Zn application. At both flowering and at harvest, application of B was decreased the Cry-FeO-Zn.

The data on interaction effects of P-Zn as well as P-B indicated that application of Zn and B along with P decreased Cry-FeO-Zn at flowering but at harvest it got increased (Table 62 to 63, Fig 7 to 9).

Fig.7 a. Initial distribution of fractions of Zn insoil with low available P(S_1)

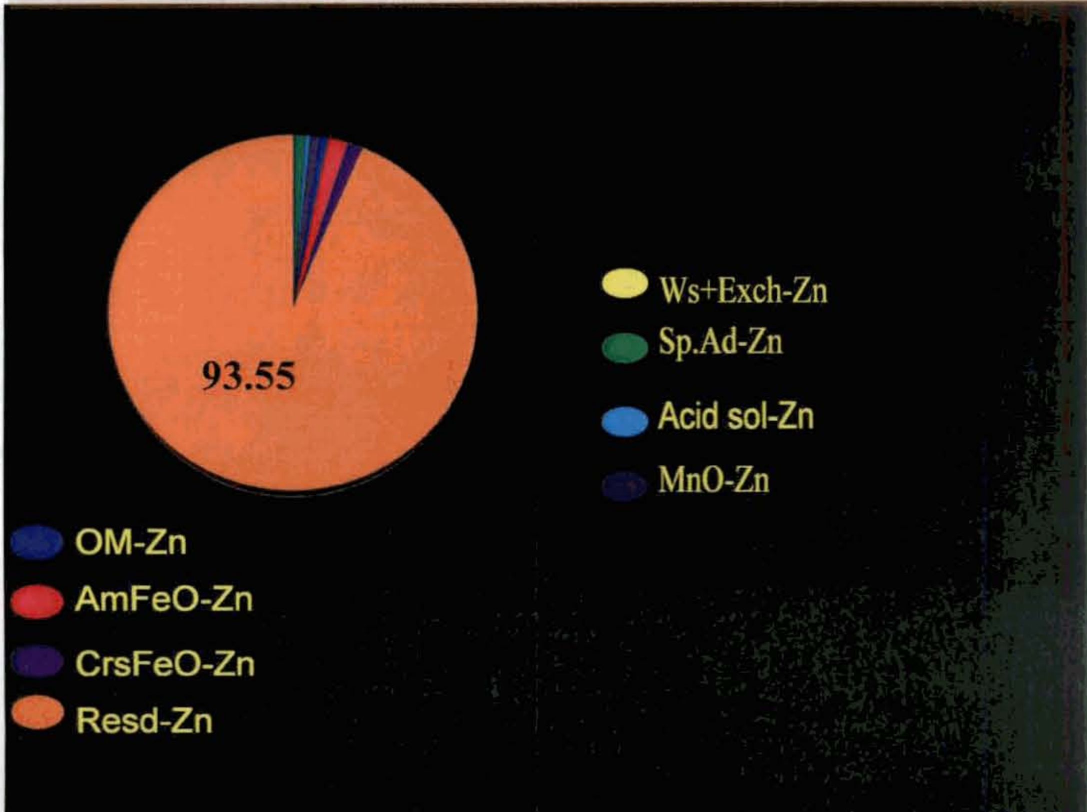


Fig.7b. Variations in fractions of Zn which directly contributed to available pool at flowering

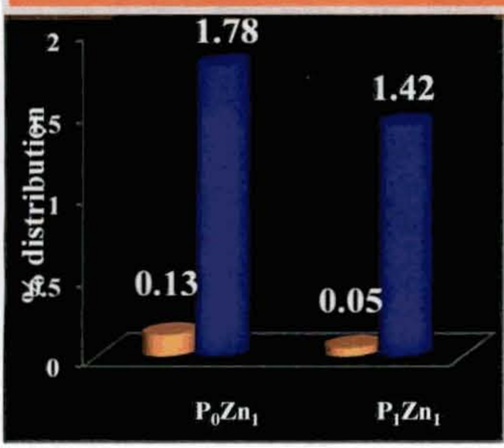


Fig.7c. Variations in fractions of Zn which directly contributed to available pool at harvest

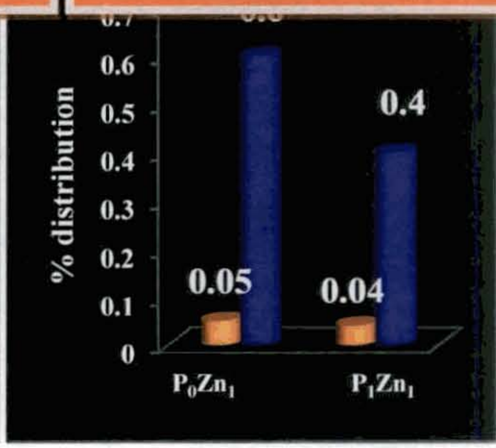


Fig.8 a. Initial distribution of fractions of Zn in soil with medium available P(S_2)

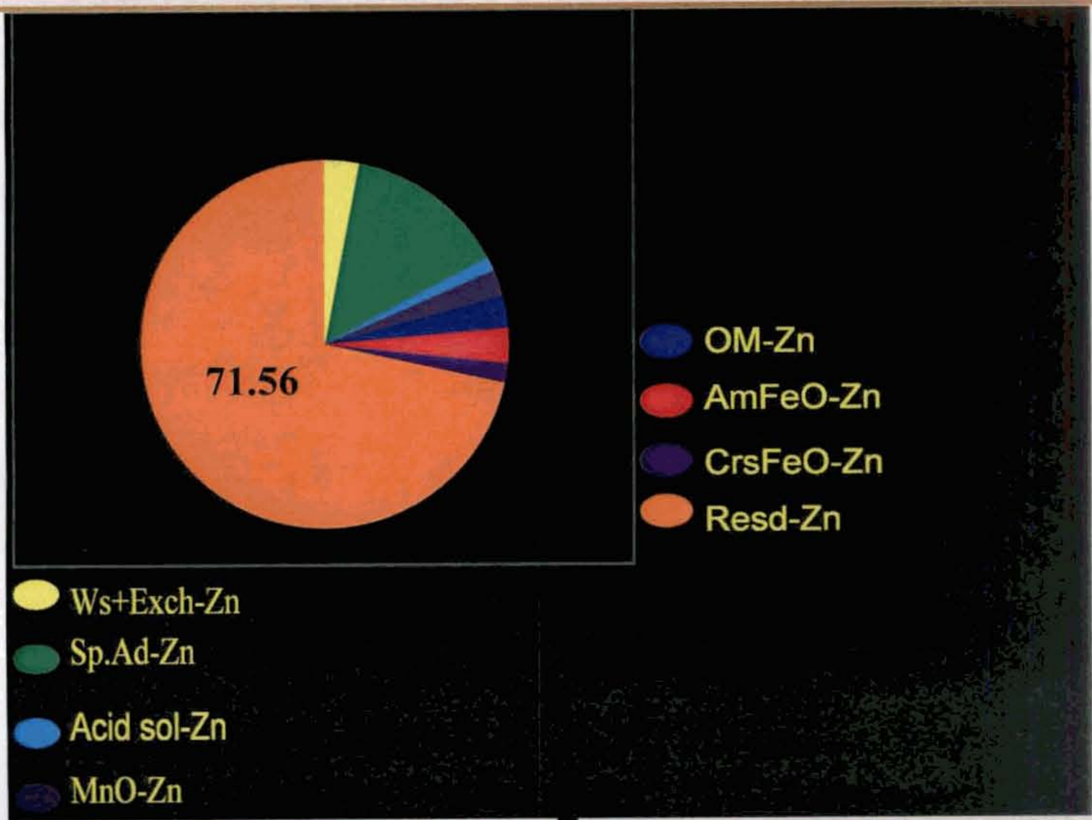


Fig.8b. Variations in fractions of Zn which directly contributed to available pool at flowering

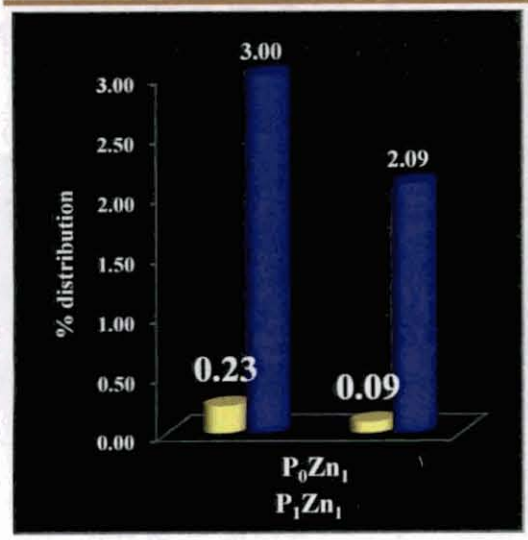


Fig.8c. Variations in fractions of Zn which directly contributed to available pool at harvest

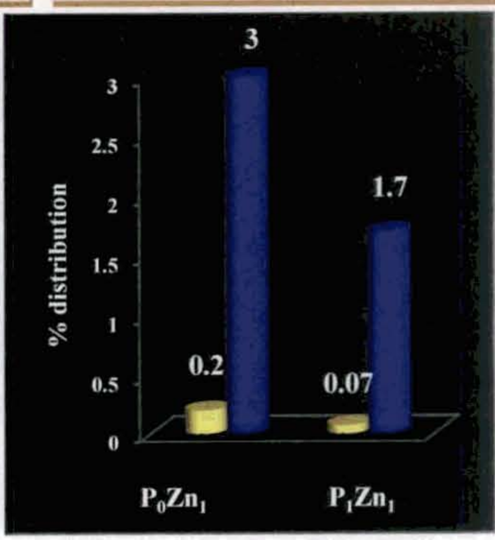


Fig. 9 a. Initial distribution of fractions of Zn in soil with high available P(S_3)

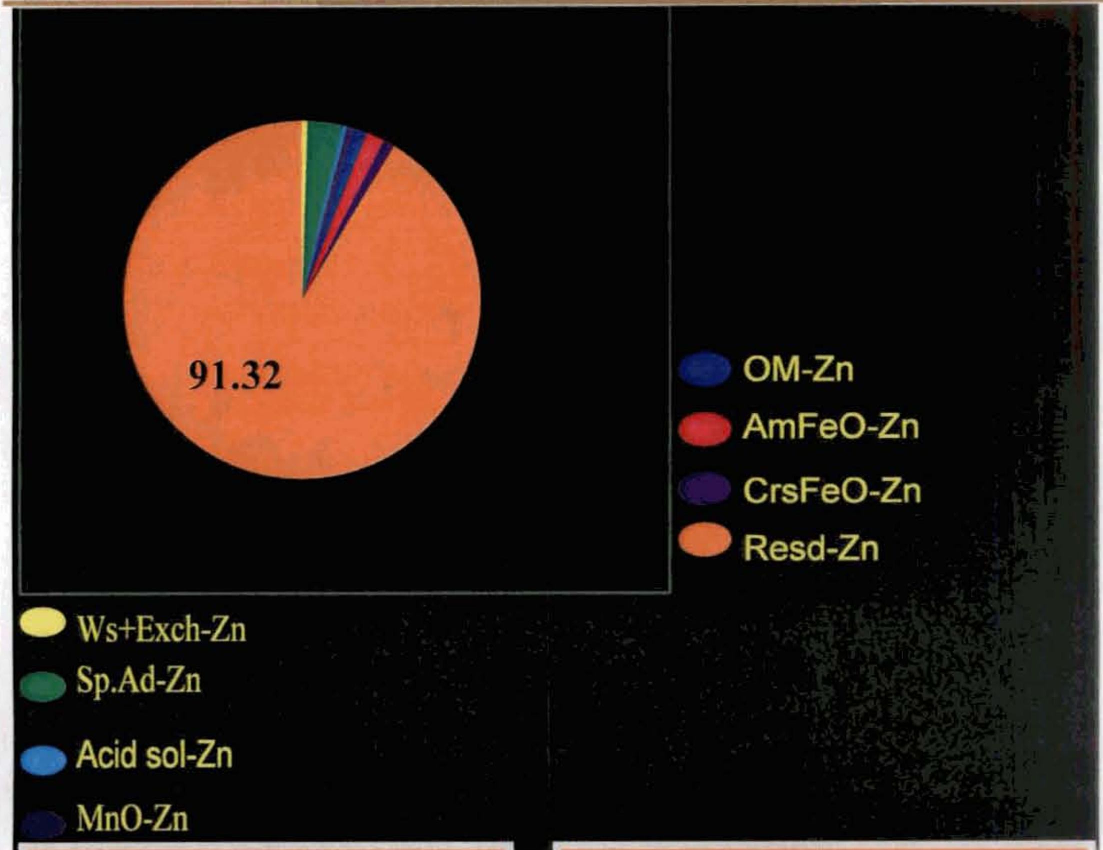
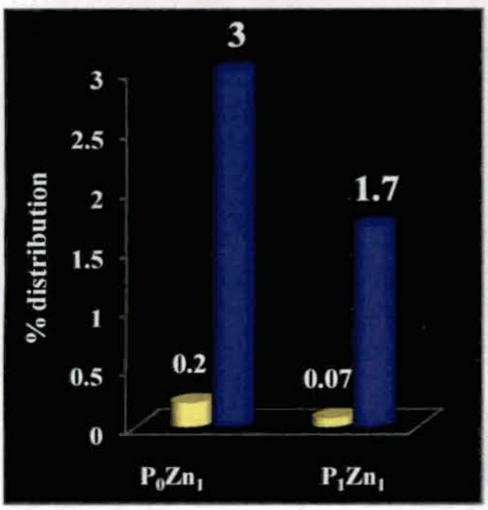
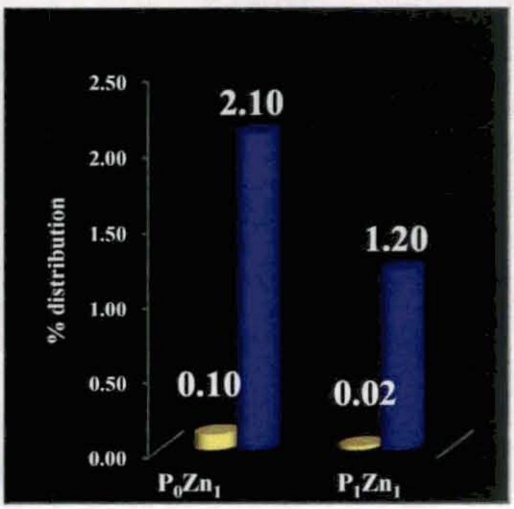


Fig .9b.Variations in fractions of Zn contributed to available pool at flowering

Fig .9c.Variations in fractions of Zn contributed to available pool at harvest





5.6.4. Fractions of boron at flowering and at harvest

5.6.4.1. Readily soluble B(RS-B)

The readily soluble soil boron decreased at flowering due to absorption by the plant roots. Though RS-B slightly increased at harvest than that at flowering, the quantity was still lesser than the initial status. This would mean that the present dose (10 kg ha^{-1}) was sufficient just to meet the plant requirement without improving the status in soil solution.

Application of P was found to reduce the readily soluble boron because of the competition effect of anionic species of phosphate ($H_2PO_4^-$) and borate (H_2BO_3) in soil solution. Application of boron significantly increased the readily soluble boron. The increase in readily soluble content without application of phosphorus also ascertained the negative interaction of phosphorus with boron both at flowering and at harvest (Table 66 to 67, Fig 10 to 12).

5.6.4.2. Specifically adsorbed B (Sp.Ad-B)

The specifically adsorbed boron decreased at flowering than initial content and then slightly increased at harvest. This trend was similar to that of readily soluble boron. Further it is clear that RS-B as well as Sp.Ad boron were significantly and positively correlated with available boron in soil as well as plant content. Both at flowering and at harvest, these two fractions (RS-B and Sp.Ad boron) mainly contributed to the available pool and absorption of boron from these two fractions by the crop resulted in decreasing the quantity of this fraction at harvest of the crop.

Both at flowering and at harvesting stage, a part of the applied boron was transformed to specifically adsorbed boron which in turn was inhibited by the presence of applied phosphorus. Adsorption of boron on specific sites was reduced by application of P. Application of boron as well as that of zinc also reduced the boron content in specifically adsorbed pool at flowering. However application of boron without P increased the specifically adsorbed boron indicating the antagonistic effect between P and B (Table 68 to 69, Fig 10 to 12).

5.6.4.3. Oxide bound B

Application of P was found to increase oxide bound boron. This might be due to the release of boron from the oxides by the process of anion exchange. Application of boron attributed to the increase oxide bound fraction both at flowering and at harvest. Increase in soluble P during flowering than the initial content also suggest the release of the P at the expense of oxide bound boron. The soil with high initial available phosphorus showing highest oxide bound boron also support the above fact. Thus application of boron with P recorded the highest OX-B. Application of zinc with P recorded high OX-B in comparison with zinc without P indicating the competitive interaction of P both for the positively charged site as well as for precipitating with zinc (Table 70 to 71, Fig 10 to 12).

The increase in OX-B from initial level till harvest of the crop indicated that a major portion of applied boron was transformed to this fraction.

5.6.4.4. Organic matter bound B

The data on organic matter bound boron at flowering and at harvesting stage indicated that application of P, Zn, and boron increase the boron content in this fraction in all the three soils. This would mean that binding of boron to organic matter either by occlusion or by adsorption is in proportion with the level of soluble phosphorus applied. This interaction of boron with organic matter independent of the applied zinc indicated by the same level of this fraction in treatment without phosphorus, with and without zinc (P0Zn0 and P0Zn1); however application of P with and without zinc or boron enhanced the OM-B fraction (Table 72 to 73, Fig 10 to 12).

Fig. 10 a. Initial distribution of fractions of B insoil with low available P(S_1)

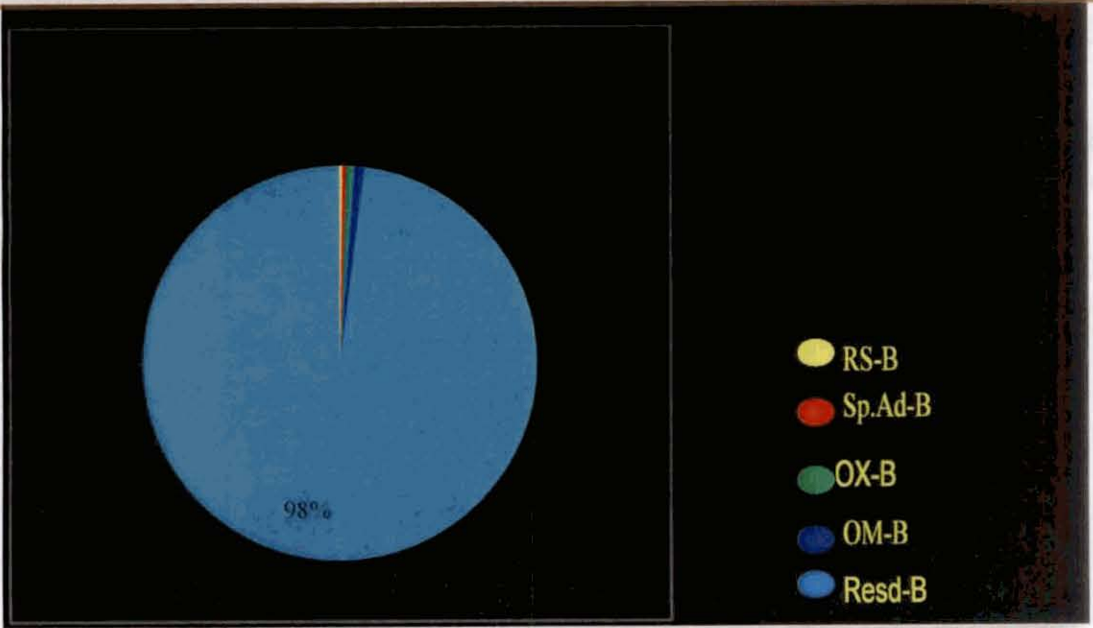


Fig. 10b.Variations in fractions of B contributed to available pool at flowering

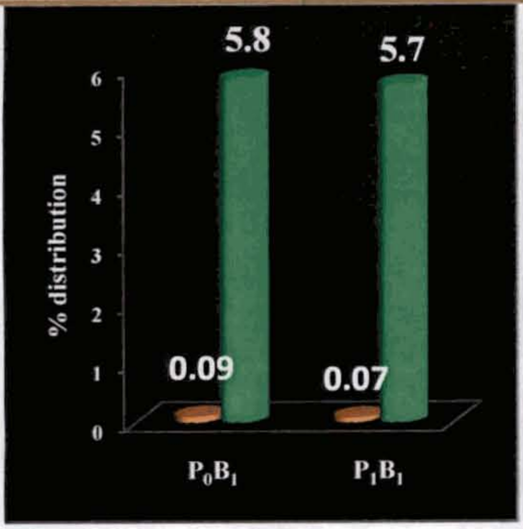


Fig.10c.Variations in fractions of B contributed to available pool at harvest

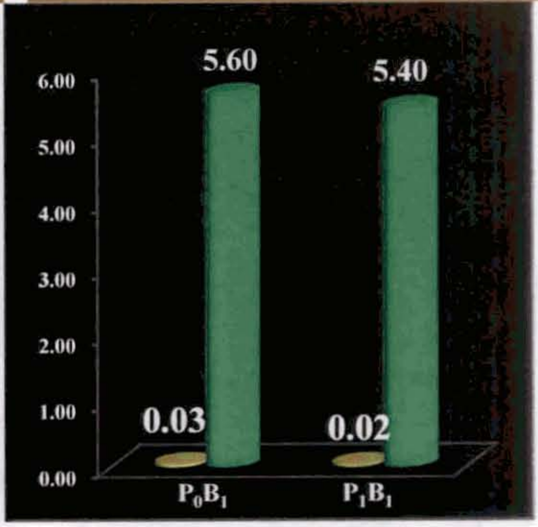


Fig.11 a. Initial distribution of fractions of B insoil with medium available $P(S_2)$

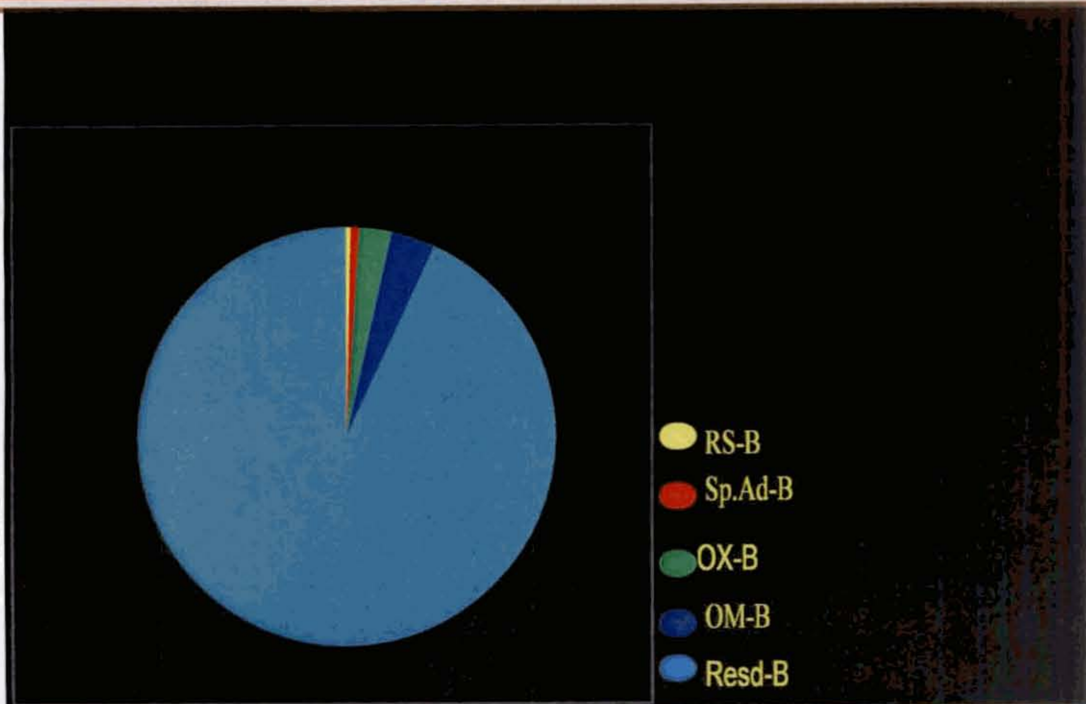


Fig.11b.Variations in fractions of B contributed to available pool at flowering

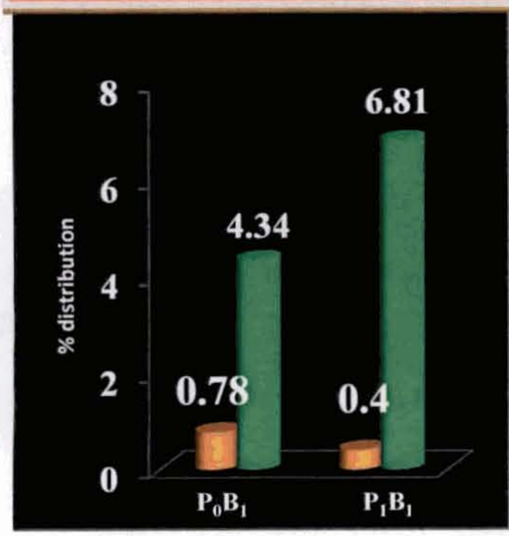


Fig.11c.Variations in fractions of B contributed to available pool at harvest

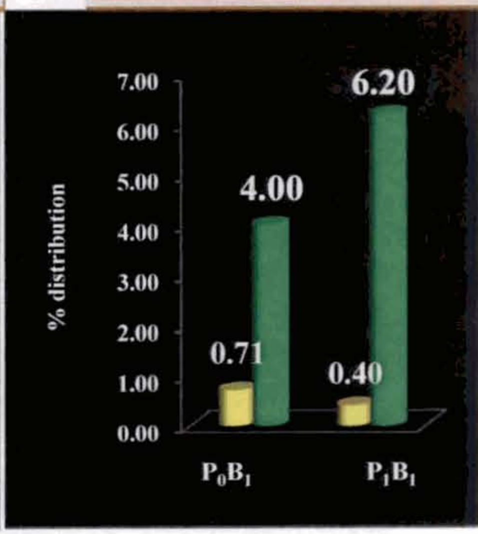


Fig.12 a. Initial distribution of fractions of B insoil with high available P(S_3)

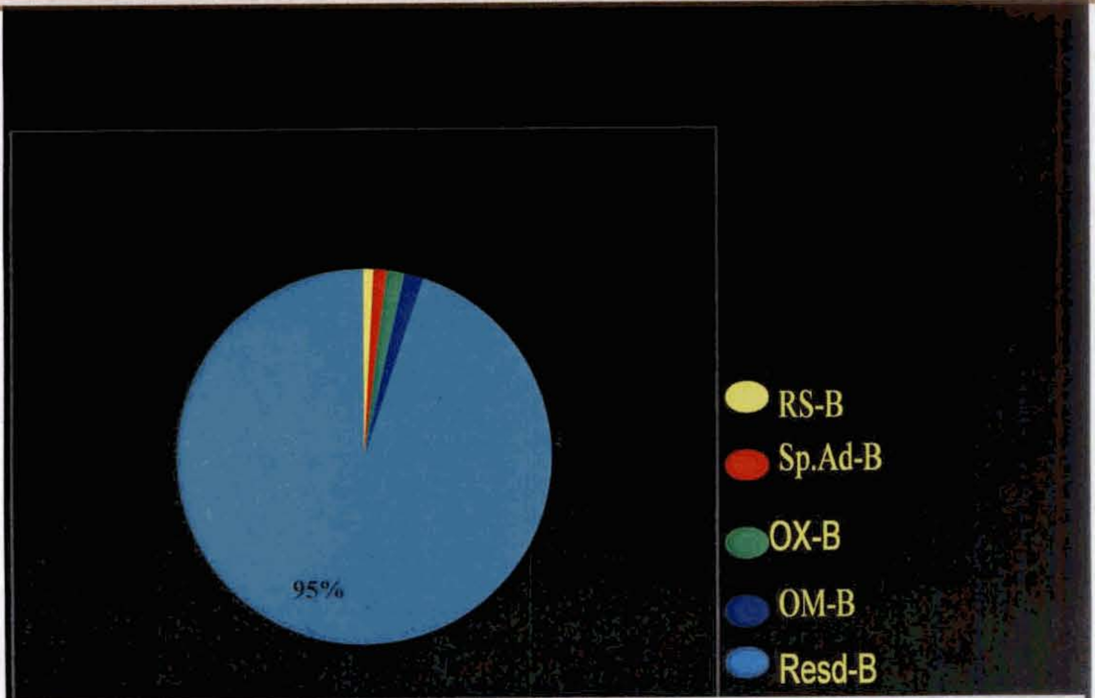


Fig.12b.Variations in fractions of B contributed to available pool at flowering

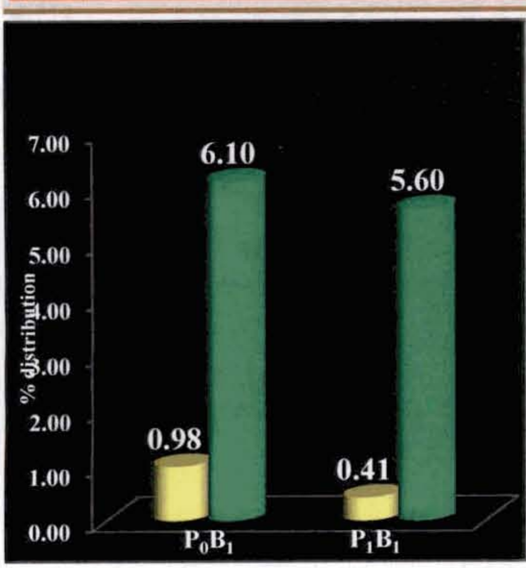
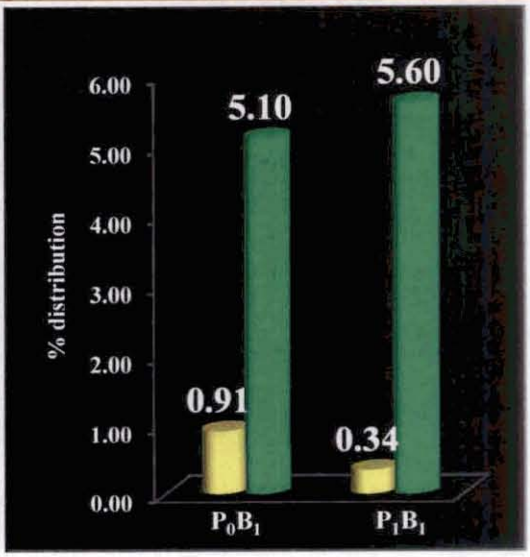


Fig.12c.Variations in fractions of B contributed to available pool at harvest



5.6.4.5. Residual boron

Application of boron was not found to increase the residual boron content while the treatment with P and Zn increased the residual boron at both the stages of sampling (Table 74 to 75, Fig 10 to 12).

5.6.5. Nutrient concentration at flowering and harvesting stage

5.6.5.2. Nitrogen

Irrespective of the soil, application of P and B was found to decrease the N content in plant both at flowering and at harvest. However, application of Zn increased the N content in plant at both the stages. In general, the N content in plant was found to decrease at harvest when compared to that at flowering.

5.6.5.2. Phosphorus

The data on plant P content indicated that irrespective of the initial available P status in soil as well as the available phosphorus status at flowering and at harvest, the plant P content increased with application of phosphorus both at flowering and harvest. Further, the P content in plant was in proportion to the initial P levels in soil. Application of zinc without phosphorus decreased the phosphorus content due to formation of insoluble zinc phosphate. A similar effect was observed in case of phosphorus -boron interaction probably due to anion competition both at flowering and at harvesting stages. Blamey and Chapman, (1979) also made similar reports based on their work in peanut. The P content in plant increased at harvesting when compared to that at flowering stage (Table 78 to 79).

5.6.5.3. Potassium

The potassium content in plant was found to be influenced synergistically by applied phosphorus and zinc; however boron application did reduce the potassium content in plant both at flowering and at harvesting stages. Between the soils the potassium absorption was higher from soil with low P (S_1) which has got the highest

Fig. 13. Path diagram of Zn fractions

Fractions of zinc contributing to available pool

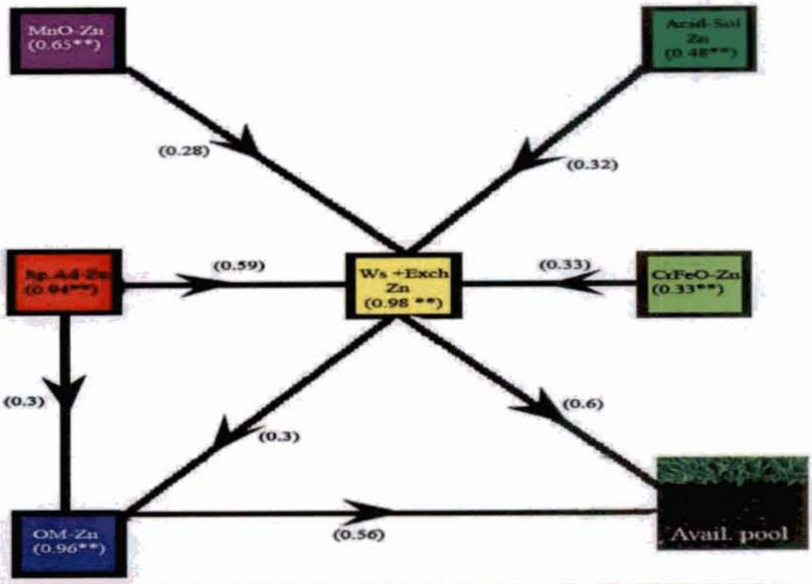
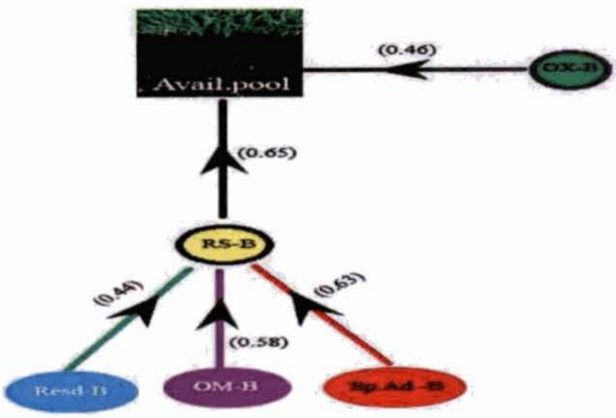


Fig. 14. Path diagram of B fractions

Fractions of zinc contributing to available pool



initial available potassium content (Table 4). As the initial available K status decreased as in soil with high P (S_3) K content in plant also got reduced. The K content was higher at harvest than that at flowering (Table 80 to 81).

5.6.5.4. Calcium

Calcium content in plant was not found to be influenced by application of P, Zn and boron either at flowering or at harvesting stages. The Ca content increased at harvest when compared to that at flowering (Table 82 to 83). .

5.6.5.5. Magnesium

Magnesium content in plant increased with application of phosphorus while application of zinc and boron did reduce the magnesium content at both stages of sampling. Thus the treatment with application of zinc and boron without P recorded the lowest magnesium content. However this effect was not observed when zinc and boron were applied with phosphorus. The Mg content increased at harvesting than that at flowering stage (Table 84 to 85).

5.6.5.6. Sulphur

Sulphur content in plant was found to be enhanced by application of zinc. Further application of zinc and boron without P increased the suphur content both at flowering and at harvest. This increase in sulphur content was due to the application of zinc as zinc sulphate. The highest sulphur content was observed in soil with medium P (S_2) in both the stages, which has got highest initial available sulphur content (table 4). The sulphur content in plant was almost same both at flowering and at harvesting stages (Table 86 to 87).

5.6.5.7. Iron

Application of P and B was found to increase the iron content in plant, while application of zinc reduced the iron content. This was clear from the data when P was applied along with zinc, iron content increased indicating the effect of P in immobilizing zinc, thereby reducing the competition with iron. The soil with high P (S_3) recorded the highest iron absorption which has got high initial available iron status at harvesting stage (Table 88 to 89).

5.6.5.8. Manganese

The influence of application of P, Zn, and B on Mn content was very similar to that of iron i.e.; phosphorus and boron enhanced manganese content while zinc reduced it. Among the interaction effects, zinc with or without P reduced the manganese content due to competition, the effect being higher without P. Application of phosphorus without boron increased manganese content at both the stages (Table 90 to 91). The soil with high P (S_3) recorded the high manganese content at both the stages because of highest available manganese in this soil (Table 4).

5.6.5.9. Zinc

At both flowering and at harvesting stages, the zinc content in plant was antagonistically influenced by application of phosphorus. Similar results were reported by Olsen (1972) which stated that high levels of available P or the heavy application of P to the soil induced Zn deficiency in plants. Application of zinc naturally increased the zinc content in plant. Boron also got positive interaction with zinc, so as to increase the zinc content. Thus application of zinc without P recorded the highest zinc content and boron and phosphorus together will reduce the zinc content (Table 92 to 93). The soil with medium P (S_2) recorded the highest zinc content in plant at both the stages of sampling, because of the highest initial available zinc in this soil (Table 4).

5.6.5.10. Copper

The copper content in plant decreased significantly due to application of phosphorus and boron while it increased by application zinc at flowering and at harvesting stages. Thus it is evident from the data that the application zinc without P recorded the highest copper content (Table 94 to 95).

5.6.5.11. Boron

With respect to the boron content in plants, the treatment involving soil with low P (S_1) was very low compared to the same treatments in the other two soils because of the initial severe deficient levels of available boron in this soil. Application P and Zn further reduced the boron content in plant (Table 96 to 97). Kaya *et al.*, (2009) made similar reports in tomato on P and B interaction. Thus the treatment with P and Zn recorded the lowest boron content, while the treatment with application of B without P recorded the highest boron content.

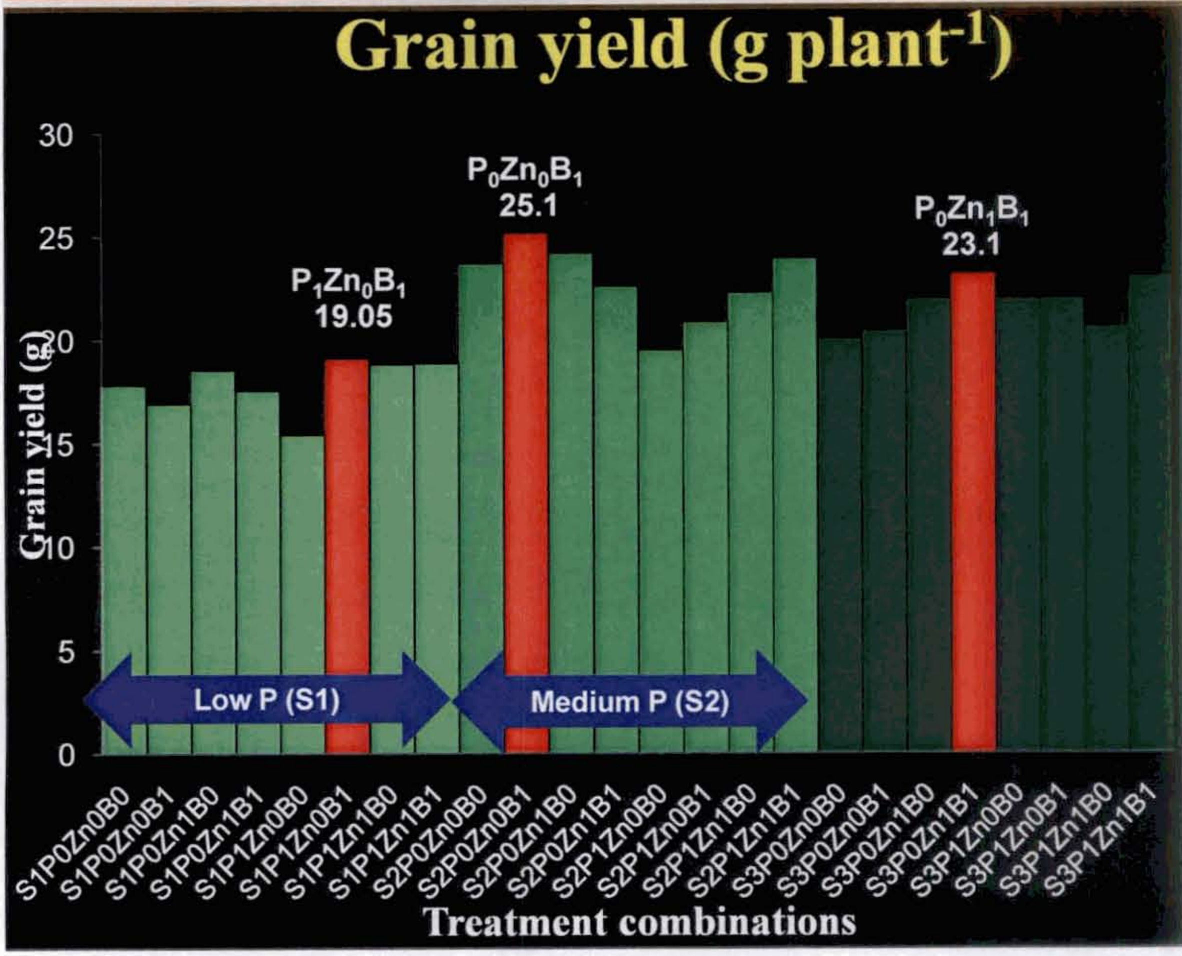
5.6.6. Pearson correlation of available P,Zn, and B with P,Zn and B content in plant

The available P in the soil was found to be negatively correlated with available zinc and boron as well as plant zinc and boron. This indicates the antagonistic interaction of P with Zn and B both in soil and plant. Similarly Zn and B content in plant was also found to be negatively correlated with plant P content. This indicates that high level of P restricts the Zn and B uptake (Table 98).

5.6.7. Biometric observations

The essentiality of phosphorus for growth and yield was clearly established from the data on biometric observations as well as yield and yield attributes. The highest yield was recorded in soil with medium P (S_2), which indicated that the available P status in this soil was sufficient to obtain optimum yield, at the same time the soil with low P (S_1) resulted in reduction in yield. Further, the available P status over and above the required level either through the native P or through the applied P did reduce the yield possibly due to antagonism as well as P induced deficiency of other nutrients. This is evident from the effect of zinc on yield. Application of zinc without P could enhance the yield. At the same time absence of zinc with P recorded

Fig. 15.Grain yield per plant



the lowest yield. The same trend was observed in the case of number of leaves. Phosphorus application could increase growth of the plant as indicated by plant height. However application of zinc and boron did not show any direct influence on yield and yield attributes. However, optimum combination of zinc and boron with sufficient available phosphorus could improve the growth and yield, which is a clear validation of law of minimum (Table 99 to 104).

Dynamics of Phosphorus, Zinc and Boron

Eighteen soil samples were characterized with respect to physiochemical properties and available nutrient status. Among these soils, six each could be categorized as low, medium and high with respect to available P status. One soil each from the above three categories (low, medium and high available P) were used for pot culture experiment. The soil with low available P(S_1) was medium in K (231.8kgha^{-1}) deficient in Ca and Mg, sufficient in Fe, S, Mn, Zn and Cu and deficient in B. The soil with medium P (S_2) was medium in organic carbon, low in available K, deficient in Ca and Mg and sufficient in micronutrients. The soil with high P was having medium OC and available K, deficient in Ca and Mg and sufficient with respect to other nutrients. The CEC of the soils were 6.7 (S_1), 7.1 (S_2) and 5.4 (S_3). The distribution of fractions of inorganic fraction in the three soils showed that Fe bound P was the dominant fraction contributing to more than 52.6% of the total inorganic P. The soluble P fraction was about 6% in all the three soils. Fe and Al-P were the main fractions contributing to available pool initially.Among the B fractions, RS-B recorded the lowest, where as the contribution of residual B was the highest.

Phosphorus

Available P status in soils with low and medium P increased due to the application of P while it decreased in soil with high P. It was clear from the data that the applied P got transformed to Fe-P and Al-P. Initially in soils with low and medium P status which contributed to the available pool. The soil with high P showed that the application of P led to the fixation of P to insoluble forms where as the soil without P application,there was solubilisation of Fe-P and Al-P resulting in increased availability. This dynamics of P can be summarized as follows.

Plant absorbed P from soluble P leading to its depletion at the end of vegetative phase. Applied P got transformed into Fe-P and Al- P initially which along with native OC-P got transformed to Ca-P which is contributing to the available pool at later stages. Application of Zn was found to reduce Al-P and Fe-P due to the formation of insoluble $ZnPO_4$. Application of Zn and B reduced the Ca-P, probably due to the formation of $ZnPO_4$ and calcium borate.

Zinc

It is clear from the data that Ws+exch.Zn and OM - Zn was directly contributing to the available pool. The other Zn fractions except Am FeO-Zn were contributing to the available pool indirectly through Ws+exch.Zn. Application of P reduced the Ws+exch.Zn fraction where as the application of B enhanced the transformation of zinc into this fraction especially when B was applied without P.

Boron

RS-B and OX-B were directly contributing to the available pool where as binding of B with OM as well as its transformation to residual B reduced B availability.Allthe fractions of boron were contributing to theavailable pool indirectly through RS B.

Application of B was found to reduce the RS B due to anion competition. The applied B either remained in the soluble form or getting transformed to Sp.Ad, OX- B and OM- B. Boron application along with P reduced the RS- B initially.

Summary

6.SUMMARY

In order to achieve the objective of elucidating the dynamics of zinc and boron influenced by phosphorus status in lateritic soils and of optimizing the level of P for balanced nutrition of cowpea with respect to Zn and B, 18 lateritic soil samples (Ultisol), six each coming under low, medium and high available P status were identified and characterized. A pot culture experiment with cowpea as a test crop was conducted in three soils, one each with low, medium and high available P status. The experiment was conducted in CRD with and without application of P, Zn and B in all the possible combinations. Thus there were 24 treatment combinations (3 soils×2 levels of P × 2 levels of Zn × 2 levels of B) which were replicated four times. Soil and plant samples were collected at flowering and at harvesting stage and analyzed for nutrient content, yield and yield attributes.

The salient findings are listed below

- The pH of 18 soils rangedfrom4.03 to 5.70.
- The electrical conductivity ranged from 0.06 to 0.21 dSm^{-1}.
- The organic carbon of the selected soil varied from 0.09 to1.96%.
- The CEC ranged from 2.37 to 10.09 cmol(p+)kg^{-1}.
- Even though the average calcium status in all the three soils was deficient, exchangeable Ca contributed more than 50% of the CEC.
- Exchangable Al^{3+} in soils with high P (S_3) was higher than that of exchangeable Mg^{2+} and it was almost same as that of exchangeable magnesium in soil with medium P (S_2) .
- Fe- P was the dominant fraction contributing to 52-62% of the total inorganic P in all the three soils and the soluble P contribution was only about 6 %.
- The Fe-P, Al-P and OC-P directly contributed to the available pool.

- Among the B fractions, residual boron recorded the highest percentage (more than 90%) of the total B while readily soluble boron recorded the lowest (less than 2%).
- Readily soluble boron and oxide bound boron were contributing directly to the available pool whereas organic matter occluded and residual boron were restricting the B availability.
- All B fractions were in dynamic equilibrium and contributing to the available pool through readily soluble boron.
- In soils with low and medium P (S_1 and S_2), available P increased with and without P application due to increase in pH, where as in high 'P' soil (S_3), available 'P' decreased due to reversion of applied P.
- Application of Zn reduced the available 'P' status due to formation of insoluble zinc phosphate.
- Soluble P decreased at flowering due to uptake as well as fixation of applied P.
- The fixed P was found to be available at later stages of plant growth.
- Both Zn and B application reduced the soluble P fraction.
- Al-P and Fe-P increased due to application of P indicating the transformation of applied P to these fractions.
- At harvest, increase in Ca-P was observed due to transformation of Al-P to Ca-P however, application of Zn and B reduced the Ca-P due to the formation of insoluble zinc phosphate and calcium borate respectively.
- Ws+Exch Zinc were found to contribute to the plant content and depletion in this fraction due to plant absorption was observed.
- The initial high P status as well as the applied soluble phosphorus was found responsible for reduction in this fraction.
- The Sp.Ad-Zn was slowly getting transformed as Ws+Exch Zinc and contributing to the available pool.

- Application of phosphorus resulted in increase in the quantity of Sp.Ad-Zn whereas the application of B reduced the quantity of this fraction.
- Application of P and Zn resulted in increased MnO-Zn, while boron application resulted a decrease in the amount of this fraction at flowering stage.
- Application of P increased the organic matter occluded zinc, whereas application of Zn and B decreased the quantity of this fraction.
- Readily soluble boron reduced from the initial status due to plant uptake even with the application of boron.
- Application of phosphorus reduced readily soluble boron whereas application of boron increased the amount in this fraction.
- RS-B as well as Sp.Ad boron contributed to the available pool resulting in decrease in the quantity of this fraction at harvest.
- Applied boron was found to be either in water soluble or Sp.Ad fraction, which was antagonistically affected by applied phosphorus.
- The increase in oxide bound boron resulted in the release of phosphorus from these binding sites.
- Part of the applied boron was getting transformed into organic matter occluded boron restricting its availability.
- The plant phosphorus content increased with the application of phosphorus.
- Application of P with Zn decreased the plant phosphorus content.
- Application of boron also reduced the plant phosphorus content.
- Application of zinc increased the zinc content in plant, however, application of phosphorus with and without boron reduced the zinc content in plants.
- Application of phosphorus and zinc reduced the boron content in plants and application of boron without phosphorus recorded the highest boron content.
- The highest grain yield was recorded in the treatment of soil with medium phosphorus (S_2) , which was inherently sufficient with zinc and in which

boron was added to correct the deficiency ($S_2Zn_0B_1$)while the high P status in soil either due to native P or due to applied P reduced the yield due to induced lower uptake of zinc and boron.

- In soils with high P status, P induced Zinc and boron deficiency was observed.

References

7. REFERENCES

Abolfazli, A., Forghani, G., and Norouzi. M. 2012. Effects of phosphorus and organic fertilizers on phosphorus fractions in submerged soil. *J. soil sci. plant nutr.* 12(2): 349-362.

Adhikari, T. and Rattan, R. K. 2007. Distribution of zinc fractions in some major soils of India and the impact on nutrition of rice. *Commun. Soil. Sci. Plant Anal.* 38: 2779-2798.

Akin. A. 2009. Chemical Fractionatio's of Soil Boron and the Fractions of Their Relationships With Soil Properties in Kazova Soils. *Agris* 41-48 p.

Alloway, B. J. 2008. *Zinc in Soils and Crop Nutrition.* International Zinc Association, Brussels, Belgium, 135p.

Anderson, P. R. and Christensen, T. H. 1988. Distribution coefficient of Cd, Co, Ni and Zn in soils. *J. Soil Sci.* 39: 15–22.

Avila, F. W., Faquin ,V., Lobato ,A. K. S., Baliza , D. P., Marques, D.J., Passos , A. M. A., Bastos, C. E. A., and Guedes, E. M. S. 2006. Growth, phosphorus status, and nutritional aspect in common bean exposed to different soil phosphate levels and foliar-applied phosphorus forms. *Sci. Res. Essays* 7(25): 2195-2204.

Bagshaw, R., Vaidyanathan, L. V., and Nye, P. H . 1972. The supply of nutrient ions by diffusion to plant roots in soil and direct determination of labile phosphate concentration gradients in a sandy soil induced by plant uptake. *Plant Soil* 37: 617–626.

Barben, S. A., Hopkins, B. G., Jolley, V. D., Webb, B. L., and Nicholas, B. A. 2010. Phosphorus and zinc interactions in chelator-buffered solution grown russet Burbank potato. *J. Plant Nutr.* 33: 587–601.

Barben, S. A., Nichols, B. A., Hopkins, B.G., Jolley, V. D., Ellsworth J., and Webb, B. L. 2007. Phosphorus and zinc interactions in potato. Western Nutrient Management Conference. Salt Lake City, UT.

Barber, S. A. 1984. *Soil Nutrient Bioavailability: A Mechanistic Approach.*John Wiley and Sons, New York, 398 pp.

Barber, S. A., Walker, J. M., and Vasey, E. H. 1963. Mechanisms for the movements of plant nutrients from the soil and fertilizer to the plant root. *J. Agric. Food Chem.* 11: 204–207.

Behera, S. K. 2011. Distribution variability of total and extractable zinc in cultivated acid soils of India and their relationship with some selected soil properties. *Geoderma* 162: 242–250

Bingham, F. T. 1982. *Methods of Soil Analysis Part 2. AgronomyMonograph.* (2nd Ed.). ASA and SSSA, Madison, pp. 431–447.

Bingham, F. T. and Garber, M. J. 1960. Solubility and availability of micronutrients in relation to phosphorus fertilization. *Soil Sci. Soc. Am. Proc.* 24:209-213.

Bingham, F. T., Martin, J. P., and Chastain. J. A. 1958. Effects of phosphorus fertilization of California soils on minor element nutrition of citrus. *Soil Sci.* 86:24-31.

Bingham, F.T., Page, A. L. Coleman, N. T., and Flach, K. 1971. Boron adsorption characteristics of selected amorphous soils from Mexico and Hawaii. *Soil Sci. Soc. Am. Proc.* 35(4): 546-550.

Blamey, P. P. C. and Chapman, J. 1979. Boron toxicity in Spanish groundnuts. *Agron. J.* 71: 57–59.

Boawn, L. C. and Leggett, G. E. 1964. Phosphorus and zinc concentrations in Russell burbank potato tissue in relation to development of zinc deficiency symptoms. *Soil Sci. Soc. Am. Proc.* 2: 229-232.

Bray, R.H. and Kurtz, L.T. 1945. Determining total, organic and available forms of phosphate in soils. *Soil Sci.* 59: 39-45.

Brown, J. C. and Tiffin. L. O. 1962. Zinc deficiency and iron chlorosis dependent on the plant species and nutrient-element balance in Tulare clay. *Agron. J.* 56:356-358.

Buerkert, A., Haake, C., Ruckwied, M., and Marschner, H. 1998. Phosphorus application affects the nutritional quality of millet grain in the Sahel. *Field Crops Res.* 57: 223–235.

Bukvi, G., Antunovi, M., Popovi, S., and Rastija, M. 2003. Effect of P and Zn fertilisation on biomass yield and its uptake by maize lines (*Zea mays* L.). *Plant Soil Environ.* 49(11): 505-510.

Cassman, K. G., Singleton, P.W., and Linquist. B.A. 1993. Input/output analysis of the cumulative soybean response to phosphorus on an Ultisol. *Field Crops Res.* 34:23–26.

Cassman, K. G., Whitney, A.S. and Fox. R. L. 1981. Phosphorus requirements of soybean and cowpea as affected by mode of nutrition. *Agron. J.* 73:17–22.

Choudhari, M. B. and Stevenson, F. J. 1957. Chemical and physicochemical properties of organic matter from soils. *Soil Sci. Soc. Am. Proc.* 21: 508-518.

Communar, G. and Keren, R. 2008. Boron adsorption by soils as affected by dissolved organic matter from treated sewage effluent. *Soil Sci. Soc. Am. J.* 72:492–499.

Conde, L. D., Chen, Z., Chen, H., and Liao, H. 2014. Effects of phosphorus availability on plant growth and soil nutrient status in the rice- soybean rotation system on newly cultivated acidic soils. *Am. J. Agric. For.* 2(6): 309-316.

Das, D. K. 1996. Transformation of different fractions of zinc in submerged soil as affected by the application of nitrogen. *Crop Res.* 11: 53-61.

Das, K., Dang, R., Shivananda, T. N., and Sur, P. 2005. Interaction between phosphorus and zinc on the biomass yield and yield attributes of the medicinal plant stevia (*Stevia rebaudiana*). *Sci. World J.* 5:390–395.

Datta, S. P, Rattan, R. K., Suribabu, K., and Datta, S. C. 2002. Fractionation and colorimetric determination of boron in soils. *J. Plant Nutr. Soil Sci.* 165:179–184.

Dharumarajan, S. and Singh, K. 2014. Variation of soil properties and phosphorous fractions in three cropping systems of lower Indo-Gangetic alluvial plain. *Afr. J. Agric. Res.* 9(24):1878-1886.

Dubus, I. G. and Becquer. T. 2001. Phosphorus sorption and desorption in oxide-rich ferralsols of New Caledonia. *Aust. J. Soil Res.* 39: 403-414.

Dwivedi, B. S., Ram, M., Singh, B. P., Das, M., and Prasad, R. N. 1990. Differential response of crops to boron fertilization in acid Alfisols. *Indian J. Agric. Sci.* 60:122–127.

Dwivedi, R. S., Randhawa, N. S., and Bansal, R. L. 1975. Phosphorus-zinc interaction. *Plant Soil* 43: 639-648.

Fathi, H., Aryanpour, H., Fathi H., and Moradi, H. 2014. Distribution of zinc and copper fractions in acid and alkaline (highly calcareous) soils of Iran. *Sky J. Soil Sci. Environ. Manag.* 3(1): 6 -13.

Fox, R. L. and Kamprath. E. J. 1970. Phosphate sorption isotherms for evaluating the P requirements of soils. *Soil Sci. Soc. Am. J.* 64:240–246.

Gahoonia, T .S., Claassen, N., and Jungk,A. 1992. Mobilization of phosphate in different soils by rye grass supplied with ammonium or nitrate. *Plant Soil* 140: 241–248.

Gaines, T.P. and Mitchell, G.A. 1979. Boron determination in plant tissue by the azomethine-H method. *Commn. Soil Sci. Plant Anal.* 10: 99-108.

Geetha, P.2008. Quantity – intensity relations of phosphorus with reference to its bioavailability in lateritic soils. M.sc. (Ag) thesis, Kerala Agricultural University, Thrissur, 188p.

Girma, K., Martin, K. L., Freeman, K. W., Mosali , J., Teal, R. K., Raun, W. R., Moges, S. M., and Arnall, D. B. 2007. Determination of optimum rate and growth stage for foliar-applied phosphorus in corn. Commun. *Soil Sci. Plant Anal.* 38(9): 1137-1154.

Goldberg, S. and Glaubig, R. A. 1985. Boron adsorption on aluminium and iron oxide minerals. *Soil Sci. Soc. Am. J. 49:1374–1379.*

Grant, C. A., Flaten, D. N., Tomasiewicz, D. J., and Sheppard, S. C. 2001. The importance of early season P nutrition. *Can. J. Plant Sci.* 81: 211–224.

Grant, C., Bittman, S., Montreal, M., Plenchette, C., and Morel, C. 2005. Soil and fertilizer phosphorus: Effects on plant P supply and mycorrhizal development. *Can. J. Plant Sci.* 85: 3–14.

Gunes, A. and Alpaslan, M. 2000. Boron uptake and toxicity in maize genotypes in relation to boron and phosphorus supply. *J. Plant Nutr.* 23: 541–550.

Gupta, R. K. and Srivastava, P. C. 1998. Distribution of different forms of phosphorus in acid soils of Sikkim. *J. Hill Res.* 11: 224-228.

Haldar, M. and. Mandal, L. N. 1981. Effect of phosphorus and zinc on the growth and phosphorus, zinc, copper, iron and manganese nutrition of rice. *Plant Soil.* 59(3): 415-425.

Hendershot, W. H. and Duquette, M. 1986. A simplified Barium chloride method for determining cation exchange capacity and exchangeable cations. *Soil Sci. Soc. Am. J.* 50:605-608.

Hopkins, B. and Ellsworth, J. 2003. Phosphorus nutrition in potato production.|In: *Abstracts Idaho Potato Conference*; 22-23 January, 2003. University of Idaho.

Hou, J., Evans, L. J. and Spiers, G.A. 1996. Chemical fractionation of soil boron. I. Method development. *Can. J. Soil Sci.* 76: 485-491.

Hou, J., Evans, L. J., and Spiers, G. A. 1994. Boron fractionation in soils. *Commn. Soil Sci. Plant Anal.* 25 (9): 1841-1853.

Hu, D., Bell , R. W., and Xie, Z. 1996. Zinc and phosphor responses in transplanted oilseed rape. *Soil Sci. Plant Nutri.* 42:333-344.

Huang, C. Y., Barker, S. J., Langridge, P., Smith, F. W., and Graham, R. D. 2000. Zinc deficiency up-regulates expression of high-affinity phosphate transporter genes in both phosphate-sufficient and -deficient barley (*Hordeum vulgare* L. Cv Weeah) roots. *Plant Physiol.* 124: 415- 422.

Iwasaki, K. and Yoshikawa, G. 1993. Fractionation of zinc in greenhouse soils. *Soil. Sci. Plant Nutr.* 39(3): 507-515.

Jackson, M.L. 1958. *Soil Chemical Analysis*. Prentice Hall of India Private Ltd., New Delhi, 498p.

Jackson, M.L. 1973. *Soil Chemical Analysis*. Prentice Hall of India Private Ltd., New Delhi, 498p.

Jaggi, R. C. 1991. Inorganic phosphate fraction as related to soil properties in some representative soils of Himachal Pradesh. *J. Indian Soc. Soil. Sci.* 39: 567-568.

James, D.W., Hurst, C. J., and Tindall, T. A. 1995. Alfalfa cultivar response to phosphorus and potassium deficiency: elemental composition of the herbage. *J. Plant Nutr.* 18:2447-64.

Jayman, T.C.Z. and Sivasubramaniam, S. 1974. The use of ascorbic acid to eliminate the interference of iron in the aluminium method for determining aluminium in plant and soil extract. *Analyst*99: 296-301

Jin, J., Martens, D. C., and Zelazny, L.W. 1987. Distribution and plant availability of soil boron fractions. *Soil Sci. Soc. Am. J.* 51: 1228-1231.

Joshi, D., Srivastava, P.C., Dwivedi, R., and Pachauri,S. P. 2014. Chemical speciation of Zn in acidic soils: suitable soil extractant for assessing Zn availability to maize (*Zea mays* L.) *Chem. Speciation Bioavail.* 26(3):148-157.

Kaya, C., Tuna, A. L., Dikilitas, M., Ashraf, M., Koskeroglu, S., and Guneri, M. 2009. Supplementary phosphorus can alleviate boron toxicity in tomato. *Scientia Horticulturae* 121: 284–288.

Keren, R. and Bingham, F. T. 1985. Boron in water, soils and plants. *Adv. Soil Sci.* 1:229–276.

Keren, R. and Mezuman, U. 1981. Boron adsorption by clay minerals using a phenomenological equation. *Clays Clay Minerals* 29 (3): 198-204.

Khorgamy, A. and Farnia, A. 2009. Effect of phosphorus and zinc fertilisation on yield and yield components of chick pea cultivars. *Afr. Crop Sci. Conference Proc.* 9: 205-208.

Kumaraswamy, K. and Sreeramulu, U. S. 1991: Relative contributions of inorganic phosphorus fractions to the labile phosphorus status of soils and uptake by rice. *J. Indian Soc. Soil Sci.* 39(2): 308-315.

Langin, E. J., Ward, R. C., Olson, R. A., and Rhoades, H. F. 1962. Factors responsible for poor response of corn and grain sorghum to phosphorus fertilisation. II. Lime and P placement effects on P-Zn relations. *Soil Sci. Soc. Am. Proc.* 26: 514-518

Liang, J., Steward, J.W. B., and Karamanos, R. E. 1991. Distribution of zinc fractions in preirie soils. *Can. J. Soil Sci.* 70: 335-342.

Lindsay, W. L .1991. Inorganic equilibria affecting micronutrients in soils. In: Mortvedt, J. J., Cox, F. R., Shuman, L. M., and Welch, R. M (eds), *Micronutrients in Agriculture.* SSSA Book Series No. 4. Madison, WI, pp. 89–112

Malik, V. S. 2014. Massive phosphorus accumulation in soils: Kerala's continuing conundrum. *Curr. Sci.* 106:343-345.

Mandal, M. and Das, D. K. 2013. Zinc in Rice-Wheat Irrigated Ecosystem. *J. Rice Res.* 1: 111

Marschner, H. 1995. *Mineral Nutrition of High Plant,* Academic Press, pp. 330-355

Marschner, H., Oberle, H., Cakmak, L., and Romheld, V. 1990. Growth enhancement by silicon in cucumber (cucumis sativus) plants depends on imbalance in phosphorus and zinc supply. *Plant Soil* 124:211-219.

Martin, W. E., Mclean, J. G., and Quick, J. 1965. Effect of temperature on the occurrence of phosphorus-induced zinc deficiency. *Soil Sci. Soc. Am. Proc.* 29:411 -41 3.

Massoumi, A. and Cornfield, A. H. 1963. A rapid method for determining sulphur in water extracts of soils. *Analyst* 88:321

May, M. G. and Pritts, M. P. 1993. Phosphorus, zinc and boron influence yield components in "Earliglow" strawberry. *J. Am. Soc. Hort. Sci.* 118:43-49.

Mckenzie, D. B. and Soper, R. J. 1983, Zinc regulation in blackbeans (Phaseolus vulgaris L.). *Commun. Soil Sci. Plant Anal.* 4:109-125.

McLaren, R.G. and Crawford, D.V. 1973. Studies on copper I .The fractionation of copper in soils. *J. Soil. Sci.* 24(2): 172-181.

Miller. W. P., Martens, D. C., and Zeolazincy, L. W .1986. Effect of sequence in extraction of trace metals from soils. *J. Soil Sci. Soc. Am.* 50: 598-601.

Mirvat, E. G., Mohamed, M. H., and Tawfik, M. M. 2006. Effect of phosphorus fertilizer and foliar spraying with zinc on growth, yield and quality of groundnut under reclaimed sandy soils. *J. Appl. Sci. Res.* 2(8):491-496.

Mishra, B., Sharma, A., Singh, S. K., Prasad, J., and Singh, B. P. 2008. Influence of continuous application of amendments to maize-wheat cropping system on dynamics of soil microbial biomass in Alfisol of Jharkhand. *J. Indian Soc. Soil Sci.* 56: 71-75.

Mondal, A. K., Pal, S., Mandal, B., and Mandal, L. N. 1991. Available boron and molybdenum content in some alluvial acidic soils of North Bengal. *Indian J. Agr. Sci.* 61:502–505.

Moraghan, J. T. 1980. Effect of soil temperature on response of flax to phosphorus and zinc fertilizers. *Soil Sci.* 129: 290-296.

Morel, C. 2002. Caracterisation de la phytodisponiblite du P du sol par la modelisation du transfert des ions phosphate entre le sol et la solution. Habilitation a Diriger des Recherches. INPL-ENSAIA Nancy. [On-line] Available: http://www.bordeaux. Inra.fr/tcem/ rubrique:Actualites. [2002 May 04]. 80 pp.

Mortvedt, J. J., Murphy, L. S., and Follette, R. H. 1999. Fertilizer Technology and Application. Meister Publishing, Willoughby, Ohio.200 p

Mosali, J., Desta , K., Teal, R. K., Freeman, K. W., Martin, K. L., Lawles, J. W., and Raun, W. R. 2006. Effect of foliar application of phosphorus on winter wheat grain yield, phosphorus uptake, and use efficiency. *J. Plant Nutr.* 29(12): 2147-2163

Mousavi, S. R. 2011. Zinc in crop production and interaction with phosphorus. *Aust. J. Basic Applied Sci.* 5: 1503-1509.

Mousavi, S., Galavi, M., and Rezaei, M. 2012. The interaction of zinc with other elements in plants: a review. *Intl. J. Agri. Crop Sci.* 4(24): 1881-1884.

Niaz, A., Ranjha, A. M., Rahamatullah, Hannan, A., and Waqas, M. 2007. Boron status of soils as affected by different soil characteristics – pH, $CaCo_3$, organic matter and clay contents. *Pak. J. Agri. Sci.* 44:428–435.

Olsen, S. R. 1972. Micronutrient interactions. In: Mortvedt, J. J., Giordano, P. M., and Lindsay, W. L. (ed.) *Micronutrients in Agriculture*. Soil Science Society of America, Madison, 243-246.

Panahpour, E., Ehtemaee, N., and Samadi, N. 2012. Assessment of soil phosphorus availability affected by different amounts of phosphorus fertilizers in soils under sugarcane culture in khozestan province, Iran. *Adv. in Environ. Biol.* 6(3): 1266-1269.

Panse, V. G. and Sukatme, P. V. 1978. *Statistical Methods for Agricultural Workers*. ICAR, New Delhi, 347p.

Parfitt, R. L. 1989. Phosphate reactions with natural allophane, ferri hydrite and goethite. *J. Soil Sci.* 40: 359-369.

Patiram, R. N., Raj, M. M., and Prasad, R. N. 1990. Forms of soil phosphorus and suitable extactants for available phosphorus in acid soils of Sikkim. *J. Indian Soc. Soil Sci.* 38(1): 237-242.

Paulsen, G. M. and Rotimi, O. A. 1968. Phosphorus-zinc interaction in two soybean varieties differing in sensitivity to phosphorus nutrition. *Soil Sci. Soc. Am. J.* 32:73-76.

Peterson, G. W. and Corey, R. B. 1966. A modified Chang and Jackson procedure for routine fractionation of inorganic soil phosphates. *Soil Sci. Soc. Am. Proc.* 30: 563-565.

Piper, C. S. 1966. *Soil and Plant Analysis*. Hans publishers, Mumbai, 365p.

Pollard, A. S., Parr, A. J., and Loughman, B. C. 1977. Boron in relation to membrane function in higher plants. *J. Expt. Bot.* 28: 831-841.

Prasad, R., Prasad, B. L., and Sakal, R. 1996. Effect of submergence on the transformation of zinc forms in old alluvial soils growing rice as related to soil properties-II. Transformation of applied zinc. *J. Indian Soc. Soil Sci.* 44: 74-76.

Rahmani, B., Tehrani, M. M., Khanmirzaei, A., and Shahbazi, K. 2012. Cadmium fractions and its uptake by the wheat plant in some calcareous soils of Iran. *Int. J. Agric. Res. Rev.* 2: 461-466.

Rahmatullah., Badr-uz-Zaman., and Salim, M. 1999. Plant utilization and release of boron distributed in different fractions in calcareous soils. *Arid Land Res. Manag.* 13:293-303.

Rajasekharan P., Nair K. M., Rajasree, G., Sureshkumar, P., and Narayanankutty, M. C. 2013. *Soil fertility Assessment and Information Management for Enhancing Crop Productivity in Kerala* (1st Ed.). Kerala State Planning Board, Trivandrum, 522p.

Ramzan, S., Bhat, M. A., Kirmani, N. A., and Rasool, R. 2014. Fractionation of Zinc and their Association with Soil Properties in Soils of Kashmir Himalayas. *Int. J. Agric. Soil Sci.* 2(8): 132-142.

Reddy, D. D., Rao, A. S., and Takkar, P. N. 1999. Effects of repeated manure and fertilizer phosphorus addition on soil phosphorus dynamics under soybean-wheat rotation. *Biol. Fertil. Soils* 28: 150-155.

Rhue, R. D. and Harris, R.G. 1999. Phosphorus sorption or desorption reactions in soils and sediments. In: Reddy K. R., O'Connor G. A., and Schleske C. L. (eds.): *Phosphorus Biogeochemistry in Subtropical Ecosystems*. Lewis Publishers, Boca Raton, 187-206.

Robson, A. D. and Pitman, M. G. 1983. Interactions between nutrients in higher plants. In: Lauchli, A. and Bieleski, R. L.(Eds). *Encyclopaedia of Plant Physiology*, Springer-Verlag, Berlin, (15): 287–312.

Rokima, J. and Prasad, B. 1991. Integrated nutrient management: II. Transformation of applied P into inorganic P fractions in relation to its availability and uptake in calcareous soil. *J. Indian Soc. Soil Sci.* 39(4): 703-710.

Rupa, T. R., Srinivasa Rao, C., Subba Rao, A., and Singh, M. 2003. Effects of farmyard manure and phosphorus on zinc transformations and phyto-availability in two alfisols of India. *Bioresource Tech.87*(3): 279-288.

Salimpour, S., Khavazi, K., Nadian, H., Besharati, H., and Miransari, M. 2010. Enhancing phosphorous availability to canola (*Brassica napus* L.) using P solubilizing and sulfur oxidizing bacteria. *Aust. J. Crop Sci.* 4(5): 330-334.

Sanchez, P.A. and Uehara, G. 1980. Management considerations for acid soils with high phosphorus fixation capacity. In: Khasawneh *et al.* (ed.): *The Role of Phosphorus in Agriculture.* ASA, CSSA, and SSSA, Madison, WI. 471-514.

Santhosh, C.2013. Chemistry and transformation of boron in soils of Kerala. Phd (Ag) thesis, Kerala Agricultural University, Thrissur, 216p.

Seena, E., Sureshkumar, P.,Sajnanath, K., and Saifudeen, N.2002. Cation exchange in laterite soils-A critical assessment based on net ionic equilibrium (NIE). *J. Indian Soc. Soil Sci.* 50:236-241.

Setia, R. K. and Sharma, K. N. 2007. Dynamics of forms of inorganic phosphorus during wheat growth in a continuous maize-wheat cropping system. *J. Indian Soc. Soil Sci.* 55(2): 139- 146.

Sharma, K., Krants, B. A., Brown, A. L., and Quick, S. 1986. Interaction of Zn and P in top and root of corn and tomato. *Agron. J.* 60: 453-456.

Sharma, P. K. and Tripathi, B. R. 1992. Fractions of phosphorus from acid hill soils of North-West India. *J. Indian Soc. Soil Sci.* 40: 59-65.

Sharma, S. P., Dhyani, B. P., and Minhas, R. S. 1995. Inorganic phosphorus fractions in an Alfisol under long-term fertilizer experiment. *J. Indian Soc. Soil Sci.* 43(2): 466-468.

Shuman, L. M. 1985. Fractionation method for soil micronutrients. *Soil Sci.* 140: 11-22.

Shuman, L. M. 1988. Fractionation method for soil micro elements. *Soil Sci.* 146: 248-254.

Sims, J. R. and Johnson, G.V. 1991. Micronutrient soil tests. In: Mortvedt, J. J., Cox, F. R., Shuman, L. M. and Welch, R. M. *Micronutrient in Agriculture* (2nd ed.), SSSA, Madison, USA, pp 427-476.

Singh J. P., Karamanos, R. E., and Stewart, J. W. P. 1986. Phosphorus-induced zinc deficiency in wheat on residual phosphorus plots. *Agron. J.* 78:668-675.

Singh J. P., Karamanos, R. E., and Stewar J. W. B. 1988. The mechanism of phosphorus-induced zinc deficiency in bean (*Phaseolus vulguris* L.). *Can. J. Soil Sci.* 68: 345-358.

Sims, J. L. and Patrick, W. H. 1978. The distribution of micronutrient cations in soil under conditions of varying redox potential and pH. *Soil Sci. Soc. Am. J.* 42:258-262.

Singh, J. P., Dahiya, D. J., and Narwal, R. P., 1990. Boron uptake and toxicity in wheat in relation to zinc supply. *Nutr. Cyc. Agroecosyst.* 24: 105–110.

Singh, B. and Gilkes, R. J. 1991. Phosphorus sorption in relation to soil properties for the major soil types of Southwestern Australia. *Aust. J. Soil Res.* 29: 603-618.

Sinha, P., Dube, B. K., and Chatterjee, C. 2003. Phosphorus stress alters boron metabolism of mustard. *Commun. Soil Sci. Plant Anal.* 34: 315–326.

Slaton, N.A., Wilson, C. E., Norman, R. J., Ntamatungiro, S., and Frizzell, D.L. 2002. Rice response to phosphorus fertilizer application rate and timing on alkaline soils in Arkansas. *Agron. J.* 94: 1393-1399.

Soon, Y. K. 1994. Changes in forms of soil zinc after 23 years of cropping following clearing of a boreal forest. *Can. J. Soil Sci.* 74(2): 179-184.

Sotiropoulos, T. E., Therios, I. N., and Dimassi, K. N., 1999. Calcium application as a means to improve tolerance of kiwi fruit (*Actinidia deliciosa* . L) to boron toxicity. *Sci. Hortic.* 81: 443–449.

Stukenholts, D. D., Olsen, R. L., Gogen, G., and Olsen, R. A. 1996. On the mechanism of phosphorus zinc interaction in corn nutrition. *Soil Sci. Soc. Am.* 30: 759-763.

Sureshkumar, P., Rattan, R. K., and Singh, A. K. 2004. Forms of zinc in soils and their contribution to available pool. *J. Indian Soc. Soil Sci.* 52: 421-425.

Tandon, H. L. S. 1987. *Phosphorus Research and Agricultural Production in India.* Fertilizer Development and Consultation Organization, New Delhi, India, 160 pp.

Tran, T. S. and N'dayegamiye, A. 1995. Long-term effects of fertilizers and manure application on the forms and availability of soil phosphorus. *Can. J. Soil Sci.* 75 (3): 281-285.

Trehan, S. and Grewal, J. 1983. Zinc–phosphorus interaction in potato. *Indian J. Ecol.* 10 (2): 215–222.

Tsadilas, C .D., Yassoglou, N., Kosmas, C. S., and Kallianou, C . H. 1994. The availability of soil boron fractions to olive trees and barley and their relationships to soil properties. *Plant soil* 162: 211-217.

Vance, C. P, Uhde-Stone, C., and Allan, D. L. 2003. Phosphorus acquisition and use: critical adaptations by plants for securing a nonrenewable resource. *New Phytol.* 157(3): 423-447.

Verma, S., Subehia, K., and Sharma, S. P. 2005. Phosphorus fractions in an acid soil continuously fertilized with mineral and organic fertilizers. *Biol. Fertil. Soils.* 41:295-300.

Verma, S. and Subema, S. K. 2005. Zinc availability in an acid Alfisol as influenced by long term cropping in a wet temperate zone of western Himalayas. *Agropedology* 15 (2): 95-99.

Walker, J. M. and Barber, S. A. 1962. Uptake of rubidium and potassium from soil by corn roots. *Plant Soil* 17: 243–259.

Walkley, A. J. and Black, I. A. 1934. Estimation of soil organic carbon by chromic acid titration method. *Soil Sci.* 31: 29-38.

Watanabe, F. S. and Olsen, S. R. 1965. Test of an ascorbic acid method for determining phosphorus in water and sodium bicarbonate extracts from soil. *Soil Sci. Soc. Am. Proc.* 29: 39-45.

Webb, M. J. and Loneagan, J. F. 1988. Effect of zinc deficiency on growth, phosphorus concentration and phosphorus toxicity of wheat plants. *Soil Sci. Soc. Am.* 52:1676-1680.

Wijebandara, D. M. D. I., Dasong, G. S., and Patil, P. L. 2011. Zinc fractions and their relationships with Soil properties in paddy growing soils of Northern dry and hill zones of Karnataka. *J. Indian Soc. Soil Sci.* 59: 141-147.

Xu, J. M., Wang, K., Bell, R. W., Yang, Y. A., Huang, L. B. 2001. Soil boron fractions and their relationship to soil properties. *Soil Sci. Soc. Am. J.* 65:33–138.

Yamanouchi, M. 1980. Effect of phosphorus, potassium, calcium, magnesium and iron treatment on the absorption and translocation of boron in several crops grown in high concentration of boron. *Nippon Dojo Hiryogaku Zasshi* 51: 126–130.

Yermiyahu, U., Keren, R., and Chen, Y. 2001. Effect of composted organic matter on boron uptake by plants. *Soil Sc. Soc. Am. J.* 65:1436–1441.

Yusran, F. H . 2009. The relationship between phosphate adsorption and soil organic carbon from organic matter addition. *J. Trop. Soils* 15(1): 1-10.

Zerrari, N., Moustaquid, D., and Verloo, M. 1999. Les forms du bore des soils: importance effect des characteristique des soils et disponibilite pour les plantes. *Agrochima* XLIII: 77-78.

Zhu, Y. G., Smith, S.E., and Smith, F. A. 2001. Plant growth and cation composition of two cultivars of spring wheat (*Triticum aestivum* L.) differing in P uptake efficiency. *J. Exp. Bot.* 52: 1277-1282.

DYNAMICS AND INTERACTION OF ZINC AND BORON WITH PHOSPHORUS IN ULTISOL

BY

SEMSHEER M.

(2013-11-141)

ABSTRACT OF THE THESIS

Submitted in partial fulfillment of the requirement for the degree of

MASTER OF SCIENCE IN AGRICULTURE

Faculty of Agriculture

Kerala Agricultural University

DEPARTMENT OF SOIL SCIENCE AND AGRICULTURAL CHEMISTRY
COLLEGE OF HORTICULTURE
VELLANIKKARA, THRISSUR – 680 656
2015

ABSTRACT

. The recent soil fertility assessment of the entire state has revealed that more than 60% of the soils in the state are having high P status due to continuous application of P fertilizers like factomphos and bone meal. It was also established that 15% of the soils are deficient in zinc and about 60% of soils are deficient in boron. Antagonistic interaction of P with zinc has already been well established. However studies on interaction of P with boron are limited.

Thepresent study was undertaken in the above background in the Dept. of Soil Science and Agricultural Chemistry during the period from 2013-2015 to understand the chemistry, dynamics and bioavailability of zinc and boron with respect to the P status of the soil, which in turn will help in modifying the fertilizer prescription in terms of quantity and method of application of these nutrients.

In order to achieve the objective of elucidating the dynamics of Zn and B as influenced by P status in lateritic soils and to optimize the level of P for balanced nutrition of cowpea with respect to Zn and B, 18 lateritic soil samples (Ultisol), six each coming under low, medium and high P status were identified from an initial 100 soil samples and characterized. A potculture experiment with cowpea as a test crop was conducted in three soils, one each with low, medium and high average P status. Soil and plant samples were collected at flowering and at harvesting stages and analyzedfor nutrient content.

The distribution of fractions of inorganic P in the three soils showed that Fe bound P was the dominant fraction contributing to more than 50% of the total inorganic P. The soluble P fraction was about 6% in all the three soils. Fe and Al-P were the main fractions contributing to the available pool initially.Among the fractionsof boron, readily soluble boron recorded the lowest, where as the contribution of residual boron was the highest.

Available P status in soils with low and medium P increased due to the application of P while it decreased in soil with high P. The soil with high P soil

showed that the application of phosphorus lead to the fixation of phosphorus in to insoluble forms whereas, if P was not applied there was solubilisation of Fe-P and Al-P resulting in increased its availability. Plant adsorbed P from soluble P led to its depletion at the end of vegetative phase. Applied P got transformed into Fe-P and Al-P initially, which along with native occluded P got transformed to calcium bound P which is contributing to the available pool at later stages. Application of Zn was found to reduce Al-P and Fe-P due to the formation of insoluble zinc phosphate. Application of Zn and B reduced the Ca-P, probably due to the formation of zinc phosphate and Calcium borate.

In case of zinc fractions, water soluble + exchangeable fraction and organic matter occluded zinc was directly contributing to the available pool. The other Zn fractions except amorphous iron oxide occluded zinc were contributing to the available pool indirectly through water soluble + exchangeable fraction. Application of P reduced the water soluble + exchangeable zinc fraction where as the application of boron enhanced the transformation of zinc into this fraction especially when boron was applied without P. Application of P resulted in adsorption of zinc into specifically adsorbed zinc.

With respect to boron fractions, readily soluble boron and oxide bound boron were directly contributing to the available pool where as binding of boron with organic matter as well as its transformation to residual boron reduced boron availability. All the fractions of boron were contributing to available pool indirectly through readily soluble fraction of boron. Application of phosphorus was found to reduce the readily soluble boron due to anion competition. The applied boron either remained in the soluble form or getting transformed to specifically adsorbed, oxide bound, organic matter bund boron. Boron application along with P reduced the readily soluble boron.

Application of Zn increased the Zn content in plant. However, the application of P with and without B reduced the Zn content in plants. Application of P and Zn reduced the boron content in plants and application of boron with and without phosphorus recorded the highest boron content. The highest grain yield was recorded in soil with medium P, while the high P status in soil either due to native P or due to applied P reduced the yield resulting from induced lower uptake of zinc and boron.

Thus, at high levels of P, enough quantities of soluble zinc should be assured, over and above the quantities of this element precipitated as zinc phosphate, both by optimizing the pH and applying enough quantities of Zn. Similarly H_3BO_3 and $H_2BO_3^-$ ions should be enough to overcome competition from $H_2PO_4^-$ ion at root surface.