Phosphorus Fixation Capacity and Release Pattern in Dominant Soil Orders of North East India

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Central Agricultural University, Imphal
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Master of Science (Agriculture)

In

Soil Science and Agricultural Chemistry

by

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Dedicated To

My Beloved Mother

And Father

COLLEGE OF POST GRADUATE STUDIES
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I also certify that the thesis or part thereof has not been previously submitted by her for a degree of any University.

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This is to certify that the thesis entitled **“Phosphorus Fixation Capacity and Release Pattern in Dominant Soil Orders of North East India”** submitted by **Ms. Bidisha Borpatragohain [Regn. No. CAU/194-A/16(PG)}** to the Central Agricultural University, Imphal – 795 004 (Manipur) in partial fulfillment of the requirements for the award of the degree of **Master of Science (Agriculture)** in the subject of **Soil Science and Agricultural Chemistry** has been approved by the Student’s Advisory Committee after oral examination jointly with a Dean’s Nominee.

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I hereby declare that the thesis entitled **“PHOSPHORUS FIXATION CAPACITY AND RELEASE PATTERN IN DOMINANT SOIL ORDERS OF NORTH EAST INDIA”** is an authentic record of the work done by me and that no part thereof has been presented for the award of any other degree, diploma, associateship, fellowship or any other similar title.

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Date: **(Bidisha Borpatragohain)**
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LIST OF ABBREVIATIONS/SYMBOLS

%	Percentage
$\mu g\ g^{-1}$	Microgram per gram
$\mu g\ ml^{-1}$	Microgram per millilitre
AAS	Atomic Absorption spectrophotometer
Al	Aluminium
ANOVA	Analysis of variance
Avl. K	Available potassium
Avl. P	Available phosphorus
Avl. S	Available sulphur
B.S.	Base Saturation
Ca	Calcium
$CaCl_2$	Calcium Chloride
$CaCO_3$	Calcium Carbonate
Ca-P	Calcium bonded phosphorus
cap.	Capacity
cc	Cubic centimetre
CEC	Cation exchange capacity
cm	Centimetre
conc.	Concentration
CPGS	College of Post Graduate Studies
DTPA	Diethylenetriaminepentaacetic acid
et al.	Et alli (and other)
Ex.Al	Exchangeable Aluminum
Fe	Iron
Fe^{2+}	Ferrous ion
Fe^{3+}	Ferric ion
Fe-P	Iron bonded phosphorus

Fig.	Figure
g	Gram
g cc^{-1}	Gram per cubic centimetre
h	Hour
H^+	Hydrogen ion
H_2O	Water
ha	Hectare
HCl	Hydrochloric acid
i.e.	That is
K	Potassium
$K_2Cr_2O_7$	Potassium dichromate
KCl	Potassium chloride
Kg ha^{-1}	Kilogram per hectare
$KMnO_4$	Potassium permanganate
L^{-1}	Per litre
M	Molar
m	Metre
M.Sc.	Master of science
m^2	Meter square
Max.	Maximum
mg	Milligram
mg kg^{-1}	Milligram per kilogram
Min.	Minimum
mm	Millimetre
mt	Million tonnes
NE	North East
N	Normality
N	Nitrogen

NaOH	Sodium hydroxide
NE	North East
NEH	North Eastern Hill Region
NH_4F	Ammonium fluoride
no.	Number
^oC	Degree Centigrade
P	Phosphorus
P_0	Organic phosphorus
P_i	Inorganic phosphorus
PFC	Phosphate fixation capacity
PRP	Phosphorus release pattern
ppm	Parts per million
PSB	Phosphate solubilising bacteria
PSM	Phosphate solubilising microorganism
PUE	Phosphorus use efficiency
P	Profile
RDF	Recommended doses of fertilizer
Res.	Research
RP	Rock phosphate
RS.Al	Readily Soluble Aluminium
rpm	Rotation per minute
S	Sulphur
Sci.	Science
SOC	Soil organic carbon
SSP	Single superphosphate
$t\ ha^{-1}$	Tonne per hectare
TGA	Total Geographical Area
TEA	Tri-ethanolamine

Temp.	Temperature
USDA	United States Department of Agriculture
viz.	Such as
vol.	Volume
wt.	Weight
yr.	Year
µ	Micron
µ m	Micro metre
µM	Micro-molar

ABSTRACT

Phosphorus (P) deficiency is wide spread in approximately 42% of arable lands in India. In North East India, approximately 95% soils are acidic, and nearly 65% soils are suffering from strong acidity ($pH<5.5$). In the event of the global phosphate crisis (natural stock can support P fertilizer supply only for 105 to 470 years) and associated very poor P-use and the P-recovery efficiencyin acid soils spiraling the challenges of P nutrition management. The fertilizer P recovery by a crop in a crop season accounts to only 10 to 30 percent ofquantity added tosoil. Remaining 70 to 90 per cent of P has been assumed to be sorbed by soil complex or precipitated by soluble cations in soil solution - a process known as"phosphorus fixation".TheP fixation capacity (PFC) and factors affecting PFC inacid soils of NE India are seldom reported. Moreover, there is lack of information on phosphate release pattern (PRP) of these soils in response to different P sources. Therefore, the objectives of the present study were: (1) to determine the PFC of dominant soil orders (*Alfisol, Ultisol, Inceptisol*and *Entisol*) of NE India, (2) to assess the phosphate release pattern (PRP) of these soils on incubation with different sources of P *viz.* single super phosphate (SSP), rock phosphate (RP), organic manure (OM), phosphate solubilizing bacterium (PSB), RP+PSB and no P source (control) in laboratory column study, and (3) to find out the relationship of PFC with soil attributes.The surface soil samples of 3 soil profiles of each of four soil orders (total 12 soil profiles) provided by the NBSSLUP Regional Centre, Jorhat, Assam were used in this study.

Results from the incubation experiment-I (P levels 0, 25, 50, 100, 200, 300,400, 500, 600 and 700 ppm for 24 h) indicated that PFC (µg P g^{-1} soil) ranged from 223 to 471 for *Alfisol*, 337 to 577 for *Ultisol,* 107 to 277 for *Inceptisol*and 67 to 92 for *Entisol*.The maximum PFC was obtained at the P application dose (µg g^{-1} soil) for *Alfisol* at 500, *Ultisol* at 600, *Inceptisol* at 300 and *Entisol* at 200.The higher percent P fixed was in order of *Ultisol* (90.2) >*Alfisol* (84.5) >*Inceptisol* (74.2) >*Entisol* (49.2). The bulk density (BD), maximum water holding capacity (MWHC) and clay content ranged from 0.91 to 1.37 g cc^{-1}, 32.7 to 55.5% and 3.7 to 55%, respectively among twelve soil profiles. The content of soil organic carbon (SOC), soil available nitrogen, phosphorus and potassium (Avl.N, Avl.P and Avl.K, respectively) ranged from 0.50 to 2.00%, 122 to 301 kg ha^{-1}, 6.6 to 62.1 kg $ha^{-1}$and 115 to 220 kg ha^{-1}, respectively. Soil pH, exchangeable aluminium (Ex.Al), readily soluble aluminium (RS.Al), exchangeable calcium+magnesium (Ex.Ca+Mg) and base saturation (BS) ranged from 4.22 to 7.74, 0.09 to 3.5 meq 100^{-1}g soil, 18.4 to 384 mg kg^{-1} soil, 1.7 to 12.9 meq 100^{-1}g soil, 16.2 to 71%, respectively.

In laboratory soil column study, six P sources imposed were: (1)control (no P addition), (2) phosphate solubilizing bacteria (PSB), (3)organic manure (OM), (4) rock phosphate (RP), (5) single superphosphate (SSP) and (6) RP+PSB.The PRP was studied in soil columns by extracting solution phase P with distilled water (5 ml) at 6 time points (0, 5, 15, 30, 45, 60 days). The amount of released P_i was dependent soil orders, whereas the pattern of released P_i was highly influenced by P sources across soil orders. Within 15 days of incubation, SSP addition caused the highest amount of released P_i and thereafter the released P_i gradually decreased.On the other hand, the amount of released P_i was increasing gradually with progression of incubation duration beyond 15 days for PSB, OM, RP and RP+PSB sources. Among the latter four P sources, application of RP+PSB could release significant higher quantity of P_i as compared to their single application.The significant higher correlation of PFC with RS.Al, Clay, Ex.Al, Avl.P, Ex.Ca+Mg, pH, BS and SOC indicated the need for formulation of suitable management practices that can improve the status of these soil attributes so as to reduce PFC of soils. The application of OM, RP and PSB showed significant positive effects on the PRP of acid soils. So, it can be suggested that PFC and PRP behaviours of acid soils of NE India are important factors to be considered while formulating P nutrition management practices.

Key words: P deficiency, Acid soil, P sources, P-use efficiency, Phosphate solubilizing bacteria

Chapter - 1

Introduction

Acid soils (defined as soils with pH <5.5 in the top layer) cover 3,950 million ha, or around 30% of global arable land, with a growing trend (Von Uexküll and Mutert, 1995). In India, out of 142 m ha of arable land, acid soils cover around 48 to 49 m ha of which 25 m ha show pH below 5.5 and 23 m ha have pH between 5.6 to 6.5 (Mandal, 1997). The strongly acid and moderately acid soils cover 6.24 (1.9%) and 24.41 (7.4%) m ha of the total geographic area (TGA) of India, respectively (Maji *et al*., 2012). The North Eastern region (NER) of India has the largest stretches of acid soils, followed by the neighbouring states of West Bengal, Bihar and Orissa; because of the climatic conditions prevailing in the region, types of rocks and minerals along with other factors involved. It is estimated that approximately 91% soils are acidic, and nearly 65% soils are suffering from strong acidity (pH < 5.5) in NE India (Sharma *et al*., 2006). The average crop productivity in acid soil regions (ASR), particularly in NE India, is very low, lagging far behind the national average. A multitude of acidity-related fertility constraints *viz.*, the toxicities of aluminium (Al), iron (Fe) and manganese (Mn), deficiency of phosphorus (P), calcium (Ca), magnesium (Mg), zinc (Zn), molybdenum (Mo), boron (B), low base saturation, impaired biological activity and other acidity-induced soil fertility and plant nutritional problems are associated with such soils (Sarkar, 2015; Thakuria *et al*., 2016).

Phosphorus is the second most limiting element in the *Alfisols, Oxisols,* and *Ultisols* of tropical and subtropical Africa, Asia, and South America (Sanchez, 1976; Le Mare, 1991; Doula *et al.*, 1996). The majority soils of NE India are categorized under *Inceptisols, Entisols, Ultisols, Alfisols* and other miscellaneous orders and their respective distribution is 49.6%, 22.2%, 15.1%, 3.6% and 9.5% of the TGA of NE India (Patiram and Ramesh, 2008). Acid soils of NE India are also P deficient. Phosphorus use efficiency (PUE) is reported to be only 15–20% for most of the acid soils. More than 80% applied P fertilizer during crop production is fixed in soil due to acidity-related factors like precipitation reaction with Al and Fe resulting insoluble $AlPO_4$ and $FePO_4$ (Patiram, 1991; Sharma *et al*., 2006; Kumar *et al*., 2012). Phosphorus deficiency is often exacerbated by a high capacity to fix (adsorb and/or precipitate) P, making it less available to crops (Quang *et al.,* 1996). The availability of inorganic P (P_i) in soil solution is controlled by the fixation mechanism (Muralidhar *et* *al.,* 2005). Phosphorus fixation in soils depends upon many factors, *viz*. soil pH, organic matter content, type of clay minerals and sesquioxides, *etc*. The causes of low P-use efficiency (PUE) in highly weathered humid sub-tropical soils of NE India are Al and Fe induced P deficiency (Sharma *et al.,* 2006; Thakuria *et al*., 2016). The process of P fixation accelerates the problem leading to low PUE in soil. Since, there lies spatial variability of P availability in soils, single blanket recommendation is not appropriate, instead site-specific nutrient management is the need of the hour. Phosphorus is also one of the scarcest nutrients in terms of its demand in both terrestrial and aquatic environments (Leinweber *et al*., 2002). It is an irreplaceable element and it reserves are finite. It is estimated that it takes about 10-15 million years for P to form (Cordell *et al*., 2010). Due to the increasing demand of inorganic P (P_i) fertilizer in agriculture, we are depleting our future's P reserve quota (Ayoub 1999; Khalil *et al.,* 2011) in the anticipated scenario of global P production peak by 2033 (Cordell *et al.,* 2009). In the face of P shortages in the near future, global food security will be impacted significantly. Hence, there is a need to create a closed loop to recycle terrestrial P sources. Despite being abundant in soil in both organic and inorganic forms, it is a major growth limiting constraint on an estimated 40% of the world's arable soil.

The PUE can be enhanced by the application of different P sources namely organic manure (OM), phosphate solubilising microorganisms (PSMs), rock phosphate (RP) and water soluble phosphatic fertilizers like single superphosphate (SSP) and di-ammonium phosphate (DAP), etc. (Sarkar *et al.,* 2015). Soil organic matter affects the binding energy of adsorbed P (Kreller *et al.,* 2003) and can therefore increase the efficiency of phosphatic fertilizer - possibly as a result of phosphate adsorption with little energy (e.g., via cation bridges; Guppy *et al.,* 2005). Recent studies in highly weathered Brazilian soils have shown that organic matter and various iron oxides have a direct effect on P adsorption/desorption and availability (Fink *et al.,* 2014; Bortoluzzi *et al.*, 2015; Fink *et al.,* 2016b). Application of inorganic P fertilizers like SSP and DAP though increase soil P concentration within 7 days of application, but its supply diminishes in long run due to fixation mechanisms or leaching through the soil. Natural rock phosphates (RP) have been recognized as a valuable alternative to industrial P_i fertilizers. It is estimated that the RP deposits in India are almost 260 million tons and this material will provide a cheap source of phosphate fertilizer for crop production (FAI, 2002). Inoculation of PSB has been reported to modify P nutrition and increase its solubilisation in soil through many process such as, they may decrease the pH of the soil by the producing organic (gluconate, acetate, succinate, butyrate, etc.) and mineral acids (Chen *et al*., 2006), phytohormones and H+ protonation (Xiao *et al*., 2017), anion exchange, chelation and siderophores production which promote P solubilisation in soil (Sugihara *et al*., 2010). Exploitation of these processes may prevent frequent addition of P into soil with inorganic P sources. Organic acids use their hydroxyl and carboxyl groups to chelate the cations (Ca, Al and Fe) bound to phosphate and release the P (Taktek *et al*., 2017). Alori *et al.* (2017) found that PSB produce the enzyme phosphatase that plays a key role in the solubilisation of P. The combine application of PSB and RP fertilization would be an appropriate substitute for chemical phosphate fertilizer application in sustainable agriculture systems (Akbari *et al*., 2010; Kaur and Reddy, 2015; Thakuria *et al*., 2016).

The judicious exploitation of above P sources for enhancing PUE of acid soils, the knowledge on P fixation capacity and the release pattern of acid soils in response to different P sources are essential. The best P management practice for location specific soils is possible only if there is clear idea on the intensity and quantity factors of soil P. Excess application of P fertilizer leads to leaching or eutrophication of water bodies and deficit of P fertilizer application leads to its fixation. So, if the maximum P fixation capacity is known for different soils, P fertilizers can be applied to soils judiciously. There is lack of comprehensive scientific data on P-fixation capacity of dominant soil orders of NE India. Besides, the release patterns of P_i in acid soils upon addition of different P sources over a time period are seldom reported for NE Indian soils.

Keeping in mind the above research gaps, the present study was formulated with the following objectives:

1. To determine the P fixation capacity in soils of dominant orders.
2. To assess the effect of P sources on the release pattern of P.
3. To find out the relationship between P-fixation capacity and soil chemical attributes.

Chapter - 2

Review of Literature

"Literature is like phosphorus, it shines with its maximum brilliance and the moment when it attempts to die."

-Roland Barthes

Soil P is finite, non-renewable and limited resource. Phosphate rock is a general term that describes naturally occurring mineral assemblages containing a high concentration of phosphate minerals about 95% of it is used to produce fertilizers, animal feeds and pesticides. It is estimated that the availability of remaining phosphatic rock reserves is 69-100 years (Vaccari, 2009). In Europe, agriculture is found to depend on the rock phosphate materials imported from countries like Morocco including Western Sahara, Iraq, Algeria, Syria, and Jordan (de Ridder *et al*., 2012). Political unrest in these countries creates low confidence in the supply of phosphate rocks for future agriculture production. Although countries such as United States and China have considerable reserves (Jasinki, 2013), yet domestic consumption and internal policies restricts the amount of P export from these countries. In 2008, China, which holds the second highest reservoir of phosphate rocks, imposed 135% tariffs on P export in order to secure adequate supply for domestic use (de Ridder *et al*., 2012). Additionally, P reserves are concentrated in few countries (including Morocco, China, USA, Russia, Syria, Iraq and South Africa) and price spikes of phosphate products in 2008 (Cordell *et al.,* 2011) served as a harbinger for future market monopoly. India has reserves of 14.7 Mt of high grade rock phosphate and 190 Mt of low grade with an average of 12% P_2O_5. Out of total rock phosphate reserve of 217.2 Mt in India, Rajasthan has the largest reserve of about 78.8 Mt (Jaggi, 2000).

There is also an expectation of 9.3 billion people in 2050 which will require agricultural production to increase by 70% of its current production to meet the food demands of the rising population (Rasmussen *et al*., 2012). Thus, agricultural intensification with associated increased fertilizer usage might be the immediate solution for food security issues. There is high probability that phosphate scarcity challenges might be exacerbated with increased fertilizer consumption.

2.1. Soil orders and its properties

Soils of India are grouped under eight orders: *Entisols* (80.1 Mha), *Inceptisols* (95.8 Mha), *Vertisols* (26.3 Mha), *Aridisols* (14.6 Mha), *Mollisols* (8.0 Mha), *Ultisols* (0.8 Mha), *Alfisols* (79.7 Mha), *Oxisols* (0.3 Mha), and mixed types (23.1 Mha). *Alfisols* and *Vertisols* are dominant soils of the peninsular India and *Aridisols* occur in extremely dry climates along with some *Entisols* and *Inceptisols*. In terms of land use and management, alluvial (*Inceptisols*) soils are the most dominant (93.1 Mha), followed by red (*Alfisols*, 79.7 Mha), black (*Vertisols*, 55.1 Mha), desert (*Entisols*, *Aridisols*, 26.2 Mha), and lateritic (Plinthic horizon, 17.9 Mha) soils. The dominant soil orders in rainfed production systems of India are *Inceptisols* followed by *Entisols*, *Alfisols*, *Vertisols*, Mixed soils, *Aridisols*, *Mollisols*, *Ultisols*, and *Oxisols*. With the exception of *Vertisols*, most soils in the rainfed areas are generally coarse-textured. Thus, their capacity to retain water and nutrients is low, and crops grown on these soils are prone to drought stress and nutrient deficiencies. With low soil organic matter (SOM) concentration, aggregate stability is low and erosion is a serious problem. Water infiltration rates are low in *Vertisols* due to clayey texture and in *Alfisols* due to formation of surface crusts. With the exception of some *Vertisols*, which are rich in bases, inherent fertility of rainfed soils is generally low (Rao *et al*., 2015).

The National Bureau of Soil Survey and the Land Use Planning (NBSSLUP) an Institute under control of the Indian Council of Agricultural Research (ICAR) did a lot of studies on Indian soils. In their effort to study soil and to make it comparable at the international level, the ICAR has classified the Indian soils on the basis of their nature and character as per the United States Department of Agriculture (USDA) Soil Taxonomy.

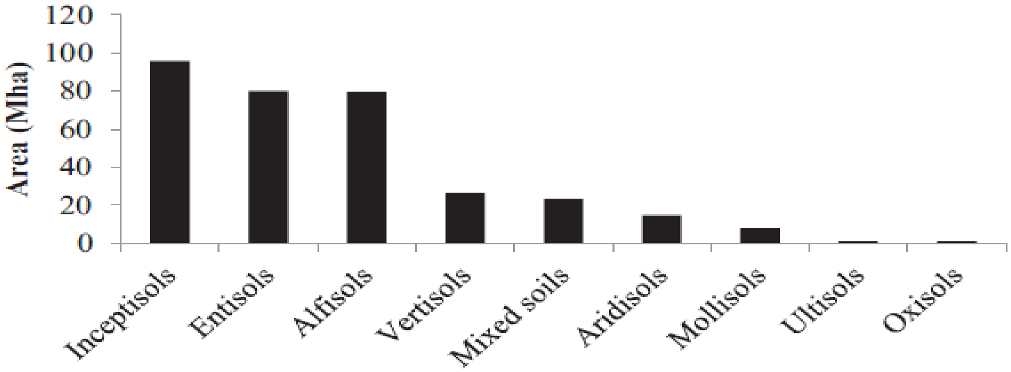


Fig. 2.1. Predominant soil orders in India and their distribution (Source: Rao *et. al*, 2013).

2.2. Dominant soil orders of North East India

The North Eastern Region of India comprising contiguous of seven sister states of Arunachal Pradesh, Assam, Manipur, Meghalaya, Mizoram, Nagaland and Tripura and the Himalayan state of Sikkim occupies an area of about 26.2 m ha lies between 21°57’ to 29°6’ N latitude and 84°41’ to 97°25’ E longitude covering 8% and 1.3% of total area and population of the country, respectively.

Table 2.1. Area coverage of different soil orders in the North Eastern States of India

State	**% coverage of the total geographical area (TGA) of the state**					
	Alfisols	***Entisols***	***Inceptisols***	***Mollisols***	***Ultisols***	**Misc.**
Arunachal Pradesh	0.3	35.6	37.3	-	14.2	12.6
Assam	12.3	32.3	49.3	-	6.1	
Manipur	0.2	23.1	38.4	-	36.4	1.9
Meghalaya	3.6	10.7	45.7	-	40.0	-
Mizoram	2.6	21.5	37.3	38.6	-	-
Nagaland	4.8	4.0	76.0	-	17.2	-
Sikkim	-	43.0	33.4	23.6	-	-
Tripura	5.0	8	80.0	-	7.0	-

(Source: Velayutham and Bhattacharya, 2000)

In NE India, soils belong to *Inceptisols* are most extensively occurred which covers 11431.5 thousand ha. The *Inceptisols* are divided into 6 great groups followed by 21 subgroups. *Entisols* covering 7040.54 thousand ha have been identified with 8 great groups further divided into 18 subgroups. *Ultisols* with 4346.3 thousand ha are grouped 8 great groups followed by 13 subgroups. *Alfisols* covering an area of 11m thousand ha have 4 great groups with 6 subgroups. Three great groups have been identified in *Mollisols* with & subgroups. The occurrence of *Histosols* is reported only from Tripura. *Mollisols* usually occur on the moderately sloping side slopes of the hills in Sikkim (Patiram and Ramesh, 2008).

2.3. Extent and distribution of acid soils

Acid soils are distributed throughout the world and these soils limit crop production on 30-40% of the world's arable land and up to 70% of the world potentially arable land (Haug, 1983) and nearly 50% of the world's potentially arable land, particularly in humid tropics (Von Uexkull and Mutert, 1995). In India, out of 142 Mha of arable land, around 48 to 49 Mha is occupied by acid soils, of which 25 Mha show pH below 5.5 and 23 Mha have pH between 5.6 to 6.5 (Mandal, 1997). Acidic Indian soils occur in the Himalayan region, the Eastern and North-eastern plains, peninsular India and coastal plains under varying topography, geology, climate and vegetation. Acid soils are widely distributed in the states of Assam, Manipur, Tripura, Meghalaya, Mizoram, Nagaland, Sikkim, Arunachal Pradesh, West Bengal, Jharkhand, Orissa, Madhya Pradesh, Himachal Pradesh, Jammu & Kashmir, Andhra Pradesh, Karnataka, Kerala, Maharastra and Tamil Nadu. Most of these soils belong to the soil order, *Ultisols, Alfisols, Mollisols, Spodosols, Entisols and Inceptisol.* In the north-eastern region of India, approximately 95% soils are acidic, and nearly 65% soils are suffering from strong acidity with pH less than 5.5 (Sharma and Singh, 2002). More than 81% soils of 26.22 million hectare arable land of North East India are in acidic range (Sharma *et al.,* 2006). Although poor fertility of acid soils is due to a combination of mineral toxicities (Al and Mn) and deficiencies (P, Ca, Mg, B and Mo), the major constraints hindering crop production on 67% of the total acid soil areas are Al toxicity and associated-P deficiency (Eswaran *et al*., 1997).

2.4. Forms of soil phosphorus

There are several forms of phosphorus in soils that can be categorized into two broad groups, organic phosphorus (P_o) and inorganic phosphorus (P_i). Organic phosphorus can account for 5-95% of the total phosphorus (TP) in soil. Soil P_o is derived mainly from manures, plant materials and products of microbial decomposition. It is important to emphasize that 20 to 80% of P in soils is found in the organic form, of which phytic acid (inositol hexaphosphate) is usually a major component (Richardson, 1994). The P_i fraction of TP originates from the addition of inorganic fertilizers, manures and weathering of primary minerals such as apatite and secondary minerals such as calcium and/or magnesium phosphates and Iron and aluminium phosphates (Morgan, 1997; Sylvia *et al*., 2005). Often the relationship between total phosphorus and that available to plants is poor in the soil. Therefore, assessment of total phosphorus content of soils may be deceptive as a parameter of soil phosphorus availability to plants.

Phosphorus is also known to exist in three pool forms in soil *viz*., the solution pool, the active pool and the fixed pool (Schmitt *et al*., 2009). The solution P pool is very small and will usually contain only a fraction of a pound of phosphorus per acre. Soil solution P concentrations can range from 0.001 mg P L^{-1} in very infertile soils to 1 mg P L^{-1} in very fertile soils, but are 0.05 mg P L^{-1} on average (Paul and Clark, 1996). Due to the low levels of P in soil solution, the inorganic forms move to plant roots primarily by diffusion, which is a slow process (approximately 0.3 to 3.3 x 10^{-9} cm^2 s^{-1} for a sandy clay loam with 20 to 40% water by volume) (Rowell *et al*., 1967; Tinker and Nye, 2000). A growing crop would swiftly deplete the P in the soluble P pool if the pool is not being continuously replenished.

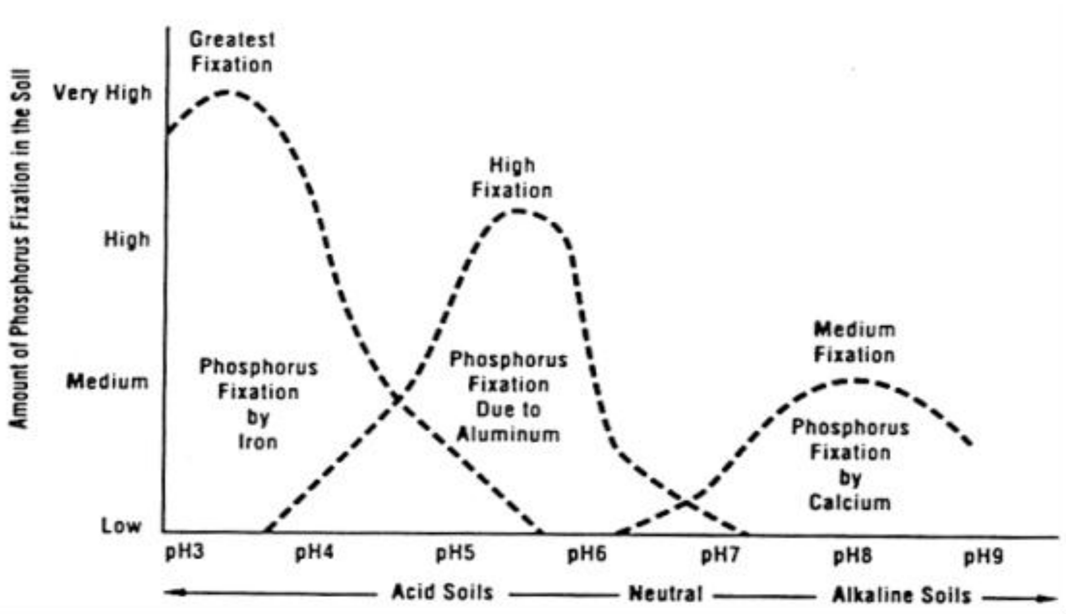


Fig. 2.2. Schematic diagram of phosphorus availability across pH ranges in soil (Halvin *et al.,* 2009).

2.4.1. Inorganic soil phosphorus

Voluminous literature is available on the distribution of various forms of inorganic P. Water in soil typically contains about 0.05 mg L^{-1} of inorganic phosphate in solution; this is equivalent to about 15 g of P in solution in one hectare of land. There are certain soil properties which regulate the distribution of inorganic forms of P which are pH, soluble and exchangeable P-reactive cations (iron, aluminium, calcium and magnesium), and the nature and surface area of soil particles. In all soils, P will occur in the adsorbed phase on the surfaces of iron and aluminium hydrous oxides and other clay minerals. Phosphorus forms insoluble compounds with iron and aluminium at low pH, more soluble compounds with calcium and magnesium at pH values near neutrality and insoluble compounds with calcium at higher pH values (Tisdale *et al.,* 1985). There is a wide range of solubility of these various phosphate compounds and their availability to crops is usually the greatest within the pH range of about 6 to 7 for most agricultural soils. Dispersive x-ray analysis of P-rich particles from heavily-fertilized soils indicated that Al not Ca was the predominant cation associated with P, regardless of soil pH (Pierzynski *et al*., 1990). The insoluble P_i compounds are mainly divided into two groups: P compounds of calcium and magnesium and P compounds of iron and aluminium.

2.4.1.1. Iron and aluminium phosphates

A number of aluminum and iron phosphate minerals have been reported to occur in soils. The most common aluminum phosphates are wavellite $\{Al_3(PO_4)(OH)_3.5H_2O\}$ and variscite **(**$AlPO_4.2H_2O$). The occurrence of variscite has been postulated in soil of slight acidity (Moreno and Lindsay, 1960). At higher pH values, variscite dissolves incongruently, whereby a more basic solid phase of aluminum hydroxy phosphate is formed (Taylor and Gurley, 1964). This material probably controls P concentration in solution in acid soil by forming a surface complex on variscite. However, in pure systems, where the pH of the equilibrium solution is less than 3.1, the solubility product of variscite controls the P concentration in solution (Chakravarti and Talibudeen, 1962). The most common iron phosphate is strengite ($FePO_4.2H_2O$). Chakravarti and Talibudeen (1962) concluded that a compound approximating to the composition of strengite may occur in temperate soils in the pH range of 3.8 to 4.2, whereas in tropical soils strengite coexists with hydrated iron oxide from pH 3.8 to 6.7. Variscite and strengite are the least soluble compounds at acidic pH (Tisdale *et al.,* 1985). Strengite is known to crystallize more rapidly when the iron phosphate is formed. The less crystalline aluminium phosphate has greater surface area which is more favorable for release of phosphorus into the soil solution. Under the conditions of high acidity, minerals of the variscite and strengite groups are precipitated (Wild, 1988).

2.4.1.2. Calcium and magnesium phosphates

Dicalcium phosphate, octacalcium phosphate and hydroxyapatite are the principal crystalline phosphates that have been identified in soil (Tisdale *et al*., 1985). The presence of octacalcium phosphate has been reported in soils which have been limed and fertilized with phosphates (Webber and Mattingly, 1970). Baifan and Yichu (1989) suggested a systematic fractionation scheme for inorganic phosphates in calcareous soils, in which they classified calcium phosphate into dicalcium phosphate, octacalcium phosphate and apatite types. They also suggested that these forms are interchangeable. It was revealed that there was the highest P availability from struvite ($MgNH_4PO_4.6H_2O$) as compared to mono or di-calcium phosphate (Tisdale *et al.,* 1985). In soils containing large quantities of magnesium, a number of insoluble magnesium phosphate compounds such as di-magnesium phosphate trihydrate, tri-magnesium phosphate and struvite may form. However, these magnesium phosphates are more soluble than di-calcium phosphate and octa-calcium phosphate.

2.4.2. Organic soil phosphorus

The amounts of organically held P vary greatly among soils. Organic P content of soil occurs from traces in arid soils to several hundred mg kg^{-1} in thick forest soils. The P_o contents of soils throughout the world range between 7 to 1056 mg kg^{-1} soil (Campbell and Racz, 1975). Up to one-half of P_o in soils occurs as phytic acid (inositol hexasphosphate), which is the main compound that plants use to store P in seeds to support early seedling growth upon germination and the remaining organic P in soils occurs as mono- and diesters, phospholipids and nucleotides, sugar phosphates, phosphoproteins, and phosphonates (Tate, 1984). Most naturally occurring organic forms of P are esters of orthophosphoric acid and numerous mono and di-esters have been characterized. The phosphate added as fertilizer is converted to organic forms in soil under young grassland due to increased root production and leaf decay added to the soils (Wild, 1988). The importance of the mineralization of organic P compounds for crop nutrition is probably universal. But it is greatest at high soil temperatures because of high mineralization rates which will thereby release considerable amounts of inorganic P in favourable conditions of moisture, pH and root activity.

2.5. Soil factors affecting P uptake

According to Kamprath and Watson (1980) the factors affecting the supply of P to plants are the amount of soil P (quantity), the concentration of soil solution P (intensity), and movement of P to roots (diffusion). In any assessment of the available P in soil by chemical tests, one needs to consider the relationship between quantity, intensity and diffusion and factors influencing availability of these components of P to plants.

2.5.1. Phosphorus buffering capacity

Phosphate buffering capacity of a soil is characterized by the P equilibrium between solid phase and solution phase. This is the ability of a soil to maintain its P concentration in solution as P immobilized by soil through various processes or as P is added by fertilization. Thus, the availability of soil phosphate is described by both intensive and extensive parameters which are determined by the concentration of P in soil solution (I) and quantity of phosphate adsorbed on the soil solids (Q), respectively. These two parameters determine the buffering capacity of soil (Barrow, 1967; Holford, 1976), which regulates the resistance of I and Q to change when phosphate is added or disturbed by the system (Holford and Mattingly, 1976). The buffering capacity of a soil is the slope of the adsorption isotherm at some arbitrary concentration, which may reflect the actual P concentration found in the solution (Beckett and White, 1964), or theoretical P concentration sufficient for plant growth (Ozanne and Shaw, 1967), or the calculated maximum slope at zero concentration (Holford and Mattingly, 1976). It is an indication of the ability of the soil to replace a unit change in soil solution P and maintain a productive solution concentration. The soil P buffering capacity may be the limiting factor in P uptake (Holford, 1976; Nair and Mengel, 1984). Soils with high phosphate adsorption maxima have higher phosphate buffering capacity than those with low phosphate adsorption maxima (Rajan, 1973). The higher or stronger the buffering capacity, the larger the proportion of P in solid phase relative to solution phase; increasing buffering capacity also lowers the rate of dissolution or desorption of P from the solid phase and vice-versa (Holford, 1989). According to Kamprath and Watson (1980) the buffering capacity of acid and neutral soils is a function of the amounts and crystallinity of hydrated oxides of Fe and Al, whereas in calcareous soils the amounts of exchangeable Ca and $CaCO_3$ determine the P buffering capacity.

2.5.2. Phosphorus diffusion in soil

The dominant mechanism governing the P-uptake by roots growing in all soils is diffusion of P through the soil to the roots, except those extremely high in P. Barrow (1989) suggested that phosphate mostly moves to plant roots by diffusion and it is only the phosphate in the soil solution that is free to move. The plant root reduces the soil-P mainly by absorbing from the adjacent soil solution, which initiates the diffusion of P in the soil solution towards the plant root and dissolution of solid phase P, termed as the labile pool (Schofield, 1955). The replenishment process, which involves the increase of P concentration in soil solution, has been regarded as the primary index of available P (Schofield, 1955; Holford, 1989). At any particular concentration of P, higher the buffer capacity, the greater is the replenishment of P. The concentration gradient in soil across the root surfaces is an important factor influencing P diffusion (Kamprath and Watson, 1980). Soil texture is another factor affecting diffusion of P (Olsen and Watanabe, 1963). As the clay content increases, the diffusion coefficients increase due to a decrease in tortuosity and an increase in buffering capacity. Diffusion coefficient of phosphate through soil is in the range of 10^{-8} to 10^{-11} $cm^2 s^{-1}$. Fitter (2002) stated that a phosphate ion normally moves less than a millimeter through the soil in a day. The diffusion coefficient for phosphate ion in water is $0.89 \times l0^{-5}$ $cm^2 s^{-1}$. According to Sibbesen (1983), the P uptake of a plant root over a period of time depends on: the initial concentration of P in soil solution; the soil medium for P diffusion; and the P dissolution of solid phase P, as a function of decreasing solution P concentration with time, changing activity of HCO_3^- and H^+ in the rhizosphere, changing activity of exuded organic anions and changing activity of phosphate precipitating cations. All the factors that govern the rate of P diffusion to the root and the extent of root growth are important in determining the availability of P to growing plants in a soil.

2.6. Available phosphorus status in soils:

Indian soils contained 165 to 1377 ppm total P with an average value of 474 ppm and that the mean total P in black, alluvial, forests, desert and red soils were 419, 415, 1268,240 and 376 ppm P, respectively (Dhir ,1956). In Indian soils, total P ranges from 120-2166 mg kg^{-1} soil and out of this total P amount, about 54-84% represents as P_i and about 16-46% as P_o (Tiwari, 2012). Kanwar (1986) reported that the abundance and activity of various P_i forms and the turnover of P_o in soils control the replenishment of labile solution P following plant uptake. Surface associated or amorphous P_i replenishes the labile P pool while more stable crystalline species act as a sink as well as long-term reservoir of P, depending on other soil properties such as pH, and a recent analysis has shown that the response of dry land crops such as sorghum differ among soil orders, with the magnitude of the responses being ranked: *Alfisols*>*Entisols*>*Vertisols*. Bansal and Sekhon (1994) studied that P deficiency is one of the major nutritional constraints to crop production in Indian *Vertisols*. Coupled with low native soil P availability is the problem of poor utilization efficiency of applied fertilizer P because of its transformation into relatively less available forms in soils. Consequently, large inputs of P are required to maintain acceptable levels of plant-available P in soil for optimum crop production.

A study conducted by Jain (1997) showed that the available macro and micro nutrient status of five hundred twelve surface soil samples representing the *Inceptisols, Alfisols* and Vertisols orders of farm of IGKVV, Raipur during summer season and analyzed for available N, P, K and DTPA–extractable Zn, Cu, Fe, Mn and found that available P varied from 7.3 to 25.4 kg ha^{-1}. Available P content varied between 12.76 to 14.00 kg ha^{-1} and was in medium level while, characterizing and classifying soils of an irrigated river flood plain in the eastern coastal region (Sahu and Mishra, 1997). Sahrawat (1977) found that in India, *Alfisols* with pH ranging from 5.5 to 6.8 the order of soil P distribution was Fe-P>Ca-P>Al-P. Shivaprasad *et al.* (1998) founded that the data on the available P status in the soils of Karnataka showed that about 83 per cent of the soils are low in P and 17 per cent area is under medium category. Reddy *et al*. (2000) reported that the *Vertisols* of Bhopal in Madhya Pradesh contained about 550 ppm total P in surface soil, of which about 18% is tied-up in organic form. Tomar (2000) reported that the total P content in soils of India varies from as low as 44 ppm to as high as 3580 ppm. Soil P occurs almost exclusively in the form of orthophosphate with total P concentration usually in the range of 500-800 mg kg^{-1} dry soil. The levels of organic P in soils vary widely, ranging from zero to over 0.2 per cent soil mass (Brady and Weil, 2002). Sen *et al*. (2002) observed that in total-P content Fe-P was the most abundant while Ca-P was the least. Organic P fraction of total P was found relatively higher on the surface. Mahmood *et al*. (2003) found lower total P in light soil (482 mg kg^{-1}) as compared with the heavy soil (690 mg kg^{-1}). Kanwar and Reddy (2003) worked over P fixation and management in Indian soils and concluded by the report that availability of native soil P as well as applied fertilizer P is reduced in soil owing to sorption and precipitation reactions of P with Fe and Al oxides in the soil. A study was investigated in the Talwara block of Hoshiarpur district (Punjab) that the available P content varied from 1.8 to 32.5 kg ha^{-1} with a mean value of 12.0 kg ha^{-1} in the surface soils (Sood *et al.,* 2003). In the surface soils, 59 per cent samples low in available P, 22 per cent samples medium in available P and 19 percent samples high in available P. Kumari *et al.* (2005) conducted a Survey and analysis of 100 soil samples of nine different mandals in Guntur district to assess an overall picture of physio-chemical properties and fertility status of the cotton (*Gossypium*) growing soils of Guntur district, Andhra Pradesh, India. Their results showed that available P ranged from 4.60 to 20.33 ppm with average of 7.82 ppm. Lakshminarayana (2007) suggested that minimum amount of P is in the saloid fraction (S-P) whereas maximum amount is in reductant soluble form (RS-P) in the soil and such high values may be attributed to the acidic to neutral soil reaction and high content of Fe_2O_3. The majority of residual fertilizer P accumulated as inorganic P (74-89%) followed by organic P (11-26%) and Olsen P (9-19%) illustrating that the inorganic P pool was a major sink for fertilizer P (Garg and Mikha , 2010). In Madhya Pradesh 31%, 58% and 11% districts were low, medium and high in available P status, respectively (Muralidharudu *et al*., 2011). Sarkar *et al*. (2014) characterized various forms of P in relation to soil maturity along a top sequence under hot, dry, sub-humid, agro-ecological sub region of West Bengal and concluded that there exist marked variation among the various inorganic P-forms in the soils of the top sequence under the hot dry sub-humid agro ecological sub region, sequential extraction of inorganic soil P fraction revealed that the mean relative abundance followed the order: Readily soluble-P>Fe-P>occluded-P>Ca-P>Al-P>S-P. These soils are fairly rich in total P reserve but the available P status is low, the overall contribution of the inorganic soil P fractions to the total soil P is 57.75%. Availability of P to plant is limited due to fixation as free oxides and hydroxides of aluminium and iron in acid soils and calcium in alkali soils (Goldstien, 1994). Turner (2007) observed that Soil-P exists in different fractions including inorganic-P and organic-P. These P-forms differ in their behavior and fate in soils and influenced by soil moisture, temperature, physico-chemical properties of soil.

2.7. Phosphorus fixation capacity

Phosphorus fixation is a process whereby the readily available forms of P are changed to sparingly soluble ones by reacting with inorganic and organic components of soil. It involves a series of reactions that remove P from the soil solution and render it unavailable for plants and occurs rapidly in soil profile. These reactions usually involve dissolved phosphate anions from applied fertilizers forming chemical complexes with metals and minerals that exist in the soil solution and on clay particles. It takes place in soil profiles typically allow only a small fraction (10-20%) of P in fertilizer to be taken up by plants. A large portion of chemical fertilizers with high P content applied to soil is immobilized rapidly and 80-85% becomes unavailable to plants (Goldstien, 1986). The availabilities of P also depend on soil pH, type of clay minerals, Fe, Al hydroxides and calcium carbonates (Kaistha *et al*., 1997). Therefore the response of phosphorus in different soils varies and the crop response varies. There is an acute deficiency of P in acid soils which, makes it the most limiting nutrient for crop production in such soils. Under normal conditions, most of the P added through chemical fertilizers is water soluble and therefore, readily available to plants. But, in case of acid soils, applied P gradually reacts with Fe and Al compounds present in the soil and consequently, gets transformed into relatively insoluble compounds (variscite and strengite), which are hardly available to plants (Brady and Weil, 2002). With time, solubility of these compounds decreases, resulting in P-fixation. The P fixation capacity is significantly and positively correlated with clay content of soil. This is due to larger specific surface area of clay associated with higher anion exchange phenomenon. Clay minerals P through co-ordination of phosphate ions on mineral surface by exchange of coordinated H_2O molecules, adsorbed SO_4^{2-} and other anions, displacement of hydroxyl and silicate ions and precipitation by exchangeable Ca^{2+} (Tomar, 2001). Comparing with other major nutrients, P is by far least mobile and available nutrient to microbes and plant. Numerous studies have been undertaken and still going on in various parts of the globe regarding the P fixing ability of soils.

2.7.1. Phosphorus fixation capacity: a global overview

The amount of P fixed by clays was shown to be proportional to the amount of free Al oxides on the clays, and that fixation occurs only as long as this form of Al is present (Ellis and Truog, 1955). Additional support for the hypothesis that free Al oxides are necessary for clay minerals to fix P was provided by the demonstration that montmorillonite will not fix P once all iron and aluminium oxides are removed from the clay. Again, the P fixation in acid soils is primarily due to the formation of iron and aluminium phosphate complexes as expressed chemically $M(H_2O)_3(OH)_2H_2PO_4$ (Hemwall, 1957). The iron and aluminium containing soil minerals, including the clay minerals, are the source of the iron and aluminium. The formation of these compounds is governed by the solubility product, the common ion, and salt effect principles. Under certain conditions, a precipitate is formed, whereas under other conditions the compounds are adsorbed. The reactions of P with clay minerals causing P fixation in soil have also been studied. It is considered probable that aluminium associated with clay is largely responsible for this P fixing property also agreed that the formation of iron and aluminium phosphate ($FePO_4$ and $AlPO_4$) is most unlikely to account for much P fixation except where the pH is less than 4.

The study from British soils ascribed the fact that free iron oxides in soils were more reactive to phosphate than those of the tropical soils, which was due to the greater crystallization of these materials in tropical soils (Lopez-Hernandez and Burnham, 1974a). The P adsorption capacity was determined by the amount of active forms of iron and aluminium. When adsorption was compared in different soil orders in tropical soils, there was a great variability in *Oxisols*; within the *Oxisols*, hardened laterite adsorbed least P. All the *Ultisols* studied had low P adsorption capacities. The *Vertisols* adsorbed moderate to high amounts of P. In general, *Entisols* had the lowest P adsorption capacity whereas the *Inceptisols* examined had high P adsorption capacities. Extractable Al was well correlated with phosphate adsorption in tropical and British soil groups.

The correlation between pH and phosphate retention capacity for a group of pedagogically similar soils was differing mainly due to the significant differences in pH (Lopez-Hernandez and Burnham, 1974b). Phosphate retention decreased with increasing pH. Exchangeable Al and acetate-extractable Al decreased with increasing pH which in turn decreased phosphate retention. In summary, the soil components affecting phosphorus adsorption include iron and aluminium oxides, clay and clay sized amorphous materials. The specific surface area of the calcium carbonate is also responsible of P adsorption in calcareous soils. Clay content has been reported to be of low importance for phosphate adsorption. The surface area and characteristics of the oxide minerals present in the soil appear to be the most important factors determining P adsorption by a soil. Further, Zhang *et al*. (2001) concluded that the Phosphate solubility and its reactions are influenced predominantly by the dissolution-precipitation activities of amorphous aluminium, iron and crystalline iron oxides. The effect of fertilizer-P application varies with climate condition, soil type, and soil test method employed, as well as the rate of fertilizer P applied (Zhang *et al.,* 2004).

Akhtar *et al*. (2003) conducted an experiment for measuring adsorption strength of dissolved P from undisturbed soil core. Soil from the upper two horizons of each series (Arkport, Hudson, Honeoye, Genesee, Lackawanna) were collected. The fitted Langmuir isotherm adsorption equations for surface and subsurface soil horizons fitted the data well with an $R^2 \geq 0.90$ except Arkport where $R^2 \approx 0.80$. The Genesee and Lackawanna soils had the greatest affinity for adsorbing P, with Lackawanna showing slightly greater affinities at low concentrations of P.

Shen *et al*. (2004) reported the crop yields, soil fertility and P fractions in response to long term fertilization under the rice monoculture system on calcareous soil and concluded that fractions of P such as Ca-P, Fe-P and Al-P can provide an effective approach for investigating soil P availability and P inter conversion among soil P fractions from different P pools. Siemens *et al*. (2004) researched over the magnitude and controls of P leaching and the risk of colloid-facilitated transport of P from sandy soils were assessed. Experimentally determined equilibrium concentrations and the degree of P saturation of soil were good predictors of mobile P concentration in drainage water. The concentration of soluble reactive P in drainage water is controlled by rapid adsorption in the sandy soils. Colloidal P was transported in P-rich subsoil when there was a large flow of water and after nitrate had been flushed from the soil profile and total solute concentrations were small.

According to Tisdale *et al*. (1985), the phosphate ions react rapidly with octahedral Al by replacing the hydroxyl groups located on the surface plane of the mineral. Generally, clays (e.g. kaolinite) with low SiO_2/R_2O_3 (sesquioxide) ratios have higher phosphate fixing capacity than clays (montmorillonite) with high SiO_2/R_2O_3 (sesquioxide) ratios. Burnham (1982) worked over the phosphate adsorption by 290 samples (top soil and sub soil) of nine soil orders from humid tropics and the seasonally dry tropics carried out in the United Kingdom indicated that the samples from *Entisols, Alfisols, Mollisols* and *Ultisols* generally had lower than average adsorption indices. *Vertisols* had higher than average and *Histisols, Inceptisols, Oxisols and Spodosols* varied greatly in their adsorption index.

Juo and Fox (1977) studied the phosphorus adsorption characteristics of soil materials from selected soil profiles belonging to *Alfisol* and *Ultisol* orders of West Africa which was mainly related to soil mineralogy, which in turn was related to the parent material, surface area, and free Fe oxide content of the soils. *Alfisols* and *Ultisols* derived from basalts had the highest P adsorption capacity. The Fe oxides in the soils derived from basaltic materials existed as very fine discrete particles in the clay fraction; specific surface area of the Fe oxides was about 300 m^2 g^{-1} which was much higher than the area of the Fe oxides derived from the acidic parent rock (50 m^2 g^{-1}). These results showed that the specific surface area characteristics of the oxide minerals present in the soil was a key factor affecting the P adsorption characteristics of the soils. Syers *et al.* (1971) studied P adsorption in surface samples of fifteen soils developed on a range of parent materials and arraying widely in crystalline iron oxide content. They found that the soils adsorbed between 60 and 490 µg P g^{-1} of the P added (500 µg P g^{-1} added as KH_2P0_4). Although P adsorption was well correlated with exchangeable Al (r=0.84), removal of exchangeable Al caused only a relatively small decrease in the amount of P adsorbed. Removal of amorphous Fe and Al components by oxalate treatment reduced P adsorption by 19 to 100 percent compared to that of the untreated sample. The amount of P adsorbed by untreated samples was less well correlated with oxalate extractable Fe (r=0.47) than extractable Al (r=0.78), suggesting that amorphous Fe components are less active per unit weight than amorphous Al in the adsorption of added P following citrate-bicarbonate-dithionite extraction was well correlated with the amounts of amorphous alumino silicates in the soils (r=0.99).

Brady and Weil (2002) concluded that in case of acid soils applied P gradually reacts with Fe and Al compounds present in soil consequently gets transformed into relatively insoluble compound which are hardly available to plants. Kennedy *et al.* (2001) revealed that the temperature affects most physical processes and the rate of chemical reactions generally increases with a rise in temperature, doubling for each 10 degree Celsius increase. The dissolution of granules of water-soluble P and the resultant reactions with soil components to produce less soluble reaction products are hastened by higher temperatures raising their action and entropy.

Agbenin (2003) studied the effect of dithionite and oxalate-extractable Fe and Al on P adsorption in a Savanna *Alfisol* was considered by examining pedons from cultivated and uncultivated sites and revealed that the Dithionite-extractable Al is Al^{3+} substituted isomorphically for Fe^{3+} in crystalline iron oxides in soils; the degree of this substitution appeared to have a profound effect on P adsorption and fertility of Savanna *Alfisols*. Abedin and Saleque (1998) conducted an experiment using surface soil (0-20 cm depth) from experimental plots receiving different amounts of P over six years of a trial. After collection of soil samples were shaken with 0.01 M $CaCl_2$ solution containing P from 0 to 75 µg mL^{-1} for 24 h at a soil to solution ratio of 1:10. The P isotherm data for all the soils at equilibrium P concentration were found to fit well to Langmuir, Freundlich and Temkin equations (R^2 = 0.979). The relationship between applied P and solution P for all the soils could be described by the equation 1/C = a + bln Pa which explained about 99 per cent of the variation. Here, C is solution P, Pa is added P, a and b are intercept and slope, respectively. When P was applied to soils that had received P for several years for each crop, and soils that had not received any applied P for several years, the soil that had received P seem to adsorb less added P than the soils that had not received applied P. Soil that had received P for several years in each crop showed consistently lower P-buffering capacity, lower maximum adsorption capacity and higher energy of adsorption than soil that received no applied P.

2.7.2. Phosphorus fixation capacity: Indian scenario

The addition of 50 ppm P from $(NH_4)_2HP0_4$ to calcareous alluvial soils of Uttar Pradesh increased Ca-P and Al-P in the initial stages but Fe-P predominated after 2 weeks and Ca-P after 60 days when the soil was kept at field capacity or under saturated conditions (Gupta *et al.,* 1972). Accordingly to Rao *et al.* (1972), the black and red soils of Mysore treated with ammonium phosphate and superphosphate at levels of 200, 400 and 600 ppm P, the largest single form of P was Fe-P and Al-P was only found in the superphosphate. Singh and Brar (1973) reported that the P added to alkaline alluvial paddy soil of Hisar (Haryana), under submerged condition, was transformed mainly to Ca-P and Fe-P fractions after 12 weeks.

The Fe-P fraction formed the major portion of native inorganic soil P fractions in rice soils reported from Jabbalpur (MP) and Al-P, Fe-P and Ca-P fractions increased with the addition of P fertilizers (Thakur *et al.,* 1975). There was no appreciable increase in the reductant soluble-P fraction. Gupta *et al*. (1977) revealed that the soil pH was linearly related to the P adsorption maximum and the bonding energy constant. Oxides of Fe and Al were also significantly correlated with P adsorption maximum. Soils with a high content of organic matter (colloidal) had very low capacities to adsorb P. Goswami and Sahrawat (1982) found that P adsorption is not always closely related to $CaCO_3$ content perhaps the critical factor was the quality of $CaCO_3$ which would affect P availability by its effects on precipitation and as an adsorber. Chemical characterization of different forms of inorganic phosphorus on four benchmark *Vertisols* with a range in extractable (0.5 M $NaHC0_3$) P showed that these soils have similar amounts of the different forms of P to other *Vertisols* in India. These results indicated that Ca-P was the dominant form followed by Fe-P with very low amount of Al-P. Interestingly, the levels of Fe-P in the *Vertisols* were similar to those found in the *Alfisols.* Nad *et al*. (1984) reported that in alluvial soils of Delhi, application of P fertilizer to a rice-wheat cropping sequence for over 10 years resulted in the increase in soil P status, particularly in the Al-P and Fe-P fractions. El–Swaify *et al.* (1985) more recently, studies on the two ICRISAT benchmark soils, a *Vertisol* and an *Alfisol*, have indicated that P fixation by the *Vertisols* should not be high. Past studies show that most of the clay in the Indian *Vertisols* was Smectitic i.e. swelling 2:1 lattice type, the dominant clay mineral was usually montmorillonite which usually does not have capacity to adsorb appreciable amounts of phosphate.

Manikandan and Sastry (1988) the effect of soil components on phosphate adsorption was studied in profiles of the soils belonging to the *Alfisols, Inceptisols* and *Entisols* orders from the Mysore Plateau. Removal of iron oxides by citrate bicarbonate- dithionite (CBD) and clay-sized amorphous material, extracted by 0.5 N NaOH showed that nearly 93% of the variation in phosphate adsorption was caused by these two components. The clay fraction contributed least to the phosphate adsorption. The amount of phosphate adsorbed by the clay-sized fraction was significantly related to the amorphous material contained in the clay and the octahedral poly hydroxyaluminium component of the amorphous materials. Bhattacharya and Ghosh (2001) from their studies on *Typic Ustochrept* of Delhi reported that available P content in soil increased due to application of highest levels of P. Paliyal *et al.* (2002) worked on adsorption of added P as influenced by the application of lime and gypsum in acid *Alfisols* of Himalayan region and the studies showed that the experimental soil had a greater affinity for P as the adsorption continued to rise with increase in equilibrium P concentration, the lime requirement applications increases and the gypsum application decreased the P adsorption. Verma (2002) evaluated the effect of chemical fertilizers and amendments on P dynamics in a long-term fertilizer experiment on an acid *Alfisol* under temperate situation. Available P status increased under treatments involving fertilizer P and other amendments like lime over control and plots receiving only N fertilization. He found that, there was a significant increase in Al-P, Fe-P, Ca-P and residual P forms with application of inorganic fertilizers along with amendments like FYM and Zn application. Further, after continuous cropping and fertilization for 29 years, there were 44 and 11 per cent increase in available P, under 150 per cent NPK and "100 per cent NPK + FYM" treatment, respectively over 100 per cent NPK application alone. Olsen's-P was positively and significantly correlated with all the fractions except H_2O-P. The highest value of coefficient of correlation was observed with $NaHCO_2$-P_i indicating maximum correlation of available P with this fraction. Further, P uptake was correlated positively. Verma *et al.* (2005) in a long-term fertilizer experiment on an acid *Alfisol* and temperate situation reported that integrated application of nutrients resulted in significantly lower P adsorption capacity of soils. At the beginning of experiment, various pools could be quantitatively ranked in the following order: residual-P > NaOH-P_o > NaOH-P_i > $NaHCO_3$-P_0 > $NaHCO_3$-P_i > HCl-P > H_2O-P. As a result of continued P fertilization and cropping, the order changed as follows: residual-P > NaOH-P_i > NaOH-P_o > $NaHCO_3$-P_i > $NaHCO_3$-P_0 > HCl-P > H_2O-P.

Muralidhar *et al.* (2005) researched over Quantity-intensity relationship and fixation of P in soils from shrimp farming areas of coastal India, to determine the P fixation and quantity-intensity relationship. The clay content was the major factor responsible for P fixation and it was high (62.1%*)* in soil from Canning with 45% clay and 8.05 pH followed by the soils from Mangalore (47.2%) having 39% clay and 4.9 pH and silt loam soil from Nellore (39.9%). The P fixation was positively correlated with clay (r = 0.961, calcium carbonate (r = 0.68) and silt (r = 0.24) and negatively correlated with phosphate potential (r = -0.399) and available P content (r = -0.313) in the soil. The average phosphate potential and equilibrium phosphate potential did not differ in soils except for acid soil, reflecting more or less similar availability of P, given the quantity of P in soils is nearly equal. Rajni *et al.* (2010) studied on dynamics of P fractions in a calcareous *Vertihaplustepts* under AICRP-LTFE soils. After a span of 8 years concluded that most of the fractions of P depleted negatively *i.e.* increased in status, but there was also found positive depletion in case of Al-P, Fe-P, Ca-P and available-P, it might be attributed to transformation of P and plant uptake as an available-P. Application of FYM also prevents depletion in available-P status of soil.

Singh *et al. (*2011) studied the effect of calcium carbonate and clay on phosphate sorption by soils, the overall conclusion was that the phosphate sorption in calcareous soil was satisfactorily described by the Freundlich equation .The x/m, XAd' Kd' Freundlich 'k' and 'n' parameters increased with increase in $CaCO_3$ content of soil and removal of $CaCO_3$ from soil decreases the sorption parameters of P. Ghosal *et al.* (2011) researched over P fixing capacity of the OxicRhodustalf—*Alfisols* soil in the Chotanagpur plateau region of Eastern India and revealed that the soil was acidic in reaction (pH-5.4) with presence of Fe (1.60%) and Al (17.2%). The P-fixing capacity of the soil was estimated to be 59.60% and 64.94% for the surface and the subsurface soil respectively showing lower P-fixing capacity of the surface soil as compared to the subsurface soil which may be due to presence of more organic matter in the surface soil as organic molecules released on decomposition of organic matter complexes with Fe and Al in the soil thereby blocking the P-fixing sites in the soil. Medhi *et al.* (2012) researched over phosphate supply characteristics of some soils in humid sub-tropic and semi-arid regions of India revealed from the present discussion that available P could be increased by minimizing the adsorption maxima, relative adsorption capacity, differential phosphate potential buffering capacity, equilibrium phosphate potential or by increasing pH and electrical conductivity in all categories of soils. Light textured normal soil with low available P had higher P-supplying capacity than heavy textured acid soils. Phosphate supplying capacity varied in accordance with the bonding energies and adsorption maximum. Working in Indian soils, it was concluded that iron-P and aluminum-P were higher in the recent alluvial soils than in old alluvial.

2.7.3. Phosphorus fixation capacity in North-East India: Present status and future research imperatives

The phosphate adsorption and buffering capacities of *Alfisols* and adjoining *Entisols* collected from different altitudes of Eastern Hills of Meghalaya indicated that *Entisols* and the soils of higher altitudes possessed a larger P adsorption capacity and buffering capacity than the *Alfisols* and the soils of medium and lower altitudes (Ram *et al.,* 1987). The higher P adsorption capacity of *Entisols* could be attributed to the presence of amorphous Al. Patiram *et al.* (1990) found that in acid soils among the different forms of P, Fe-P dominated. As soil is a heterogeneous medium, many factors are involved in P fixation and in each soil the factors having major influence on P fixation may vary. So, in order to know the P fixation capacity of soils, a better understanding of soil properties is important (Mallikarjuna *et al.*, 2003). It is worth noting that none of the studies concerning P fixation capacity evaluation in acidic soils of northeast India covered most of the pockets of NEI other than Meghalaya. But, the present study covers the dominant soil orders of northeast India.

While P fixation continues to receive much attention it is more important to know the effect of soil characteristics on P fixation of NE region of India.

Majumdar *et al.* (2004) studied the effect of different farming system on P fractions in an acid *Alfisols* of Meghalaya and the study revealed that the agriculture, agri-horti-silvipastoral and livestock based farming systems, which received proper soil conservation measures along with manures, fertilizers and liming could improve and maintain higher level of the various fractions of P as compared to other farming system, among the inorganic fractions of P, the highest value was recorded for reductant soluble-P, followed by Al-P, Fe-P, occluded –P, Ca-P and saloid-P respectively in the system, there was a continuous increase in all the p fractions from top to bottom of the watersheds under different farming system. The effect of liming on P adsorption and desorption behavior of acid *Alfisols* and *Entisols* of Meghalaya was studied (Majumdar *et al*., 2005) and revealed that the acid soils of the region had very high P adsorption and more that 99% of added P was up to 150 µg P g^{-1} soil addition. P desorption was very low in *Alfisols* but was relatively more in *Entisols* and liming acid soils induces P fixation and does not reduce the P requirement of crops from external sources .

The effect of P, FYM and lime on yield uptake by maize and forms of soil acidity in typichapludalf of Meghalaya was studied (Venkatesh *et al*., 2002) and concluded that available P and exchangeable Ca and Mg in post-harvest soil also increased due to application of P, FYM and lime but there was a considerable decline in exchangeable Al due to liming. Soil available P showed significant negative correlation with exchangeable acidity. Kumar (2015) conducted batch adsorption studies to assess the P sorption characteristics and standard P requirement (SPR) of two representative acidic soils of northeast India: (1) *Alfisol* with pH 4.5 ($S_{4.5}$), and (2) *Inceptisol* with pH 5.0 ($S_{5.0}$). It was found that the actual P requirement of the acidic soils in northeast India may be higher than its present recommendation; and also, there exists considerable variation in P requirement of soils within the same region, which underlines the need of site-specific nutrient recommendation rather than a single blanket recommendation for the whole region.

2.8. Factors affecting Phosphorus fixation in soils

The P retention in soilss is a natural process although certain agronomic practices may delay or speed up the process. Studies on organic amendments of soils have been reported to reduce the sorption capacity of soils (Marshall and Laboski, 2006; Kafkafi *et al.,* 1998; Bolan, 1994). According to Afif *et al.* (1995), soils amended with organic matter may delay P sorption but does not prevent it from occurring. Therefore, the P retention in soils is a continuous process that occurs in soils to gradually render inorganic P temporarily unavailable to plants Batjes (2011). This definition out-rules the possibility of P fixation where P is almost unavailable to plants. In a strict sense, P retention is a characteristic of the soil through which its natural processes restrict the availability of P for plant uptake (Probert, 1983).

2.8.1. Soil texture

Phosphorus is very reactive in soil which binds with the soil mineral particles and also complex with the elemental constituents in the soil (Jalali and Ranjbar, 2009). In terms of soil texture, the amount of P adsorbed to soil particles depends on the size of the soil particles. Silt and clay mineral particles with a size of less than 20 µm have large surface areas and are found to have high sorption capacity for P (Sanchez *et al.,* 2003). Sanchez *et al*. (2003) reported that, clay soils with more than 20% iron or aluminium oxides sorb large quantities of added P in soils. Other studies have shown positive correlation for clay contents and P sorption (Horta *et al*., 2013). Over a period of time, the sorbed P on soil surface is either loss through leaching or erosion, or is diffused into the interior of soil particles and become occluded for plant uptake (Agbenin and Tiessen 1995). This process is known as sorption. However, on large particle sizes like sandy soils have low surface areas and thus have low binding capacity for P.

2.8.2. Soil pH

Soil pH affects chemical reactions and microbial activities in soil. At pH < 5.5, iron and aluminium cations dominate in soil solution which can form strong bonds with phosphate ions. Previous studies have explained that, under such low pH conditions, variscite and strengite are possible controlling factors in inorganic P solubility (Pierzynski *et al.,* 2005). In alkaline conditions, two separate approaches have been used to explain P retention and solubility in soils. The former postulates that inorganic P form various phosphate compounds through precipitation while the latter is based on adsorption of P unto hydrated Al and Fe surfaces. In alkaline soils, the stable mineral controlling P availability or retention is calcium phosphates. Currently, it has been found that, changes in soil pH affect microbial activities which in turn mineralize or immobilize P to soils where microbial activity is increased under alkaline conditions (Rousk *et al*., 2009).

2.8.3. Soil organic matter

A significant contribution of inorganic P from organic P in soil solution is achieved through decomposition of soil organic matter or organic P amendments. Application of manure and biosolids to fields has been found to increase the total organic P in the soil (Marshall and Laboski, 2006). However, increase in inorganic P has also been reported (Rubaek and Sibbesen, 1993). Addition of labile organic carbon to soil stimulates microbial activities which mediate the release of inorganic P from organic matter to soil solution. Oehl *et al*. (2001) showed that, initial introduction of organic matter results in rapid decrease in soil solution P which temporarily immobilizes inorganic P in the soil as a result of microbial population growth. Microbes release inorganic P to soil solution when readily available carbon sources are depleted (Oehl *et al*., 2001). Turner *et al*. (2003) also explained that microbial P is released when cells are disrupted due to changes in soil water content. Microbial P released to soil solution are readily mineralized and become potentially available to plants. As stated above, organic amendments to soils temporarily reduce soil sorption capacity there by increasing P concentrations in soil solutions.

2.8.4. Soil moisture and temperature

Generally, the rate of chemical reaction increases with increasing temperature. For biogeochemical reactions that control P availability, increasing temperature has been found to increase the adsorption capacity of Al and Fe bound P (Rajput *et al.,* 2014). However, reduced sorption capacity for Ca bound P has been reported for increasing temperature (Fixen and Grove, 1990). Additionally, rate of immobilization and mineralization of microbial P will increase with increasing temperature.

Inorganic P dissolves in water to become available for plant uptake. Labile P is also at equilibrium with inorganic P concentration in soil solution. Therefore, low moisture content in soils is likely to limit the amount of labile P dissolved in soil solution. Zhang *et al.* (2011) found seasonal variations of bioavailable P in wetlands where lower P concentrations were observed in dry seasons. Also, at water saturated conditions, redox sensitive Fe-P will reduce in sorption of P to increase inorganic P in soil solutions. Since plant take up inorganic P in soil solutions, reduced moisture content is likely to impact P uptake in plants and microbial activities could be reduced. As stated above, these factors act in continuum to drive the phosphorus cycle in soils.

2.8.5. Effect of Time

P adsorption by soils and many soil components follow two distinct patterns: an initial fast reaction followed by a very much slow reaction. The adsorption reaction involving exchange of phosphate for anions and ligands on the surface of iron and aluminum oxides are extremely rapid (White and Payne, 1980; Tisdale *et al*., 1985). The slower continuing adsorption reactions involve a shift in the form of P held at the surface from more loosely bound to more tightly bound types which are less accessible to plants. An important practical aspect of time is the period after application of fertilizer. On some soils with high adsorption capacity, the period of reaction is short, whereas on others the period may last for months or even years.

2.8.6. Free Iron and Aluminum

Researchers have long recognized that oxides and hydroxides of Al and Fe play a significant role on P availability and sorption properties. Singh and Singpuri (1986) reported that oxides of Fe and Al were correlated significantly with P adsorption maxima. The higher value of P adsorption maxima in cases of soil containing higher content of oxides of Fe and Al might be due to formation of their respective metal phosphate (Maida, 1980). A significant and positive relationship between P bonding energy content and free oxides of Fe and Al was observed and suggested a mechanism of phosphate adsorption by two point attachments mainly through the colloidal surface and Al. The sorption of inorganic phosphate of soils with pH less than 7.0 is closely related to the amount of reactive Fe and Al compounds (Syers *et al*., 1977).

It has been shown that the amorphous hydrous metal oxides of Fe and Al sorb relatively greater amounts of P than their crystalline counterparts (McLaughlin *et al*., 1981). In addition, Tisdale *et al.* (1990) also showed that about 1 meq exchangeable Al per 100 gram soil when completely hydrolyzed can sorb up to 102 mg P L^{-1} in soil solution. With respect to the relative importance of the two elements, Al plays a dominant role in P retention than Fe (Bromfield, 1965, Williams *et al*., 1958). Owusu- Bennoah and Acquaye in 1989 also showed that dithionate-extractable Al was a more important determinant of P sorption maxima of some selected Ghanaian soils. The sorption of P on to Al / Fe surface is usually considered to be important under acidic conditions.

2.8.7. Soil Carbonate

Lajtha and Bloomer (1988) regarded calcium carbonate as the primary geochemical agent capable of retaining P in the soils of a desert ecosystem. Tiessen *et* *al*. (1984) suggested that Ca-bound forms of P constitute the dominant pool of mineral-soil P in arid and semi-arid soils of southwestern United States. The presence of calcium or magnesium ions must accompany high pH values. At pH values above 7.5 the ions of calcium and magnesium as well as their carbonates cause precipitation of the added P, and their availability decreases. The equation below explains further.

$$3CaCO_3 + H_2O + 2H_3PO_4 \rightarrow Ca_3(PO_4)_2 + 3CO_2 + 4H_2O$$

If the increase of these ions (calcium and magnesium) continues, there will be a decrease in solubility of soil phosphorus.

2.8.8. Plant Root Geometry

Phosphate uptake is more dependent on plant root activity than is the case for other major nutrients. Plant root geometry and morphology are important for maximizing P uptake, because root systems that have higher ratios of surface area to volume will more effectively explore a larger volume of soil (Lynch, 1995). For this reason mycorrhizae are also important for plant P acquisition, since fungal hyphae greatly increase the volume of soil that plant roots explore (Smith and Read, 1997). In certain plant species, root clusters (proteoid roots) are formed in response to P limitations. These specialized roots exude high amounts of organic acids (up to 23% of net photosynthesis), which acidify the soil and chelate metal ions around the roots, resulting in the mobilization of P and some micronutrients (Marschner, 1995).

2.9. Phosphorus release pattern

Fertilizer amendment with soils is aimed at increasing the inorganic P concentration, in practice, dissolved inorganic P undergoes adsorption and desorption processes on soil particle surfaces until equilibrium is reached where uptake of P is replaced by desorption of P from soil surfaces. Studies have shown that, the rate at which P is desorbed into soil solution is biphasic; an initial rapid P release from soil surfaces and followed by a slow P release into solution (Agbenin and Tiessen, 1995). Tthe rate of P released into soil solution decreased with increasing time in calcareous soils (Jalali and Ranjbar, 2009). McDowell and Sharpley (2003) reported the rapid P release followed by a slow P release from animal manure and compost in a five day rain simulated experiment and concluded that, P desorption and diffusion from soil particles were the rate limiting steps in short- and long-term P release reactions. Agbenin and Tiessen (1995) reported similar observations and attributed P release to soil sorption-diffusion reactions. Primarily, soil sorption theory is commonly used to explain the phenomena of P release in soils. The rapid release is explained to occur from desorption of adsorbed P on soil surfaces. Over a period, adsorbed P on soil surfaces diffuses into soil vacant sites and becomes occluded or less available for plant uptake (Cabrera *et al.,* 1981) leaving less inorganic P to be desorbed to soil solution. Also, inorganic P in soil solution could precipitate with metal cations in the soil solution and reduce its concentration in soil solution. This process explains the slow release rate of inorganic P to soil solution (McDowell and Sharpley, 2003; Shariatmadari *et al.,* 2006; Jalali and Ranjbar, 2009; Rajput *et al*., 2014).

2.10. Effect of P-sources on soil available P

It is important that P removed in product is balanced by plant-available form of P input in order to make farming systems sustainable (Richardson *et al*., 2009). However, this is not always the case. Often there is a net export of soil P from farming systems where P is either not applied, or supplied at rates and in forms that do not balance removal of P in plant products (McLaughlin *et al*., 1991; Oehl *et al*., 2002; Burkitt *et al*., 2007). Such agronomic practices are unsustainable, and depending on soil type, are usually associated with declining yields over time (Richardson *et al*., 2009). Even in conventional farming systems that receive adequate amounts of soluble P to maintain production, there is poor recovery of P from fertiliser inputs, which invariably results in a net accumulation of total soil P. A major limitation to plant access to P from soil is that a large proportion of the P that occurs naturally in soil (i.e. native soil P), or having been applied as a fertilizer, occurs in forms that are not immediately available for plant uptake (McLaughlin *et al*., 1991). For agricultural systems, this fixation of P in soils is an inefficiency that adds to the cost of P fertilizer inputs by farmers, but it also presents both safeguards and risks for the wider environment. Although retention of P in many soils helps to reduce or prevents leaching of soluble P into sub-soils and seepage into streams, the surface transport of soil and organic matter through erosion inevitably carries with its retained P, which even in small amounts, can contribute significantly to the eutrophication of water bodies.

2.10.1. Effect of organic manure on soil available P

Soil organic matter is known to exert a synergetic effect on availability of phosphorus when applied with P fertilizer together. It undergoes following mechanism resulting in increased available P (Dalton *et al*., 1952, Moreno and Lindsay*,* 1960; Barrow, 1989; Havlin *et al*., 2009).

a) Formation of organic-phosphate complexes that are more easily assimilated by plants.

b) Anion replacement of $H_2PO_4^-$ ion on adsorption sites.

c) Coating of Fe/ Al oxides by humus to form a protective cover and thus reduces P adsorption.

d) Increasing the quantity of organic phosphorus mineralized to inorganic phosphorus.

So, the addition of organic materials including manures, crop residues, composts and other rural and urban biogenic wastes improves soil P availability (Reddy *et al*., 2005; Gichangi *et al.,* 2009). Olsen *et al*. (1970) observed an increase in content of available P (34-159 ppm) with the application of organic manures, particularly at high rates. Organic amendments provide microbes not only with P but also C and N during decomposition and are, therefore, likely to induce changes in P pools that differ from those of inorganic P addition (Malik *et al*., 2012). Additionally, microbes indirectly affect P availability by changing the soil pH and via organic molecules released during decomposition of organic materials which may block P sorption sites and complex Fe, Al and Mn (Hue 1991; Erich *et al.,* 2002; Iyamuremye and Dick, 1996). Therefore, organic P sources, particularly those with high P concentration can stimulate the formation of organic P forms in soil which may provide a long term slow-release P source for plants and soil organisms (Malik *et al.,* 2012).

2.10.2. Effect of single super phosphate on soil available P

Calcium phosphate fertilizer-single superphosphate (16-22% P_2O_5) has 90% water soluble phosphate (WSP) and no appreciable effect on soil pH, unlike H3PO4 and NH4+ phosphate. It is an excellent source of P with sulphur (12%) because of its low P concentration. Therefore, it is an important P source in worldwide (Havlin *et al.,* 2009). But, as already mentioned as during application on agricultural field, about 85-90% of the added inorganic P becomes unavailable to plants in the year of application due to adsorption and precipitation with Fe, Al and Ca in the soil (Brady and Weil, 2008; Gichangi *et al.,* 2009; Khan and Joergensen, 2009) and generally reaches a maximum of around 50% over time due to residual value (Holford, 1997). The extent of this inefficiency in the recovery of applied P is dependent on soil type, soil P status, and on the form of P that is applied (Richardson *et al.,* 2009). In the meantime according to Lindsay (1999) superphosphate contains a sufficient amount of calcium to precipitate half of its own P, in the form di-calcium phosphate or di-calcium phosphate dehydrated. However, Prochnow *et al.* (2008) stated that at soil pH 5.2, the fertilizers required 73 to 95% WSP to reach the maximum dry-matter yield, while they required 60 to 86% WSP at pH 6.4. To reach 90% of the maximum yield, all superphosphate fertilizers required <50% WSP.

2.10.3. Effect of rock phosphate on soil available P

The application of fertilizer P in 'water-soluble', such as superphosphate widely interest in agricultural soil, but particularly in organically managed systems using alternative sources of P which are less soluble such as poorly soluble forms of P fertilizer rock phosphates are generally less effective on most soils in promoting plant growth (Bolland *et al.,* 1997). High cost of importing soluble P fertilizers is, therefore, forcing many developing countries to turn increasingly to use local RP resources to improve agricultural production (Van-Kauwenberg, 1991; Buresh *et al.,* 1997; Van-Straaten, 2002). The relative effectiveness of rock phosphates is increased when 'reactive' or acidulated forms are used, where soil conditions facilitate the dissolution of the fertilizer, and in sandy soils that have a high propensity for leaching of soluble P (Bolland *et al.,* 1997; Garden *et al.,* 1997; Bolland and Gilkes, 1998). The solubilized phosphate may react with Ca and Mg present in the rock phosphate as soon as pH of growth medium increases (Mahidi *et al.,* 2011). In a study, Mandal and Khan (1972) reported that RP always maintained in the soil a higher amount of available phosphorus than superphosphate. So, direct use of such RP could minimize pollution and decrease the cost of chemical treatment. But only RP application is also not economically feasible under soil conditions characterized by high P sorption capacity, low cation exchange capacity, high pH, low rainfall, low organic matter content, and low microbial activity (Panhwar *et al.,* 2011). Common efforts include the use of physicochemical means, such as partially acidulating RP with synthetic and natural organic acids and decreasing particle size can increased the efficiency of this fertilizer (Singh and Amberger, 1998). Hence, there is growing interest in manipulating RP by biological methods in order to enhance its agronomic effectiveness. Currently, there is increasing emphasis on application of P- solubilizing microorganisms for RP solubilisation in soils (Rodriguez and Fraga, 1999; Whitelaw, 2000; Vassilev *et al*., 2001, Thakuria *et al.,* 2009).

2.10.4. Effect of PSB on soil available P

Phosphate rock minerals are often too insoluble to provide sufficient P for crop uptake. Use of PSMs can increase crop yields up to 70 percent (Verma, 1993). Combined inoculation of arbuscular mycorrhiza and PSB give better uptake of both native P from the soil and P coming from the phosphatic rock (Goenadi *et al.,* 2000; Cabello *et al.,* 2005). Higher crop yields result from solubilization of fixed soil P and applied phosphates by PSB (Zaidi, 1999). Microorganisms with phosphate solubilizing potential increase the availability of soluble phosphate and enhance the plant growth by improving biological nitrogen fixation (Kucey *et al.,* 1989; Ponmurugan and Gopi, 2006). *Pseudomonas spp*. enhanced the number of nodules, dry weight of nodules, yield components, grain yield, nutrient availability and uptake in soybean crop (Son *et al.,* 2006). Phosphate solubilizing bacteria enhanced the seedling length of *Cicer arietinum* (Sharma *et al.,* 2007), while co-inoculation of PSM and PGPR reduced P application by 50 % without affecting corn yield (Yazdani *et al.,* 2009). Inoculation with PSB increased sugarcane yield by 12.6 percent (Sundara *et al.,* 2002). Single and dual inoculation along with P fertilizer results 30-40 % better than P fertilizer alone in improving grain yield of wheat, and dual inoculation without P fertilizer improved grain yield up to 20 % against sole P fertilization (Afzal and Bano, 2008). Mycorrhiza along *with Pseudomonas putida* increased leaf chlorophyll content in barley (Mehrvarz *et al.,* 2008). Rhizospheric microorganisms can interact positively in promoting plant growth, as well as N and P uptake. Seed yield of green gram was enhanced by 24 % following triple inoculation of *Brady rhizobium* + *Glomus fasciculatum* + *Bacillus subtilis* (Zaidi and Khan, 2006). Growth and phosphorus content in two alpine Carex species increased by inoculation with *Pseudomonas fortinii* (Bartholdy *et al.,* 2001). Integration of half dose of NP fertilizer with biofertilizer gives crop yield as with full rate of fertilizer while reducing the fertilizers input leading to minimized cost of production and maximized the net return (Jilani *et al.,* 2007).

2.11. Phosphate solubilizing microorganism (PSM) and its role on P availability in soil

There are certain microorganisms which are involved in solubilization of insoluble-P i.e. the unavailable form of P *viz.,* bacteria, fungi, actinomycetes and arbuscular mycorrhizal fungi (AMF) (Thakuria *et al.,* 2004; Khan *et al.,* 2007; Wani *et al.,* 2007; Xiao *et al.,* 2009). Several fungal and bacterial species, popularly known as PSMs assist plants in mobilization of insoluble forms of phosphate. Bacteria are more effective in phosphorus solubilization than fungi (Alam *et al.,* 2002). Microorganisms involved in phosphorus acquisition include mycorrhizal fungi and PSMs (Fankem *et al.,* 2006). Among the whole microbial population in soil, phosphate solubilising bacteria (PSB) constitute about 1 to 50 %, while phosphorus solubilizing fungi (PSF) are only 0.1 to 0.5 % in P solubilization potential (Chen *et al.,* 2006). Among the soil bacterial communities, ectorhizospheric strains from Pseudomonas and Bacilli, and endosymbiotic rhizobia have been described as effective phosphate solubilizers (Igual *et al.,* 2001). Bacterial strains from the genera *Pseudomonas, Bacillus*, *Rhizobium* and *Enterobacter* along with *Penicillium* and *Aspergillus* fungi are considered as the the most powerful P solubilizers (Whitelaw, 2000).

PSMs convert the insoluble minerals (insoluble phosphatic compounds) into soluble forms in soil and make them available for plants to absorb (Pradhan and Sukla, 2005). The insoluble P_i are broken down by a group of heterotrophic microorganisms excreting organic acids that dissolve phosphatic materials and/or chelate cationic partners of the P ions that is, PO_4^{3-} directly, releasing P into solution (He *et al.,* 2002). This biological approach for extracting phosphate from slowly dissolving rock phosphate was proposed as a less expensive and lower-energy technique compared with the conventional fertilizer application (Goldstein and Rogers, 1999; Thakuria *et al.,* 2009). Not only the plant growth promotion through enhancement of P nutrition but also secretion of other metabolites, which are responsible for biological control of soil borne phyto-pathogens as well (Vassilev *et al*., 2006).

2.12. Knowledge gap

It is now beyond doubt that phosphate absorption is highly correlated with the concentration of reactive Al and Fe compounds in soil and the clay content. The phosphate fixation capacity is known to vary with soil type. In India, especially in NE India, the phosphate fixation capacity of soils belong to major soil orders is seldom not reported. It is also not clear how the phosphate fixation capacity in soils of different orders behave and what relationship is maintained with soil attributes. As the phosphate fixation capacity was not studied earlier, the present recommendation of phosphatic fertilizer in NE Indian soils is blanket recommendation in fact. The different P sources are recommended from time to time in different soils as the recommended P management practice. There is no scientific data available on the release pattern of P from P sources when applied as fertilizer/ or amendment in acid soils of different soil orders. Therefore, the aims of the present study are to fill the knowledge gap on understanding the phosphate fixation capacity in major soil orders of NE India. The conventional P sources are scarce, very expensive and beyond the reach of resource-poor farmers. For both logistic and economic reasons, it is often not practicable for the resource-poor farmers of developing countries like India to apply high rates of P amendments to the acid soils. Excess application of P fertilizer leads to leaching or eutrophication of water bodies and deficit of P fertilizer application leads to its fixation. So, if the maximum P fixation dose is known then, P fertilizers can be applied to the soils judiciously. The present study also reports the amount of phosphorus recovered from different P sources when used as a fertilizing material in soil incubation study in different soil orders. The scientific data on the P release patterns in soils of dominant soil orders under different P sources are seldom reported from NEH region of India.

Chapter-3

Materials and Methods

The two broad objectives of this investigation were addressed through independent laboratory incubation experiments. Both incubation experiments were carried out in the Biogeochemistry Laboratory, School of Natural Resource Management, College of Post Graduate Studies, CAU-Imphal, Umiam (Meghalaya). The procedures involved in these laboratory incubation experiments and analytical techniques for soil physico-chemical and biological attributes are described hereunder.

3.1. Brief description of soil orders

The soil of North Eastern region is predominantly acidic in nature comprising of four dominant soil orders *viz.*, A*lfisol, Ultisol, Inceptisol* and *Entisol.* From each of four soil orders, 3 representative soil profiles were considered in this study. Altogether 12 soil profiles were considered (Table 1) and soil samples from surface layer (0-10 cm depth) were collected for laboratory analysis. All soil profiles were studied by the Regional Centre, National Bureau of Soil Survey and Land Use Planning, Jorhat. The information on sampling location of soil profiles (Fig.3.1) and soil orders maintained by NBSSLUP Jorhat Center are presented in Table 3.1.

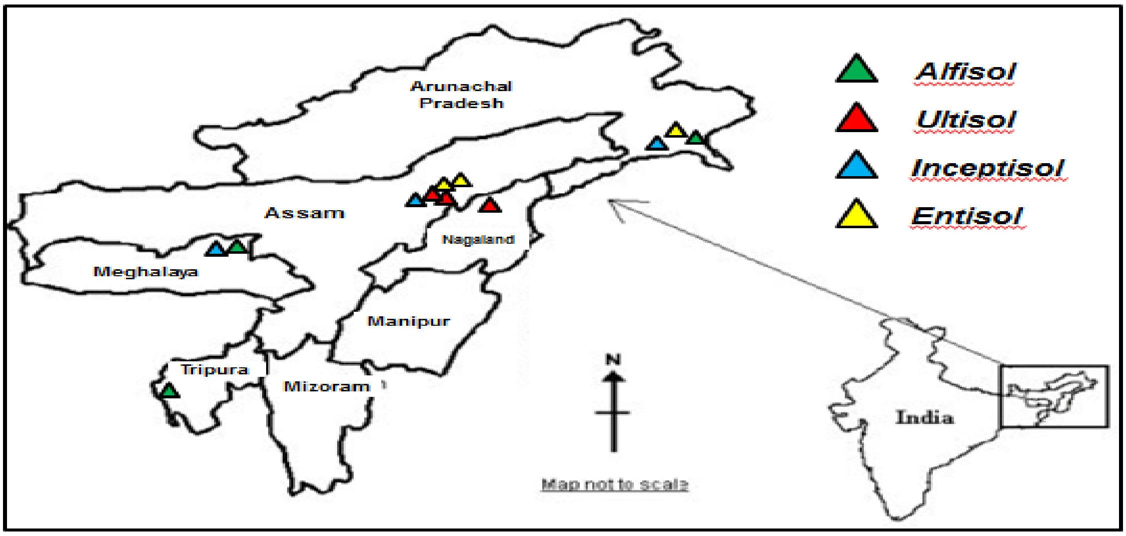


Fig.3.1. Sampling locations for soil profiles representing four soil orders

Table 3.1. Basic information on soil profiles and their respective soil orders used for determination of phosphate fixation capacity and P release pattern

Soil orders	Soil profile	Profile information	Date of sampling
Alfisol	P1	Changlang, Arunachal Pradesh	April-16
	P2	Sepahijala, Tripura	March -16
	P3	Ri-Bhoi, Meghalaya	April-16
Ultisol	P4	North-West Jorhat, Assam	Jan-16
	P5	Mokokchung, Nagaland	March -16
	P6	North-West Jorhat, Assam	April-16
Inceptisol	P7	Ri-Bhoi, Meghalaya	Feb-16
	P8	Changlang, Arunachal Pradesh	April-16
	P9	North-West Jorhat, Assam	Jan-16
Entisol	P10	Changlang, Arunachal Pradesh	April-16
	P11	North-West Jorhat, Assam	Jan-16
	P12	North-West Jorhat, Assam	Jan-16

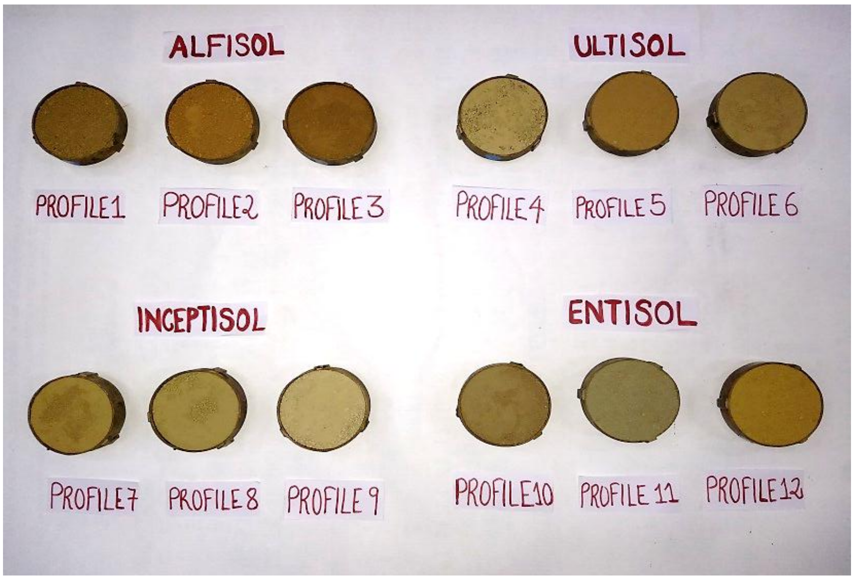


Fig.3.2. Colour of surface soil of 12 soil profiles representing four dominant soil orders.

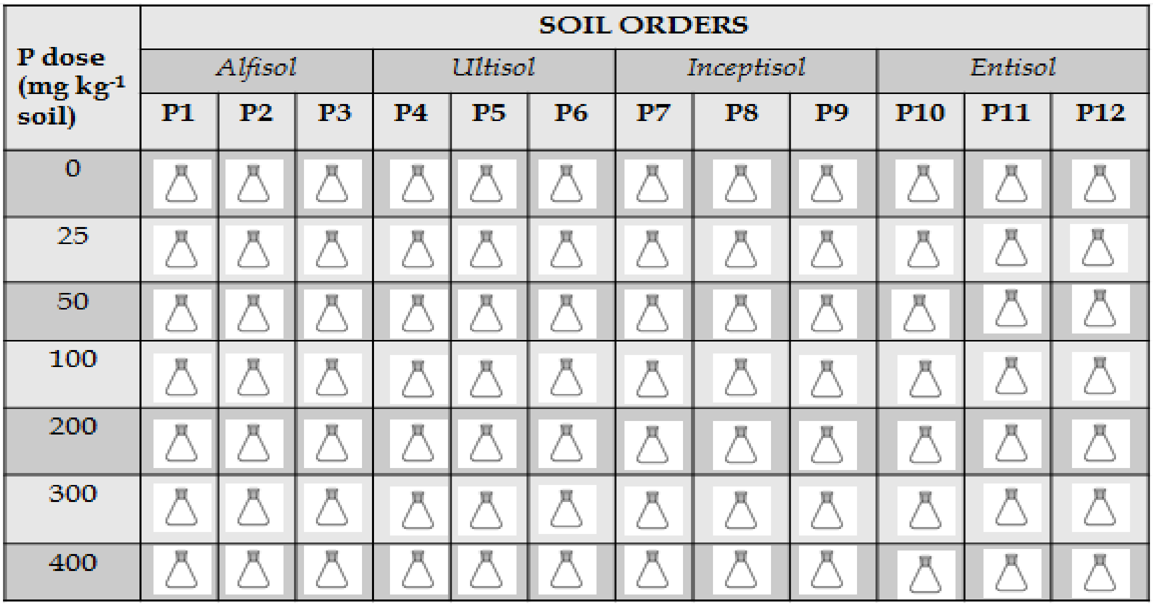
The samples were taken for laboratory analysis and some basic physico-chemical properties (Soil texture, soil colour, pH, SOC, Available. N, P, K, Exchangeable Ca and Mg, Readily soluble Al, CEC, Exchangeable aluminum, Base saturation) of the soils were determined. The basic properties of these soils are given in Table 4.1 and Table 4.2 in the result section.

The details of materials used and methods adopted during the course of investigation are presented objective-wise hereunder:

3.2. Incubation experiments

3.2.1. Incubation experiment for PFC under objective-I

Altogether 360 conical flasks (12 soil profiles x 10 levels of P x 3 replications) were arranged for PFC determination. An amount of 5 g soil was taken in each conical flask (capacity 100 ml). The graded levels of P (0, 25, 50, 100, 200, 300, 400, 500, 600 and 700mg P_2O_5 kg^{-1} soil) were imposed to each profile soil maintaining 3 replicate flasks (Fig. 3.3). Immediately after addition of P levels, 25 ml of 0.01 M $CaCl_2$ solution was added to each conical flask and these flasks were incubated for 24 h in a gyratory shaker at rpm 120 (Fig. 3.4). After incubation, soil suspension was filtered through Whatmann filter paper no. 42 and then the concentration of P in the clear supernatant was determined using stannous chloride blue colour method described in the later section.



P dose (mg kg^{-1} soil)	SOIL ORDERS											
	Alfisol			*Ultisol*			*Inceptisol*			*Entisol*		
	P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**	**P11**	**P12**
0	⚗	⚗	⚗	⚗	⚗	⚗	⚗	⚗	⚗	⚗	⚗	⚗
25	⚗	⚗	⚗	⚗	⚗	⚗	⚗	⚗	⚗	⚗	⚗	⚗
50	⚗	⚗	⚗	⚗	⚗	⚗	⚗	⚗	⚗	⚗	⚗	⚗
100	⚗	⚗	⚗	⚗	⚗	⚗	⚗	⚗	⚗	⚗	⚗	⚗
200	⚗	⚗	⚗	⚗	⚗	⚗	⚗	⚗	⚗	⚗	⚗	⚗
300	⚗	⚗	⚗	⚗	⚗	⚗	⚗	⚗	⚗	⚗	⚗	⚗
400	⚗	⚗	⚗	⚗	⚗	⚗	⚗	⚗	⚗	⚗	⚗	⚗

Up to 700ppm

Fig. 3.3. General layout of the incubation experiment-I

Fig. 3.4. Equillibriation of soil with added P levels in 0.01 M $CaCl_2$ (25 ml) for 24 h.

Fig. 3.5. Filtration of solution phase after equillibriation with 0.01 M $CaCl_2$ (25 ml) for 24 h for determination of solution P content using Bray's-I method.

3.2.2. Calculation of PFC of soils

A stock solution having 5000ppm P strength was prepared using KH_2PO_4(AR grade). From this stock, aliquots (µl) of 25, 50, 100, 200, 300, 400, 500, 600, 700 were withdrawn and added to conical flasks in order to obtain a graded P doses of 25, 50, 100, 200, 300, 400, 500, 600 and 700 µg g^{-1} soil, respectively. After equilibration with 25 ml of 0.01 M $CaCl_2$ for 24 h, the P concentration in the solution phase was determined.

The percent P fixed was calculated by dividing fixed P amount with added P amount and multiplying it with 100. The formula used to calculate percent P fixed is given below:

$$\% \text{ P fixed} = \frac{\text{Fixed P}}{\text{Added P}} \text{x}100$$

Qunatity of fixed P = (Quantity of P applied - Quantity of P in solution – Quantity of solution P inblank)

3.2.3. Incubation experiment for PRP under objective-II

To study PRP in soil, the laboratory soil column was prepared using 50 ml capacity disposable syringe. Each syringe contained 10 g soil. The delivery end of the syringe was plugged with glass wool in such way that soil particle free aliquot can be collected while applying pressure through syringe plunger. The field capacity (FC) soil moisture content was maintained in the soil column throughout the incubation period (up to 60 days). The FC moisture content varied according to soil profile type (data are presented in the result section). On basis of soil bulk density of each soil, the height of soil column was maintained. . In each profile soil, seven (7) treatments were imposed and maintained 3 replicate soil columns per treatment. The treatment combinations were: no P input (control), PSB, OM, RP, SSP and RP+PSB and the quantity of P sources added per 10 g soil are presented in Table 3.4. All syringes were incubated at room temperature (ranged from 20°C to 25°C) and soil columns were leached with distilled water (5 ml per syringe) at 0, 5,15, 30, 45, and 60 days of incubation. The leachate P content represented solution phase P at different time point. The P content in the leachate was determined by the stannous chloride blue colour method as described inthe later section.

3.2.4. Calculation of P sources:

The different P sources along with their application doses in soil column used for PRP determination are presented in Table 3.4.

Table 3.2. P sources applied in the incubation experiment–II for PRP study

Treatment	**Control**	**PSB**	**OM @ 5 t ha^{-1}**	**RP @ 60 kg P$_2$O$_5$ ha^{-1}**	**SSP @ 60 kg P$_2$O$_5$ ha^{-1}**	**RP @ 60 kg P$_2$O$_5$ ha^{-1} + PSB**
Amount (mg 10 g^{-1})	No P input	200 µl	22.32	1.22	1.67	1.22 + 200µl

The contents of N, P and K in the OM were 2.45%, 1.74% and 1.28%, respectively.

3.2.5. Preparation of PSB:

An effective strain of PSB (*Bacillus* sp. strain F15) was selected and multiplied in 250 ml nutrient broth in an environmental shaker (120 rpm at 30±1°C for 36 h). The population of PSB achieved was 3.4 x 10^{9}cfu ml^{-1} broth. An aliquot (200 µl) was added to each of the soil column of the respective PSB treatment. The PSB aliquot was prepared as follows:

Two (2) ml of F15 inoculated nutrient brothwas transferred to a 2 ml capacity eppendoff tube and centrifuged at 10,000 rpm for 45 s. The clear supernatant was discarded and 2 ml sterile water was added to the pallet and vortexed for mixing. Then again centrifuged and supernatant was discarded and added 1 ml sterile water to the clean pallet followed by vortexing to make uniform bacterial suspension. An aliquot of 200 µl from this suspension was used to inoculate the soil column.

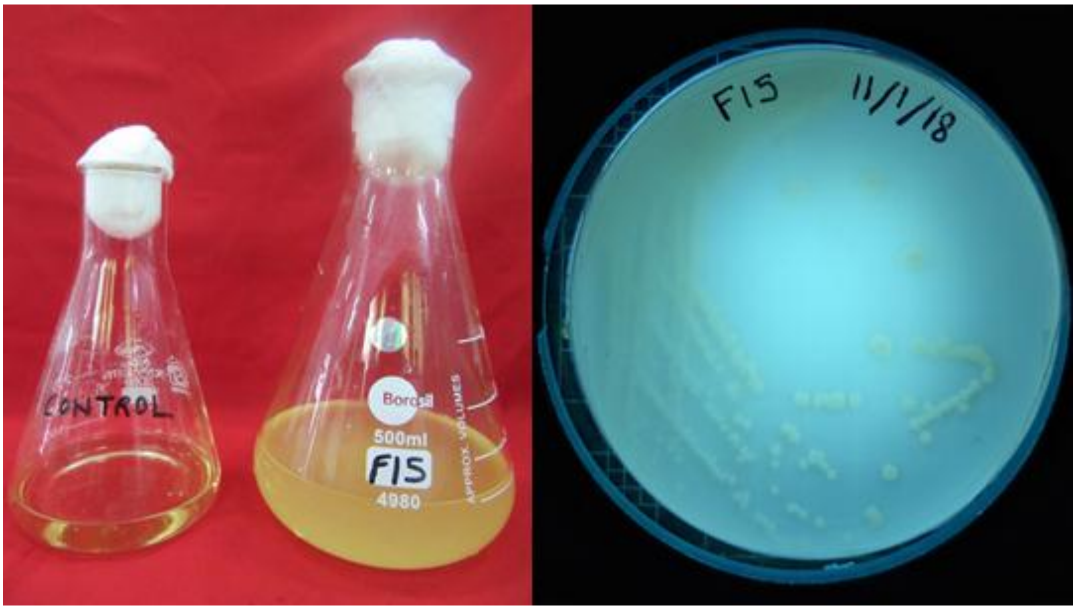


Fig. 3.6. PSB strain used for inoculation of soil column.

3.2.6. Mixing of P sources:

The calculated amount of P amendments were applied to the soil as per treatment combinations for the soils of 12 profiles and mixed thoroughly. The amended soils were placed in the 50 ml syringe and covered. Field capacity for each of the profile was estimated and calculated amount of distilled water was poured accordingly. For PSB treatment, 200 µl was added and for rest of the samples 200 µl of distilled water was added and covered for incubation experiment.

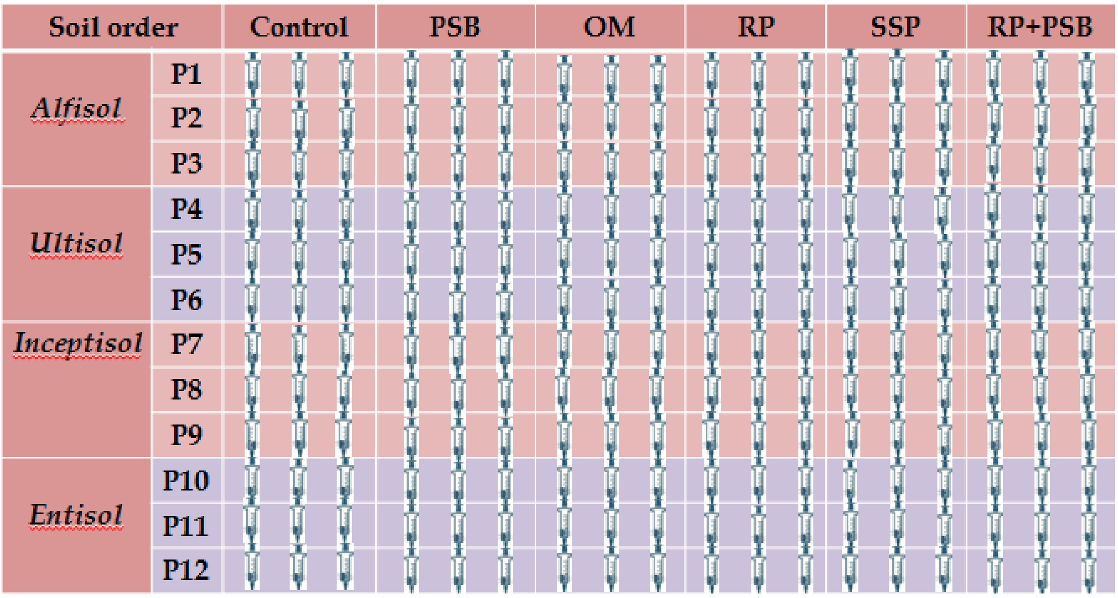


Fig. 3.7. Layout of the incubation experiment-II for phosphate release pattern study.

3.2.7. Extraction of leachate

At every time point, 5 ml double distilled water added to each syringe and pressure applied through plunger to expel that 5 ml added water as the aliquot and available P in the leachate was analysed by Bray's 1 method.

3.2.8. Phosphate release pattern

The P content in leachates obtained from different treatment combinations at 0, 5, 15, 30, 45 and 60 days of incubation were used to draw the trend graph of P released over the 60 days duration.

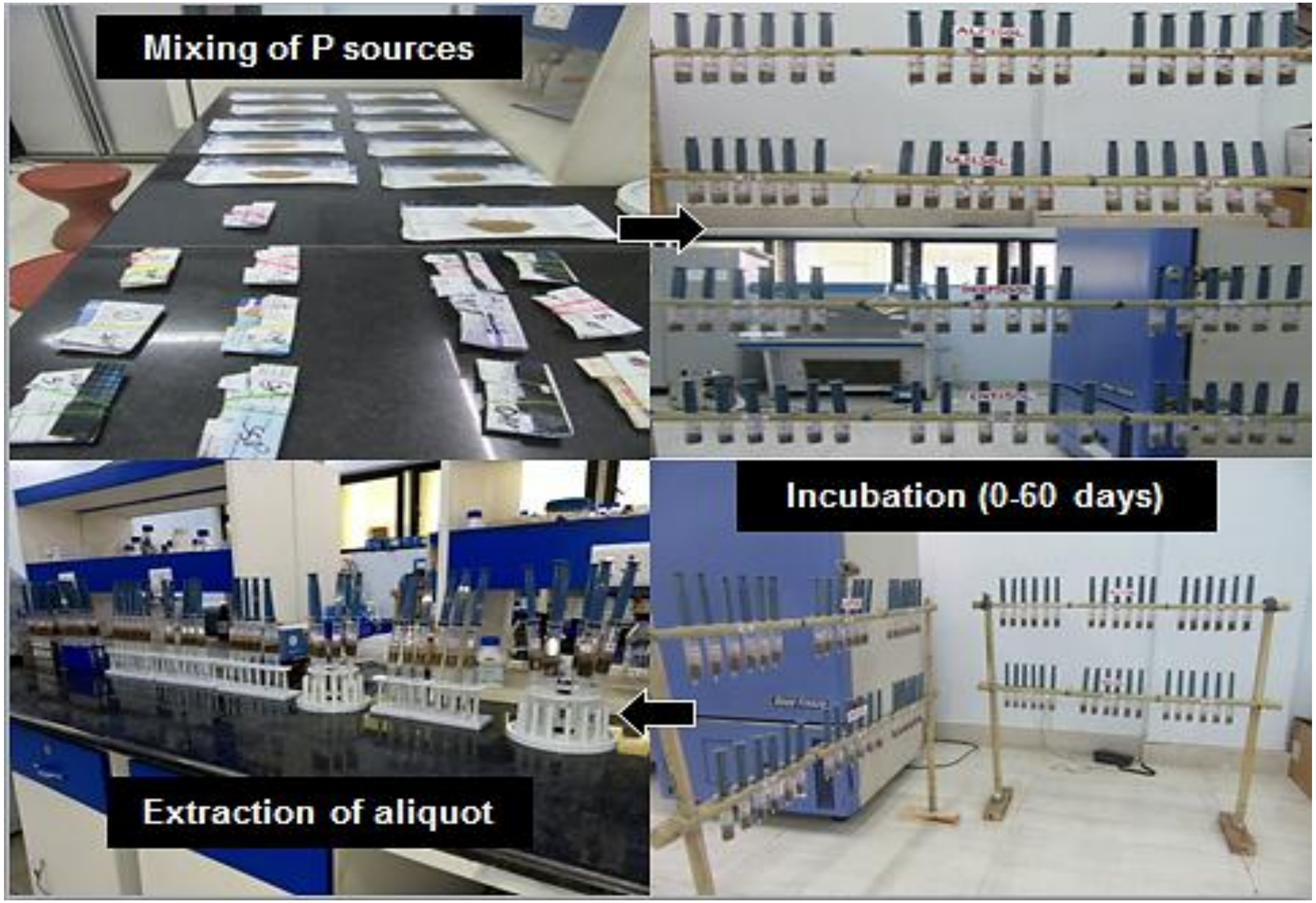


Fig. 3.8. Depiction of the P release incubation experiment amended with different P sources.

3.3. Soil analysis

3.3.1. Soil Colour

The dry and moist colour of the soil was determined by Munsell Colour Chart.

3.3.2. Soil texture

The particle size distribution of soil was determined by International pipette method (ISSS, 1929). Soil texture expressed as %.

3.3.3. Maximum water holding capacity (Keen Raczkowski Box method)

Maximum water holding capacity (MWHC) of soil was determined by equilibrating the soil with water through capillary action in a Keen Raczkowski Box as described by Baruah and Borthakur (1999). It was estimated using the following formula:

$$\mathbf{MWHC\ (\%)} = \left[\left(\frac{\textbf{Water in the wet soil after equilibration}}{\begin{array}{c}\textbf{Oven dry weight of the soil equilibrated}\\ \textbf{with water}\end{array}}\right) \times \mathbf{100}\right]$$

3.3.4. Bulk density

The bulk density (BD) of the soil was derived mathematically from the MWHC determination mentioned in section 3.5.3 by using the formula:

$$\mathbf{BD\ (Mg\ m^{-3})} = \left[\left(\frac{\begin{array}{c}\textbf{Oven dry weight of the soil equilibrated}\\ \textbf{with water for MWHC detrmination}\end{array}}{\textbf{Volume of the air dry soil (= volume of Keen box)}}\right) \times \mathbf{100}\right]$$

3.3.5. Field Capacity

Field capacity of the soils were determined by weighing 50g soil in a glass funnel plugged with cotton and was placed above a cylinder. It is then saturated with 100 ml water upto the rim and was allowed to stand for 24 hours. After 24 hours, the top and bottom portion of the soil were scraped out and the weight of the middle portion of the soil on wet and dry basis was taken into account.

3.3.6. Soil reaction (pH)

The pH of the soils were measured in soil water suspension (1:2.5) using a combined glass electrode (Mettler Toledo, Switzerland) as given by Jackson (1973).

3.3.7. Soil Organic Carbon (SOC)

Soil organic carbon was determined by the rapid titration method of Walkley and Black, 1934. Soils (0.5 g) of 0.2 mm sieve was mixed with 10 ml of 1 N $K_2Cr_2O_7$ and 20 ml of conc H_2SO_4 in a 500 ml conical flask and stood for 30 min. After oxidation, 200 ml of distilled water and 10 ml of H_3PO_4 was added and then the residual $K_2Cr_2O_7$ in the flask was titrated with freshly prepared 0.5 N ferrous ammonium sulphate in presence of diphenylamine indicator. SOC content in soil was expressed in percentage (%).

3.3.8. Available N

Available Nitrogen in soils was determined by the modified alkaline potassium permanganate method (Subbiah and Asija, 1956). Five grams soil was taken in Kjel tube and added 25 ml of 0.32% $KMnO_4$ and 25 ml of 2.5% NaOH. Then the mixture was distilled for 6 min in an automated distillation chamber (Classic DX, Pelican Equipment, Chennai). The ammonia gas generated during distillation was collected in 20 ml of 2% boric acid and the amount of boric acid used for absorption of ammonia was determined by titrating with standardised 0.02 N H_2SO_4. Available of Nitrogen was expressed as kg ha^{-1}.

3.3.9. Available P

Soil available phosphorus was determined by Bray's P-1(0.03N NH_4F+0.025N HCl) method of Bray and Kurtz (1945). Air dried soil samples were sieved with 2mm sieve and took 5 g soil with 50 ml Bray P-1 extractant and shaken for 5 min in a reciprocating shaker. Soil suspension was filtered through Whatman No. 42 and 5 ml of the supernatant filtrate was used for developing blue colour using Dickman Bray's reagent and stannous chloride. The blue colour intensity was measured at 660nm (Spectrascan UV-2600, Thermo Scientific, USA) and concentration of P was read from the standard curve. Available P was expressed as mg kg^{-1} soil in case of incubation experiment.

3.3.10. Available K

Soil available potassium was determined by the ammonium acetate method (Hanway and Heidel, 1952). An air dried soil (5 g) was extracted with 25 ml of I N ammonium acetate (pH 7) by shaking 5 min in a reciprocating shaker. Then, the soil suspension was filtered through Whatman No. 1 and the concentration was measured using a flame photometer. Soil available potassium was expressed in kg ha^{-1}.

3.3.11. Exchangeable Ca and Mg

Exchangeable form of Ca and Mg was determined by EDTA (versenate) titration method (Gupta, 2007). Five grams soil was mixed with 25 ml 1 N ammonium acetate (pH 7) and shaken for 5 min on a mechanical shaker. The suspension was filtered through Whatman No. 1. The concentration of Ca+Mg and Ca in the filtrate was determined by complexometric titration using 0.01N EDTA in presence of erichrome black T (EBT) and ammonium purpurate indicator respectively. Exchangeable Ca and Mg were expressed as meq per 100 g soil.

3.3.12. DTPA extractable Iron

DTPA-Fe was determined by DTPA method (0.005M DTPA+0.1M TEA+0.01M $CaCl_2.2H_2O$, at pH 7.3) of Lindsay and Norvell (1978). Air dried, 2mm sieve of 10 g soil with 20 ml DTPA extractant was shaken for 2 hrs on a mechanical shaker. Then, the soil suspension was filtered with Whatman No. 42 and the concentration of Zn was measured using Atomic absorption spectrophotometer. Available Fe was expressed as mg kg^{-1} soil.

3.3.13. Exchangeable acidity and Al

Exchange acidity is the acidity exchanged by an unbuffered neutral salt solution. The method of exchange acidity was determined as per the procedure described by McLean (1965). Air dried soils of 40 g was mixed with 100 ml of IN KCl and agitated for 10 min. The suspension was filtered and 20 ml of the filtrate was taken in 250 ml conical flask. The flask was heated to take out the CO_2 and titrated against 0.1N NaOH in presence of Phenolpthlaein indicator. The exchangeable acidity of soil was expressed in meq per 100^{-1} g soil.

Exchangeable Al was determined by continuation of the exchange acidity. The titrated solution of exchange acidity was mixed with 5 ml of freshly prepared 4% NaF and stood for 4 min. Then, the solution was titrated against 0.1 N HCl. The exchangeable Al was expressed as meqper 100^{-1} g soil.

3.3.14. Readily soluble Al

Readily soluble Al was determined by colorimetric method (Hoyt and Webber, 1974). Air dried soil of 10 g was taken in 50 ml centrifuge tube and added 20 ml of 0.02M $CaCl_2$. The solution was shaken for 5 min and then centrifuged at 1250 g for 1 min. then the solution was filtered through Whatman no. 42. Aluminium in the extracting solution was determined by transferring 2 ml of filtrate into plastic centrifuge tube and then added 0.5 ml each of PCV, OP, and HH. Then, 6 ml of buffer solution was added and the tubes were inverted three times and allowed to stand for 1h. The absorbance was measured at 580 nm using UV visible spectrophotometer. Al was expressed as mg kg^{-1} soil.

3.3.15.Cation Exchange Capacity (CEC)

A finely grinded air dry soil sample (10 g) was incubated with 100ml of 1 NNH_4OAC (pH 7.0) solution for 30 min at 200 rpm shaking speed. This helps to saturate the cation exchange site with NH_4^+. After incubation, soil suspension was quantitatively transferred to a buchner funnel with a Whatman No. 42 filter paper. The residual electrolytes including free NH_4^+ present in the suspension were removed successively washing with 99% isopropyl alcohol. Then, the soil was washed with 10% acidified NaCl and 50ml of the leachate was placed inside N-distillation tube and distilled NH_4^+ by kjeldahl distillation method by absorbing released ammonia in 2% H_3BO_3. The boric acid containing ammonium borate was titrated by standard acid in the presence of bromo-cresol green-methyl red mixed indicator to find out the meq of exchangeable NH_4^+ adsorbed by soil sample. CEC of soil was expressed in meq per 100g soil.

3.3.16. Base saturation (BS)

Base saturation of the soils was determined by dividing exchangeable bases with the CEC and the values were expressed in percentage.

Base saturation (%) = (Ex. bases/ CEC) x100

3.4. Statistical analysis

Univariate statistical analysis was performed using SPSS v.21 (Statistical Packages for Social Science Inc., Chicago, IL, USA). For each parameter, the effects of different treatments at each time point were determined by performing one-way analysis of variance (ANOVA) incorporating Tukey’s Honestly Significant Difference (HSD) test for the pair-wise comparison among treatment means. The repeated measures-ANOVA was also performed to test the significant difference among marginal means of treatments considering the different time intervals as replicate measurements for each parameter analysed and the relationship between P fixation capacity with soil attributes according to soil order types wasperformed using Pearson’s correlation coefficient.

Chapter 4

Results

There were three objectives in this study and the experimental design was setup separately for each objective. Two independent incubation experiments were conducted for objective 1 and objective 2, while the relationship between phosphorus fixation capacity and other soil attributes was performed under objective 3. The objective-wise data are interpreted in this section.

4.1. Objective 1: physico-chemical properties of soil orders

The surface soil samples of 12 soil profiles were used in this study those representing four dominant soil orders *viz., Alfisol, Ultisol, Inceptisol and Entisol* of NE India were provided by the NBSS-LUP Regional Centre, Jorhat, Assam. The physical and chemical attributes of these 12 profile soils determined in this investigation are represented in Table 4.1 and Table 4.2, respectively.

4.1.1 *Alfisol*

The order *Alfisol* comprised of 3 profiles *viz.*, P1, P2 and P3 representing Changlang (Arunachal Pradesh), Sepahijala (Tripura) and Ri-Bhoi (Meghalaya), respectively. The physical and chemical attributes of 3 *Alfisol* profiles are represented in Table 4.1 and Table 4.2, respectively.

4.1.1.1. Physical properties

The colour of soils in dry conditions ranged from strong brown to yellowish brown *viz.*, 7.5 YR 4/6 to 10YR 5/6 and under moist conditions ranged from dark red to dark yellowish brown *viz.*, 2.5 YR 3/6 to 10YR 3/4. The sand content varied from 50 to 65%, clay content ranged from 15 to 40%. The maximum clay content was 40% in P2 and minimum was 15% in P1. The silt content values varied from 10-20%. The texture varied from sandy loam to sandy clay. The values of BD ranged from 0.91 to 1.00 g cc^{-1} among the 3 profiles and the highest was found in P3. Among 12 soil profiles, P2 had the least bulk density. The water holding capacity ranged from 32.7% in P3 to a maximum of 51.8% in P1. Among all 12 soil profiles, P3 had the least capacity to hold water.

4.1.1.2. Chemical properties

The pH of soils ranged from 4.40 to 6.33 that are from extremely acidic to slightly acidic. The pH of P3 was the highest and P2 was the lowest among *Alfisols*. Soil organic carbon varied from 1.4%- 1.8%. The content of SOC was the highest (1.8%) for P1 and the least (1.4%) was for P3*.* The content of soil Avl.N ranged from 270 kg ha^{-1} to 301 kg ha^{-1} and the P2 soil contained maximum SOC and minimum was for P1 soil. The content of Avl.P varied from 9.7 kg ha^{-1} to 22.8 kg ha^{-1}. The highest P was found in P1 soils and the lowest in P3 soils. The P1 soil contained maximum Avl.K (220 kg ha^{-1}) and the minimum content (155 kg ha^{-1}) for P3 soils. Exchangeable alumina (Ex. Al) ranged from 0.12 meq 100^{-1}g to 3.59 meq 100^{-1}g. The P2 soil had the highest amount and P1 had the least amount of Ex. Al. The higher content of readily soluble aluminium was due to low soil pH of the soil. The P3 soil contained the highest amount of readily soluble aluminium (354 mg kg^{-1}) and the lowest (18.8 mg kg^{-1}) was P1 soil. The content of DTPA-Fe varied from 20.0 mg kg^{-1} to 29.7 mg kg^{-1}. The content of Exch.Ca+Mg ranged from 2.8 meq 100^{-1}g soil to 8.1 meq 100^{-1}g soil. The values of CEC ranged from 8.0 to 15.6 cmol kg^{-1} and the percent BS ranged from 39.9% to 55.3% for 3 soil profiles belongs to *Alfisol*. Higher values of BS was in P1 soil due to higher CEC and high amount of Ex.Ca+Mg and the lower BS values was in P3 soil due to low CEC and low amount of Ex.Ca+Mg**.**

4.1.2 *Ultisol*

The order *Ultisol* comprised of 3 profiles *viz.*, P4, P5 and P6 representing North-West Jorhat (Assam), Mokokchung (Nagaland) and North-West Jorhat (Assam), respectively. The physical and chemical attributes of 3 *Ultisol* profiles are represented in Table 4.1 and Table 4.2, respectively.

4.1.2.1. Physical properties

The colour of the soils in dry conditions ranged from light olive brown to yellowish brown *viz.*, 2.5Y 5/4 to 10YR 5/4 and under moist conditions ranged from olive brown to dark brown *viz.*, 2.5 Y 4/4 to 10YR 3/3. The sand content varied from 35 to 85%, clay content ranged from 10 to 55%. The maximum clay content was 55% in P5 and minimum was 10% in P6. The values of silt content varied from 5-10%. The texture varied from loamy sand to clay. The values of BD ranged from 0.95 to 1.16 g cc^{-1} among the 3 profiles and the highest was found in P6. The water holding capacity ranged from 36.0% in P6 to a maximum of 54.9% in P5.

4.1.2.2. Chemical properties

Soil pH values ranged from 4.22 to 4.56 that are from extremely acidic to very strongly acidic. The pH of P6 profile soil was the highest and P4 soil was the lowest among *Ultisols*. Soil organic carbon varied from 1.0%- 2.0%. The content of SOC was the highest (2.0%) for P5 and the least (1.0%) was for P6. The highest percent SOC may be due to the clayey nature of soil from P5. The content of soil Avl.N ranged from 176 kg ha^{-1} to 216 kg ha^{-1} and P5 contained maximum Avl.N and minimum was for P6 soil. The content of Avl.P varied from 7.6 kg ha^{-1} to 62.1 kg ha^{-1}. The highest P was found in P4 soils and the lowest in P6 soils. The P5 soil contained maximum Avl.K (205 kg ha^{-1}) and the minimum comtent (108 kg ha^{-1}) for P6 soils. The P6 had the least amount of Avl.K among all the profiles. Exchangeable alumina (Ex. Al) ranged from 0.46 meq 100^{-1}g to 2.81 meq 100^{-1}g. The P6 soil had the highest amount and P4 had the least amount of Ex.Al. The higher content of readily soluble alumina was due to low soil pH of the soil. The P5 soils contained the highest amount of readily soluble alumina (384 mg kg^{-1}) and the lowest (34.6 mg kg^{-1}) was P4 soil. The content of DTPA-Fe varied from 20.3 mg kg^{-1} to 24.5 mg kg^{-1}.The content of Exch.Ca+Mg ranged from 1.7 meq 100^{-1}g soil to 2.1 meq 100^{-1}g soil. The values of CEC ranged from 6.6 to 14.2 cmol kg^{-1} and the percent BS ranged from 16.2% to 30.2% for the 3 soil profiles belonging to *Ultisol*. Higher values of BS was in P6 due to high CEC and high amount of Ex.Ca+Mg and low BS values was in P5 due to low amount of Ex.Ca+Mg**.**

4.1.3. *Inceptisol*

The order *Inceptisol* comprised of 3 profiles *viz.*, P7, P8 and P9 representing Ri-Bhoi (Meghalaya), Changlang (Arunachal Pradesh) and North-West Jorhat (Assam), respectively. The physical and chemical attributes of 3 *Inceptisol* profiles are represented in Table 4.1 and Table 4.2, respectively.

4.1.3.1. Physical properties

The colour of the soils in dry conditions ranged from pale yellow to yellowish brown *viz.*, 2.5Y 7/4 to 10YR 2/4 and under moist conditions ranged from light olive brown to dark greyish brown *viz.*, 2.5 Y 5/4 to 10 YR 4/2. The sand content varied from 35 to 65%, clay content ranged from 20 to 45%. The maximum clay content was 45% in P9 soil and minimum was 20% in P7 soil. The silt content values varied from 5-35%. The texture varied from sandy clay loam to sandy clay. The values of BD ranged from 0.94 to 1.15 g cc^{-1} among 3 *Ultisol* profiles and the highest was for P7 and the lowest was for P8. The water holding capacity ranged from 38.1% in P9 soil to a maximum of 52.6% in P8 soil.

4.1.3.2. Chemical properties

Soil pH values ranged from 4.62 to 6.11 that are from very strongly acidic to slightly acidic. The pH of P8 *soil* was the highest and P9 soil was the lowest among *Inceptisol*. Soil organic carbon varied from 1.0%- 1.9%. The content of SOC was the highest (1.9%) for P7 soil and the least (1.0%) was for P9 soil. The content of soil Avl.N ranged from 173 kg ha^{-1} to 229 kg ha^{-1} and the P8 soil contained maximum Avl.N and minimum was for P7 soil. The content of Avl.P varied from 6.6 kg ha^{-1} to 16.9 kg ha^{-1}. The highest P was found in P8 soils and the lowest in P9 soils. The P8 soil contained maximum Avl.K (159 kg ha^{-1}) and the minimum content (124 kg ha^{-1}) for P9 soils. Exchangeable alumina (Ex.Al) ranged from 0.34 meq 100^{-1}g to 1.03 meq 100^{-1}g among 3 *Inceptisol* profiles. The P9 soil contained the highest amount of Ex.Al and the minimum amount was in P8 soil. The P9 soil contained the highest amount of readily soluble alumina (377 mg kg^{-1}) and the lowest amount (24.2 mg kg^{-1}) was in P8 soil. The content of DTPA-Fe varied from 18.7 mg kg^{-1} to 26.7 mg kg^{-1}. The content of Exch.Ca+Mg ranged from 2.1 meq 100^{-1}g soil to 7.6 meq 100^{-1}g soil. The values of CEC ranged from 9.92 to 23.6 cmol kg^{-1} and the percent BS ranged from 24.4% to 33.9% for 3 *Inceptisol* profiles. Higher BS values was in P8 soil due to high CEC and high amount of Ex.Ca+Mg and low base saturation was in soils of P9 due to low CEC and low amount of Ex.Ca+Mg**.**

4.1.4. *Entisol*

The order *Entisol* comprised of 3 profiles *viz.*, P10, P11 and P12 representing Changlang (Arunachal Pradesh), North-West Jorhat (Assam) and North-West Jorhat (Assam), respectively. The physical and chemical attributes of 3 *Entisol* profiles are represented in Table 4.1 and Table 4.2, respectively.

4.1.4.1. Physical properties

The colour of soils in dry conditions ranged from light brownish gray to brown *viz.*, 2.5 Y 6/2 to 10 YR 5/3 and under moist conditions ranged from dark reddish brown to dark grey *viz.*, 5 YR 3/2 to 5 Y 4/1. The sand content values varied from 75 to 95%, clay content ranged from 3.7 to 10%. The maximum clay content was 10% in P12 soil and the minimum was 3.7% in P11 soil. The silt content values varied from 1.3-20%. The texture varied from fine sand to sandy loam. The values of BD ranged from 1.02 to 1.37 g cc^{-1} among 3 *Inceptisol* profiles and the highest BD values in P12 soil and the lowest BD value in P11 soil. The water holding capacity ranged from 33.6% in P10 to a maximum of 55.5% in P11. It was also found out that among all the 12 profiles, P11 had the maximum ability to hold water.

4.1.4.2. Chemical properties

The pH of the soils ranged from 5.81 to 7.74 that are from medium acidic to mildly alkaline. The pH of P11 was the highest and P10 was the lowest among *Entisols*. P11 also attained highest value among all the profiles. The soil organic carbon varied from 0.5%- 1.2%. The content of SOC was the highest (0.5%) for P10 and the least (1.2%) was for P12. The content of soil Avl.N ranged from 122 kg ha^{-1} to 226 kg ha^{-1} and the P10 soil contained maximum Av. N and minimum was for P11 soil. The content of Avl.P varied from 20.8 kg ha^{-1} to 24.6 kg ha^{-1}. The highest P was found in P11 and the lowest in P10 soils. The P10 soil contained maximum Avl.K (126 kg ha^{-1}) and the minimum content (115 kg ha^{-1}) for P11 soils. Exchangeable alumina (Ex. Al) ranged from 0.09 meq 100^{-1}g to 0.28 meq 100^{-1}g. The P10 soil had the highest amount and P12 had the least amount of Ex. Al within the profiles as well. The higher content lower content of readily soluble alumina was due to high soil pH of the soil. The P10 soil contained the highest amount of readily soluble soluble aluminium (22.6 mg kg^{-1}) and the lowest (18.4 mg kg^{-1}) was P12 soil. The least amount among the profiles was observed in P12. The content of DTPA-Fe varied from 20.5 mg kg^{-1} to 26 mg kg^{-1}. The content Exch.Ca+Mg ranged from 6.8 meq 100^{-1}g soil to 12.9 meq 100^{-1}g soil. The values CEC varied from 16.1 to 18.4 cmol kg^{-1} and the percent BS ranged from 44.4% to 71.0% for 3 soil *Entisol* profiles. Higher value of BS was in P11 soil, which was also the highest among all 12 soil profiles.

Table 4.1. Physical properties of surface soils of twelve soil profiles representing four dominant soil orders of NE India

Soil Order	Profile	Soil colour		Coarse sand (%)	Fine sand (%)	Silt (%)	Clay (%)	Textural Class	BD (g cc^{-1})	MWHC (%)	FC (%)
		Dry	Moist								
Alfisol	P1	10 YR 4/4	10 YR 3/4	42.5	22.5	20	15	sandy loam	0.92±0.006ab	51.8±0.84de	39.1±0.40f
	P2	7.5 YR 4/6	2.5 YR 3/6	8.9	41.1	10	40	sandy clay	0.91±0.005a	49.5±0.50d	37.1±0.40e
	P3	10 YR 5/6	5 YR 3/3	33.2	21.8	10	35	sandy clay loam	1.00±0.005c	32.7±2.36a	24.3±0.46a
Ultisol	P4	2.5 YR 6/4	2.5 Y 4/4	14.7	65.3	5	15	sandy loam	1.14±0.005e	36.3±0.88abc	26.3±0.12bc
	P5	10 YR 5/4	7.5 YR 3/4	3.85	31.15	10	55	clay	0.95±0.005b	54.9±0.404e	41.2±0.29g
	P6	2.5 Y 5/4	10 YR 3/3	11.85	73.15	5	10	loamy sand	1.16±0.011ef	36.0±0.69abc	27.0±0.52c
Inceptisol	P7	10 Y R 2/4	10 YR 3/4	33.9	31.1	15	20	sandy clay loam	1.15±0.011ef	39.3±0.40c	29.5±0.17d
	P8	2.5 Y 5/4	10 YR 4/2	2.85	32.15	35	30	clay loam	0.94±0.011ab	52.6±0.53de	39.5±0.23f
	P9	2.5 Y 7/4	2.5 Y 5/4	7.7	42.3	5	45	sandy clay	1.09±0.0054d	38.1±0.58bc	28.6±0.06d
Entisol	P10	10 YR 5/3	5 YR 3/2	60.7	14.3	20	5	loamy sand	1.18±0.0054f	33.6±0.64a	25.2±0.23b
	P11	2.5 Y 6/2	5 Y 4/1	12.6	82.4	1.3	3.7	fine sand	1.02±0.0054c	55.5±0.38e	41.7±0.06g
	P12	2.5 YR 6/8	10 YR 4/6	23.4	51.6	15	10	sandy loam	1.37±0.005g	34.1±0.51ab	25.6±0.12b

Values ± means, n = 3; Within a column (parameter) values followed by different letters are statistically significant as determined by one-way ANOVA incorporating Tukey's HSD test for multiple pair-wise comparisons among means.

BD – bulk density, MWHC – maximum water holding capacity and FC– field capacity

Table 4.2. Chemical properties of surface soils of twelve soil profiles representing four dominant soil orders of NE India

Soil Order	Profile	pH	SOC (%)	Avl.N (kg ha^{-1})	Avl.P (kg ha^{-1})	Avl.K (kg ha^{-1})	DTPA-Fe (mg kg^{-1} soil)
Alfisol	P1	6.33±0.015g	1.80±0.115de	270±4.6e	22.8±0.53f	220±5.8a	20.02±1.15a
	P2	4.40±0.060ab	1.70±0.115cde	301±5.5f	10.6±0.55c	174±1.67ab	22.48±1.00ab
	P3	5.31±0.0404d	1.40±0.057bcd	276±6.1e	9.70±0.519c	155±2.10b	29.74±2.52b
Ultisol	P4	4.22±0.058a	1.20±0.057bc	210±4.9cd	62.1±0.55g	195±2.06c	21.20±1.86a
	P5	4.33±0.036a	2.00±0.288e	216.30±4.0d	9.20±0.529bc	205±4.0cd	24.46±2.08ab
	P6	4.56±0.066bc	1.00±0.057ab	176±5.7b	7.60±0.321ab	108±1.334cd	20.26±0.58a
Inceptisol	P7	4.72±0.048c	1.90±0.057de	173±1.8b	9.73±0.218c	149±2.36cd	18.68±1.53a
	P8	6.11±0.057f	1.60±0.115cde	229±5.5d	16.9±0.32d	159±0.58de	26.67±1.53ab
	P9	4.62±0.034c	1.00±0.115ab	191±6.2bc	6.60±0.321a	124±0.50e	24.2±2.34ab
Entisol	P10	5.81±0.049e	1.20±0.057bc	226±6.1d	20.8±0.21e	126.0±1.53f	26.0±1.15ab
	P11	7.74±0.050h	0.90±0.057ab	122±5.9a	24.6±0.53f	115±2.51g	20.5±0.90a
	P12	6.44±0.057g	0.50±0.057a	138±5.8a	23.2±0.46f	116.5±2.00g	24.1±1.53ab

Values ± means, n = 3; Within a column (parameter) values followed by different letters are statistically significant as determined by one-way ANOVA incorporating Tukey's HSD test for multiple pair-wise comparisons among means.

SOC – soil organic carbon, Avl.N – soil available N, Avl.P – soil available P, Avl.K – soil available K, DTPA-Fe – soil available Fe

(Table 4.2 continued.....)

Table 4.2. Chemical properties of surface soils of twelve soil profiles representing four dominant soil orders of NE India

Soil Order	Profile	Ex.Al (meq 100 $^{-1}$ soil)	RS.Al (mg kg^{-1} soil)	Ex.Ca+Mg [cmol (P^{+}) kg^{-1} soil]	CEC [cmol (P^{+}) kg^{-1} soil]	BS (%)
Alfisol	P1	0.12±0.011ab	18.8±2.32a	8.10±0.173d	15.6±.46de	55.3±1.52f
	P2	3.59±0.056g	287±5.8b	4.60±0.289b	11.8±0.52bd	42.5±1.66e
	P3	1.06±0.036e	354±2.3d	2.80±0.231a	8.00±0.867ab	39.9±2.51de
Ultisol	P4	0.46±0.022d	34.6±1.73a	2.10±0.231a	8.90±0.923ab	28.9±1.70bc
	P5	1.06±0.030e	384±5.8e	1.80±0.115a	14.2±1.27cd	16.2±1.13a
	P6	2.81±0.100f	318±5.7c	1.70±0.0578a	6.60±0.058a	30.2±2.86bc
Inceptisol	P7	0.93±0.055e	302±5.8b	2.90±0.231a	11.4±1.46bc	28.7±1.61bc
	P8	0.34±0.016cd	24.2±2.08a	7.60±0.115cd	23.6±0.73f	33.9±0.61cd
	P9	1.03±0.010e	377±5.0e	2.10±0.173a	9.92±0.290ab	24.4±1.33b
Entisol	P10	0.28±0.010bc	22.6±1.53a	6.80±0.289c	16.1±0.58de	44.4±0.45e
	P11	0.12±0.003ab	19.6±1.00a	12.9±0.72f	18.7±0.68e	71.0±1.22g
	P12	0.09±0.003a	18.4±1.53a	9.30±0.289e	18.4±1.26e	52.3±0.41f

Values ± means, n = 3; Within a column (parameter) values followed by different letters are statistically significant as determined by one-way ANOVA incorporating Tukey's HSD test for multiple pair-wise comparisons among means.

Ex.Al – exchangeable aluminium, RSA – readily soluble aluminium, Ex.Ca+Mg – exchangeable ca+Mg, CEC – cation exchange capacity and BS – base saturation

4.2. Incubation experiment-I on phosphate fixation capacity

Four soil orders comprising of twelve soil profiles (P1 to P12) were used for the incubation experiment under objective 1. Results are presented based on the incubation experiment-I (P levels 0, 25, 50, 100, 200, 300, 400, 500, 600 and 700 ppm for 24 h equilibration with 0.01 M $CaCl_2$) and subsequent determination of soil solution P concentration.

4.2.1. The PFC of *Alfisol*

Values of maximum quantity of applied P fixed and % P fixed ranged from 223.3 to 470.7 µg P g^{-1} soil and 74.4 to 94.1%, respectively for *Alfisol* profiles P1, P2 and P3 (Fig. 4.1). The P dose at which maximum PFC value obtained for P1, P2 and P3 profiles were 300, 500 and 500 µg P g^{-1} soil, respectively (Fig. 4.1).

4.2.2. The PFC of *Ultisol*

Values of maximum quantity of applied P fixed and % P fixed ranged from 102.8 to 576.7 µg P g^{-1} soil and 51.4 to 96.1%, respectively for *Ultisol* profiles P4, P5 and P6 (Fig. 4.2). The P dose at which maximum PFC value obtained for P4, P5 and P6 profiles were 200, 600 and 400 µg P g^{-1} soil, respectively (Fig. 4.2).

4.2.3. The PFC of *Inceptisol*

Values of maximum quantity of applied P fixed and % P fixed ranged from 106.7 to 277.3 µg P g^{-1} soil and 53.4 to 92.4%, respectively for *Inceptisol* profiles P7, P8 and P9 (Fig. 4.3). The P dose at which maximum PFC value obtained for P7, P8 and P9 profiles were 300, 200 and 300 µg P g^{-1} soil, respectively (Fig. 4.3).

4.2.4. The PFC of *Entisol*

Values of maximum quantity of applied P fixed and % P fixed ranged from 66.6 to 92.3 µg P g^{-1} soil and 33.3 to 68.2%, respectively for *Entisol* profiles P10, P11 and P12 (Fig. 4.4). The P dose at which maximum PFC value obtained for P10, P11 and P12 profiles were 100, 200 and 200 µg P g^{-1} soil, respectively (Fig. 4.4).

Table 4.3. The maximum quantity of applied P fixed at the P dose where the highest % P fixed in soils of four dominant soil orders

Profile	Soil order	Maximum quantity of applied P fixed (µg P g^{-1} soil)	P fixed (%)	P dose at which max. PFC point achieved (µg P g^{-1} soil)
P1	***Alfisol***	223.3±1.7c	74.4	300
P2		425.6±2.9g	85.1	500
P3		470.7±5.8h	94.1	500
P4	***Ultisol***	102.8±3.1b	51.4	200
P5		576.7±4.6i	96.1	600
P6		337.0±4.0f	84.3	400
P7	***Inceptisol***	277.3±5.9e	92.4	300
P8		106.7±4.0b	53.4	200
P9		230.6±4.0d	76.9	300
P10	***Entisol***	68.2±2.3a	68.2	100
P11		92.3±2.3b	46.2	200
P12		66.6±2.3a	33.3	200

Values ± means, n = 3; Within a column (parameter) values differed significantly are followed by different letters as determined by one-way ANOVA incorporating Tukey's HSD test for multiple pair-wise comparisons among means.

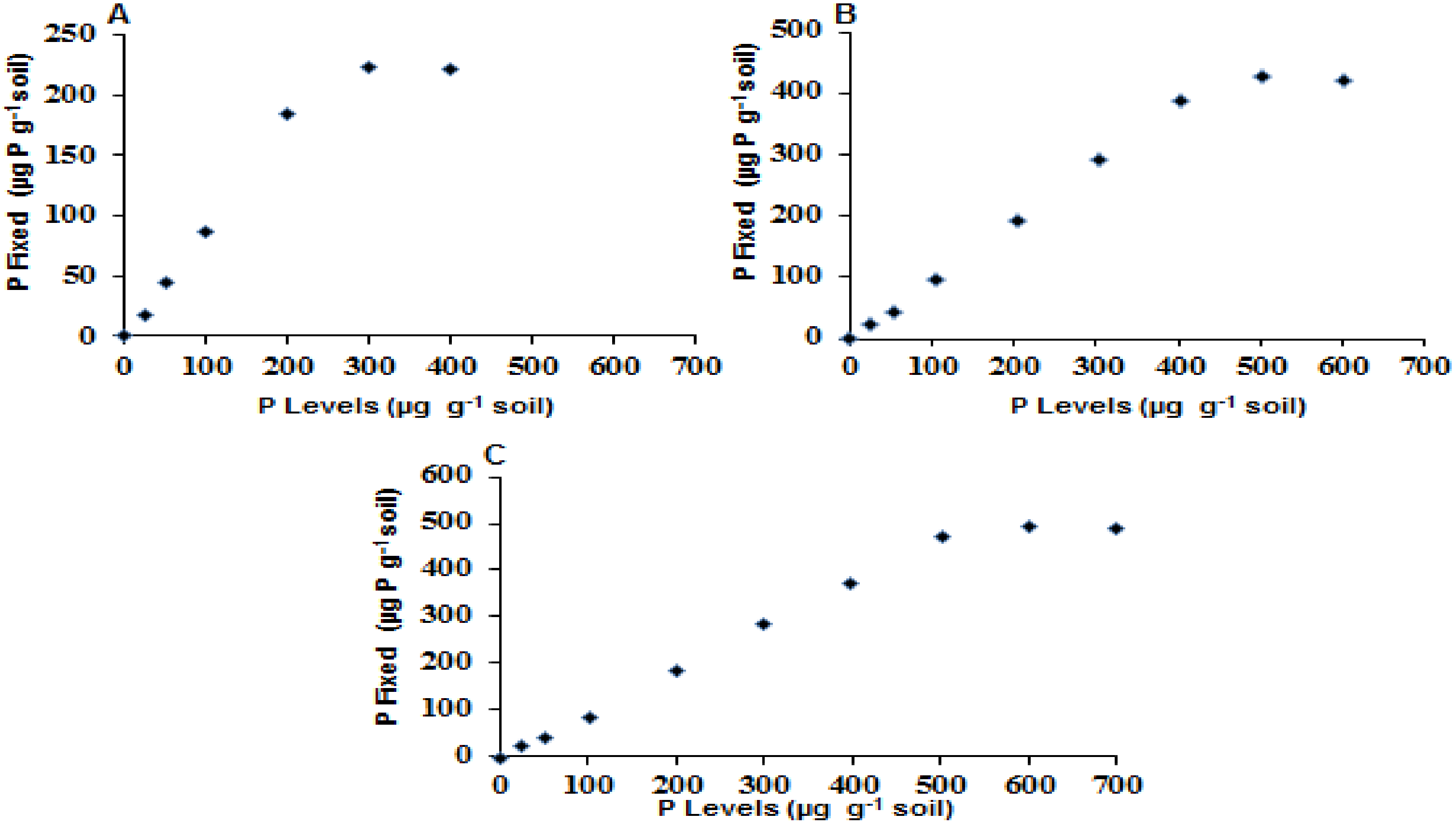


Fig. 4.1. Phosphate fixation capacity curves of *Alfisols* representing by 3 soil profiles (A) Profile 1, (B) Profile 2, and (C) Profile 3.

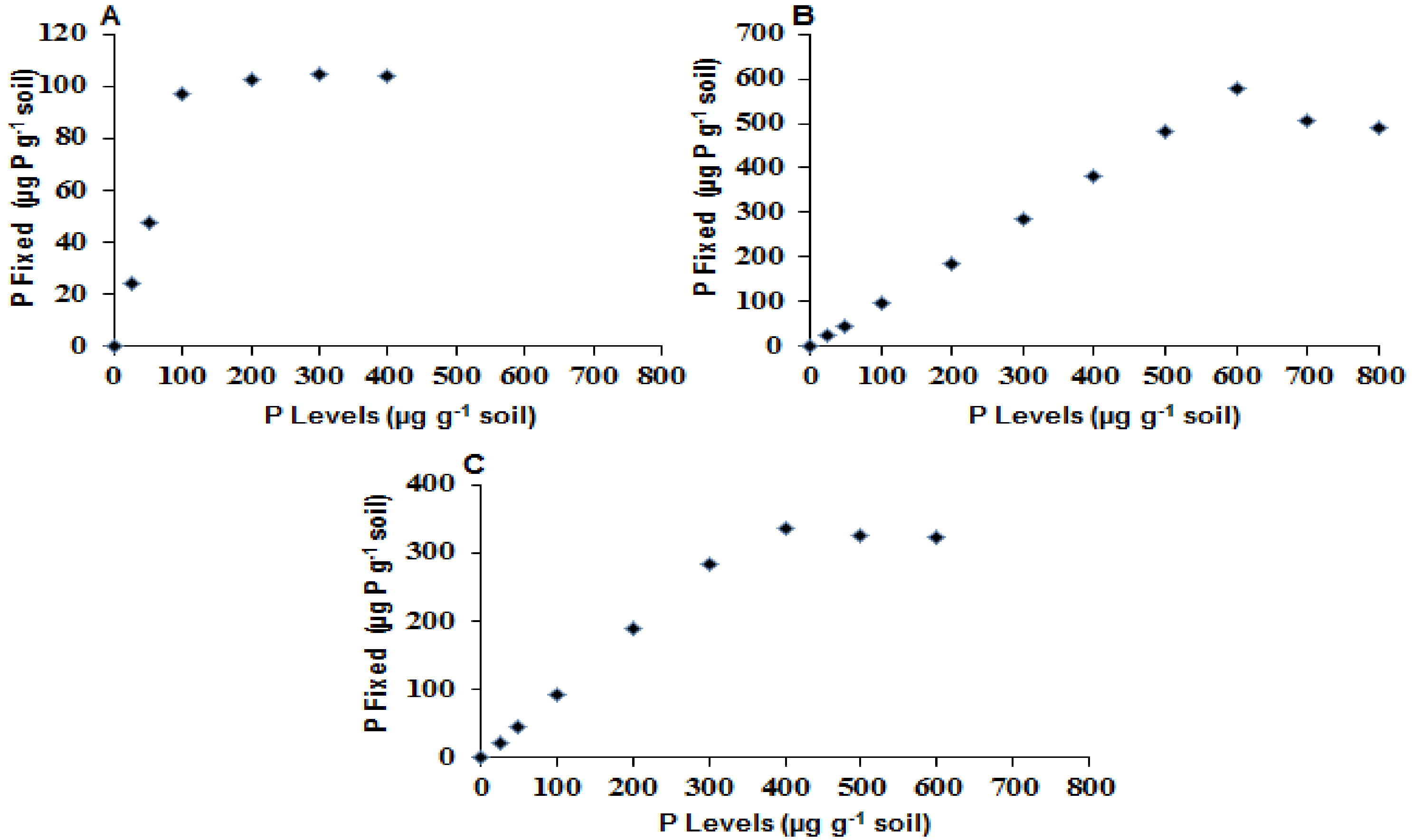


Fig. 4.2. Phosphate fixation capacity curves of *Ultisols* representing by 3 soil profiles (A) Profile 4, (B) Profile 5, and (C) Profile 6.

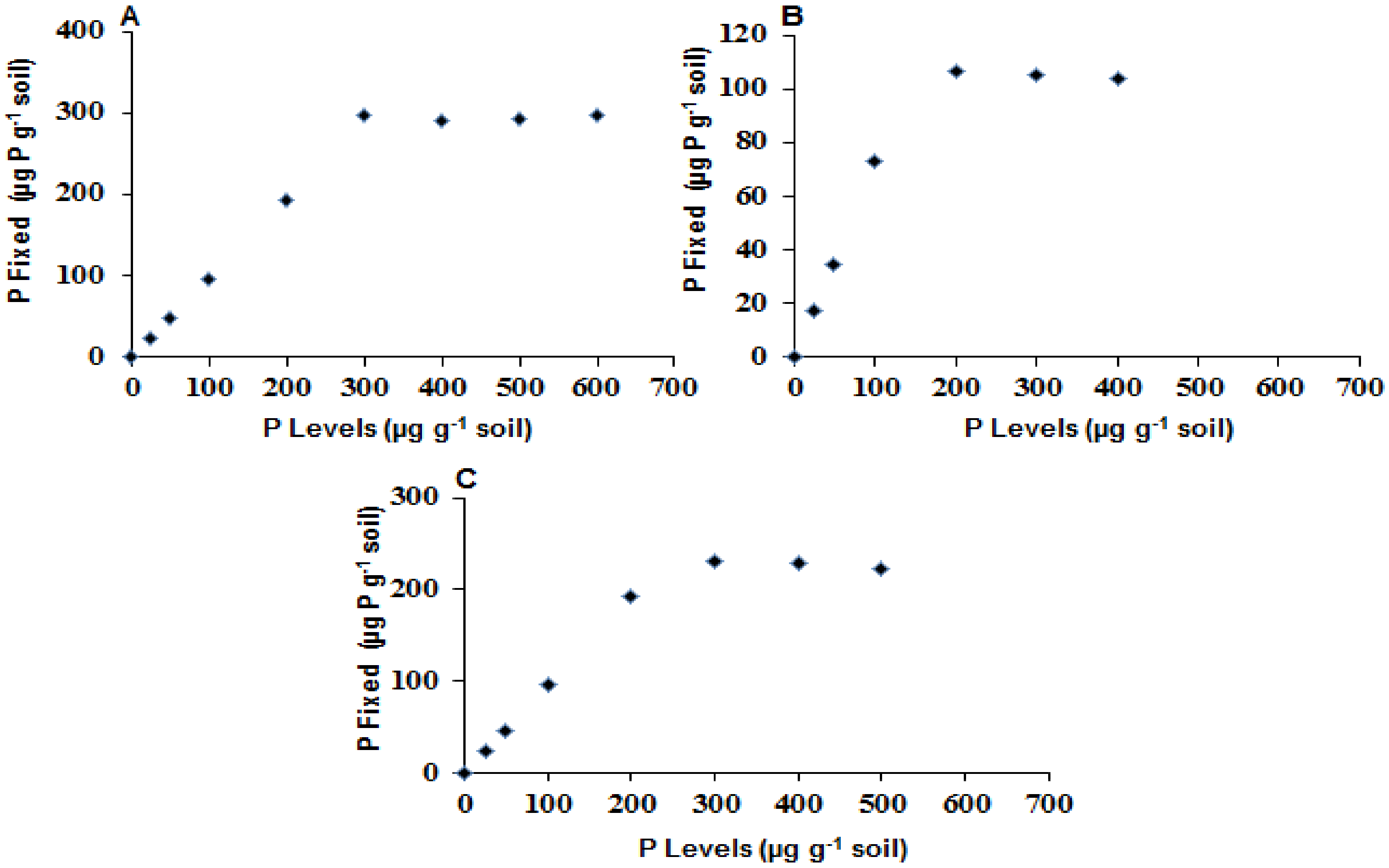


Fig. 4.3. Phosphate fixation capacity curves of *Inceptisols* representing by 3 soil profiles (A) Profile 7, (B) Profile 8, and (C) Profile 9.

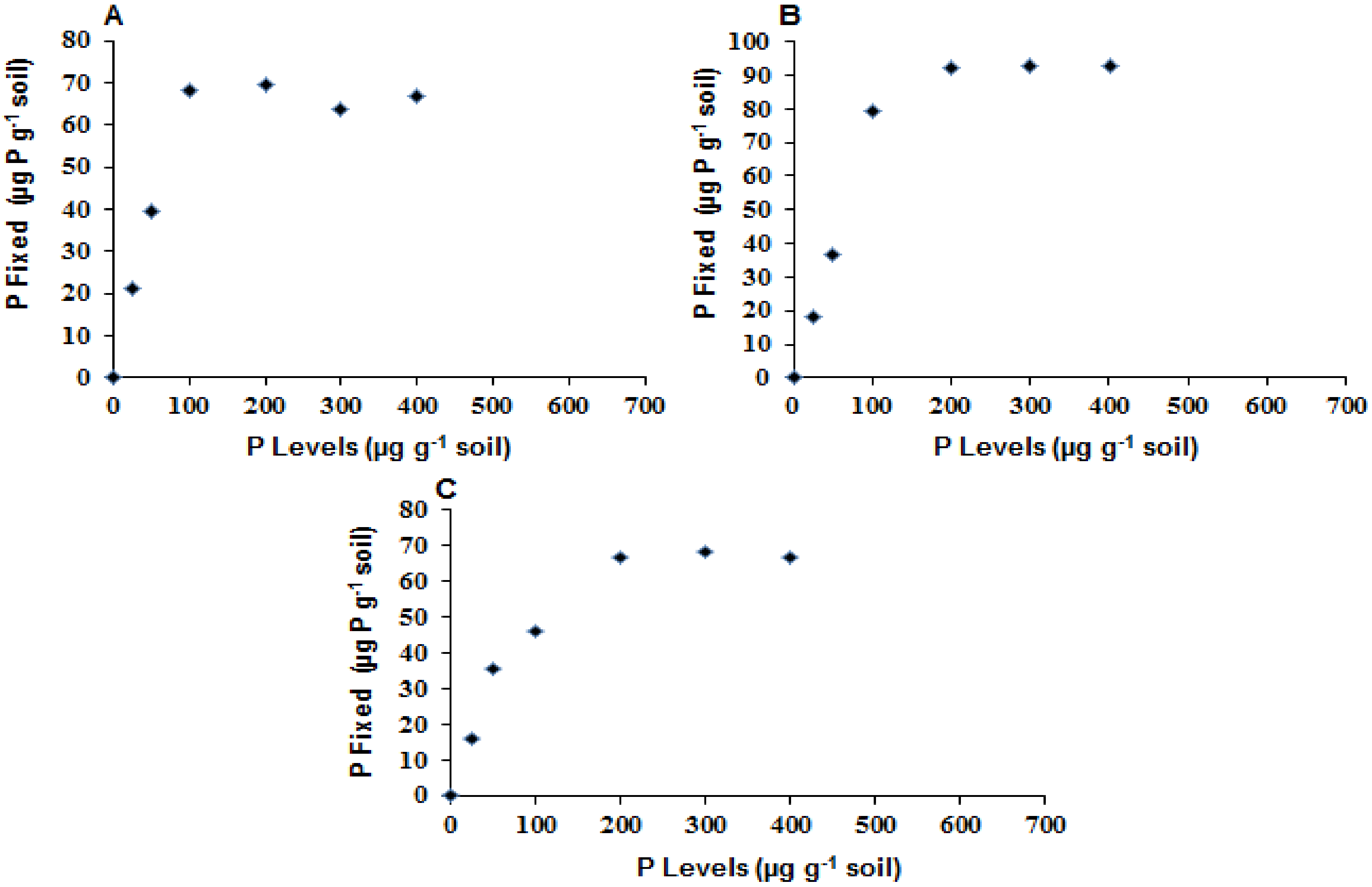


Fig. 4.4. Phosphate fixation capacity curves of *Entisols* representing by 3 soil profiles (A) Profile 10, (B) Profile 11, and (C) Profile 12.

4.2.5. The comparative PFC among soil orders

The mean values for the maximum quantity of applied P fixed (µg P g^{-1} soil) differed significantly among four soil orders ($P < 0.05$, one way ANOVA) and the higher values were in order of *Ultisol* (457) > *Alfisol* (373) > *Inceptisol* (212) > *Entisol* (76) (Fig. 4.5). The values of percent P fixed also differed significantly among soil four orders ($P < 0.05$, one way ANOVA) and the higher values were in order of *Ultisol* (90.2) > *Alfisol* (84.5) > *Inceptisol* (74.2) > *Entisol* (49.2) (Fig. 4.5).

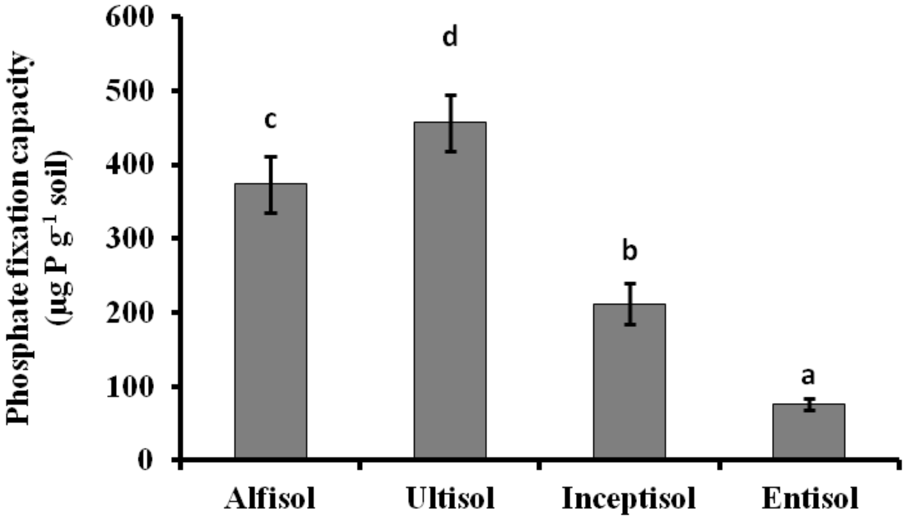


Fig. 4.5. Comparative phosphate fixation capacity among four dominant soil orders of NE India. Each bar represents mean±SD, n = 9. Values (column) differed significantly are followed by different letters as determined by one-way ANOVA incorporating Tukey's HSD test for multiple pair-wise comparisons among means.

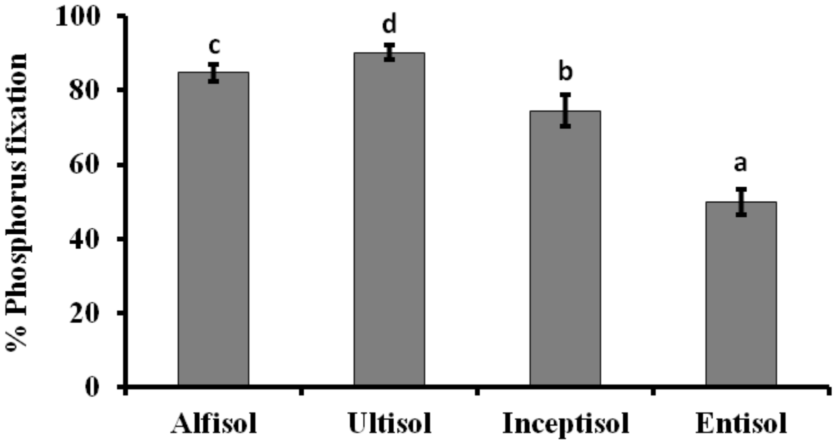


Fig. 4.6. Comparative percent P fixed among four dominant soil orders of NE India. Each bar represents mean±SD, n = 9. Values (column) differed significantly are followed by different letters as determined by one-way ANOVA incorporating Tukey's HSD test for multiple pair-wise comparisons among means.

4.3. Incubation experiment-II on phosphate release pattern

In the laboratory soil column study, six (6) treatments on P sources imposed were: (1) control (no P addition), (2) phosphate solubilizing bacteria (PSB), (3) organic manure (OM), (4) rock phosphate (RP), (5) single superphosphate (SSP) and (6) RP+PSB. The temporal PRP was studied in soil columns by extracting solution phase P using 5 ml distilled water at 6 time points (0, 5, 15, 30, 45, 60 days of incubation).

4.3.1. The PRP of *Alfisols* as influenced by P sources

The quantity of P released at different time points (0, 5, 15, 30, 45 and 60 days of incubation) by soils of 3 *Alfisol* profiles are presented in Figure 4.7 to 4.9. The extent of P_i released due to addition of different P sources were significantly higher at time point 5 days and onward compared to that in no input control (Fig. 4.7 to 4.9). The maximum quantity of P_i released was attained within 7 days of incubation of P1, P2 and P3 soils with SSP and then P_i released was gradually decreased with progression of time till 60 days. Except SSP, the rest of the P sources (PSB, OM, RP and RP+PSB) could able to release higher quantity of P_i at the later stages of incubation (between 45 to 60 days) indicating a gradual increase in quantity of P_i released from the start of incubation to till 60 days. Among OM, PSB, RP and RP+PSB applications, the combined application of RP+PSB could released higher quantity of P_i during incubation period 15 to 60 days (Fig. 4.7 to 4.9). Among 3 *Alfisol* profiles, soils of P2 and P3 showed relative higher P_i release capacity in SSP alone treatment during 0 to 30 days of incubation except P1 soil (0-15 days) as compared to other P sources. The marginal means of P_i released across time points during the incubation period (0-60 days) differed significantly among P sources and higher quantity of P_i released was in order of RP+PSB > PSB > OM > SSP > RP > control (P <0.05, as determined by repeated measures-ANOVA; Fig. 4.7 to 4.9) .

	Marginal mean of P_i released (µg g^{-1} soil)
Control	1.14a
PSB	1.75d
OM	1.70d
RP	1.48b
SSP	1.62c
RP+PSB	1.97e

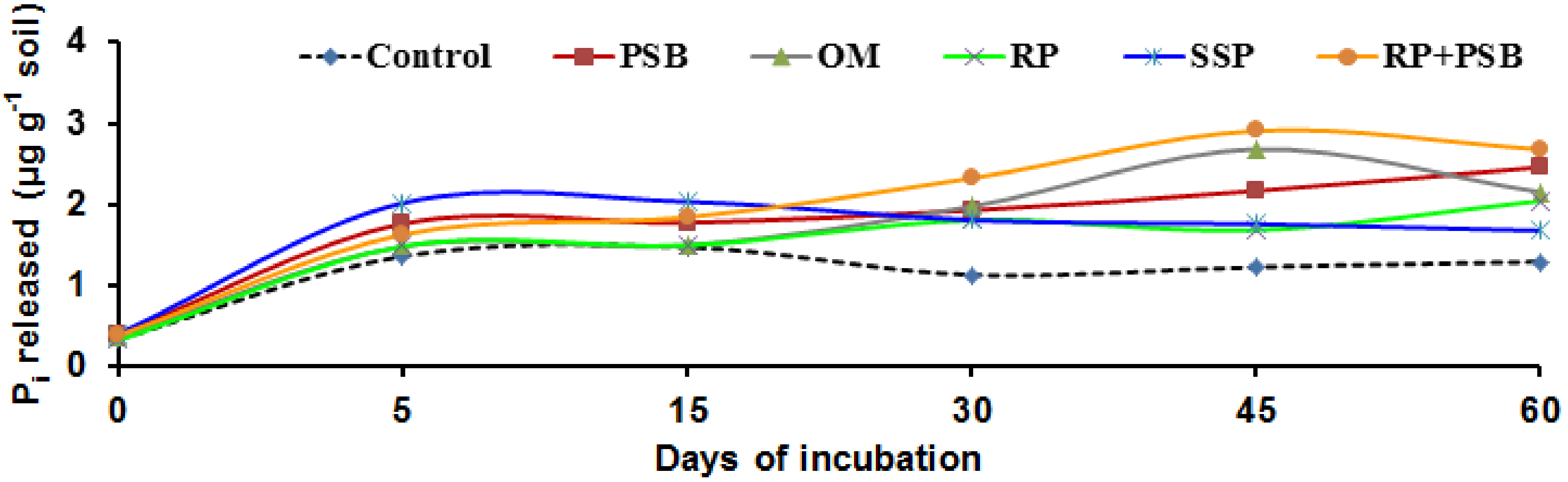


Fig. 4.7. Influence of phosphorus sources on phosphate release for profile 1. The repeated measures-ANOVA was performed to determine the significant difference among the derived marginal mean of phosphate released in different treatments considering different time points as replicate analysis. Values (marginal means) with different letters indicate statistically significant difference at $P<0.05$ using Tukey's honestly Significance Difference for multiple pair-wise comparisons.

	Marginal mean of P_i released ($\mu g\ g^{-1}$ soil)
Control	0.98a
PSB	1.38b
OM	1.75c
RP	1.73c
SSP	1.92d
RP+PSB	2.05e

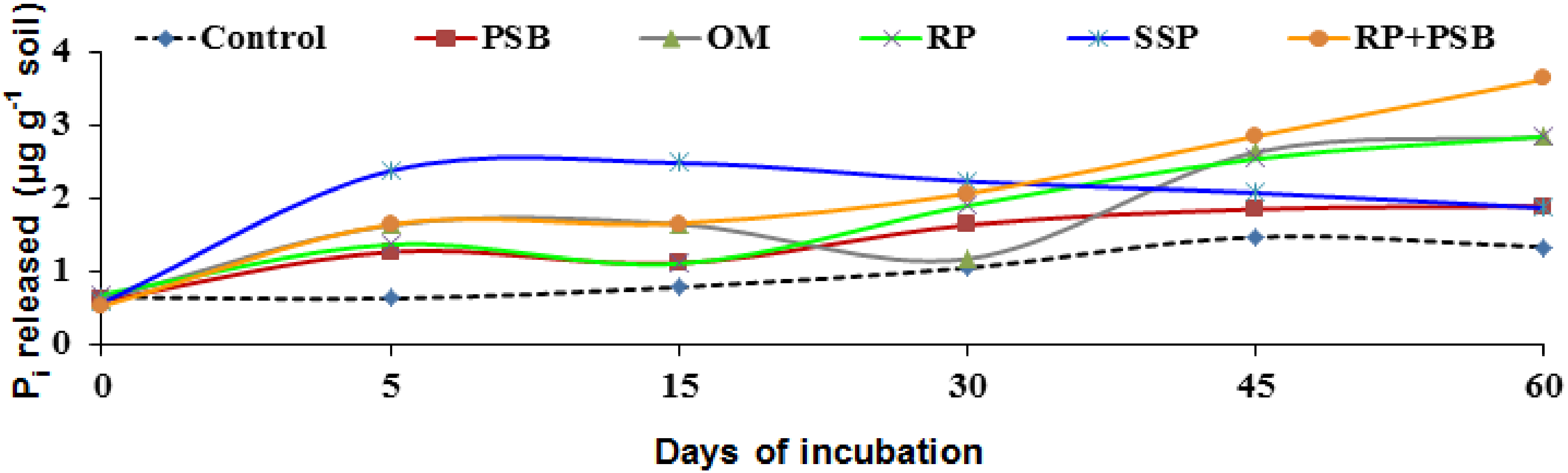


Fig. 4.8. Influence of phosphorus sources on phosphate release for profile 2. The repeated measures-ANOVA was performed to determine the significant difference among the derived marginal mean of phosphate released in different treatments considering different time points as replicate analysis. Values (marginal means) with different letters indicate statistically significant difference at P<0.05 using Tukey's honestly Significance Difference for multiple pair-wise comparisons.

	Marginal mean of P_i released (µg g^{-1} soil)
Control	0.76a
PSB	1.25c
OM	1.11b
RP	1.31c
SSP	1.71e
RP+PSB	1.56d

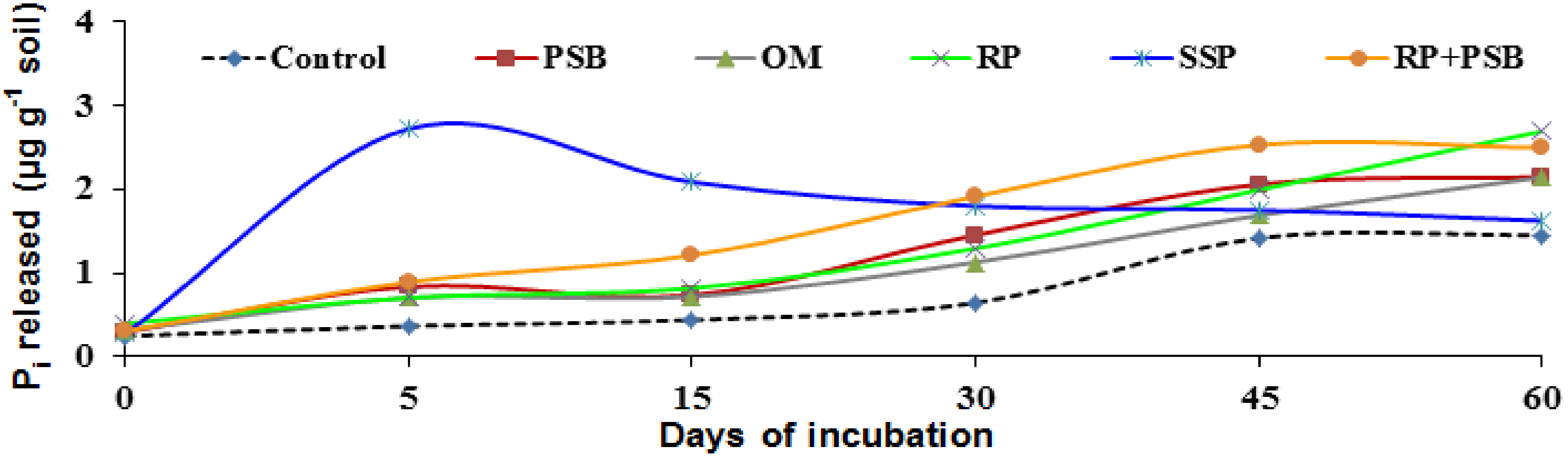


Fig. 4.9. Influence of phosphorus sources on phosphate release for profile 3. The repeated measures-ANOVA was performed to determine the significant difference among the derived marginal mean of phosphate released in different treatments considering different time points as replicate analysis. Values (marginal means) with different letters indicate statistically significant difference at $P<0.05$ using Tukey's honestly Significance Difference for multiple pair-wise comparisons.

4.3.2. The PRP of *Ultisols* as influenced by P sources

The quantity of P released at different time points (0, 5, 15, 30, 45 and 60 days of incubation) by soils of 3 *Ultisol* profiles are presented in Figure 4.10 to 4.12. The extent of P_i released due to addition of different P sources were significantly higher at time points 5 days and onwards compared to that in no input control (Fig. 4.10 to 4.12). The maximum quantity of P_i released was attained within 7 days of incubation of P5 and P6 soils with SSP and within 15 days of incubation of P4 soils with SSP and then P_i released was gradually decreased with progression of time till 60 days. In comparison to SSP, the rest of the P sources (PSB, OM, RP and RP+PSB) could able to release higher quantity of P_i at the later stages of incubation (staring from 15 days onwards in case of P5 and P6 soils and starting from 30 days onwards in case of P4 soil) indicating a gradual increase in quantity of P_i released from the start of incubation to till 60 days. Among OM, PSB, RP and RP+PSB applications, the combined application of RP+PSB could released higher quantity of P_i during incubation period 15 to 60 days (Fig. 4.10 to 4.12). Among 3 *Ultisol* profiles, soils of P5 and P6 showed relative higher P_i release capacity in SSP alone treatment during 0 to 15 days of incubation except P4 soils (0-30 days) as compared to other P sources. The marginal means of P_i released across time points during the incubation period (0-60 days) differed significantly among P sources and higher quantity of P_i released for P5 and P6 soils was in order of RP+PSB > RP > OM > PSB ~ SSP > control and for P4 soils was in order of SSP > RP+PSB ~ PSB > RP > OM > control (P <0.05, as determined by repeated measures-ANOVA; Fig. 4.10 to 4.12).

	Marginal mean of P_i released (µg g^{-1} soil)
Control	1.76a
PSB	2.52d
OM	2.02b
RP	2.38c
SSP	2.69e
RP+PSB	2.51d

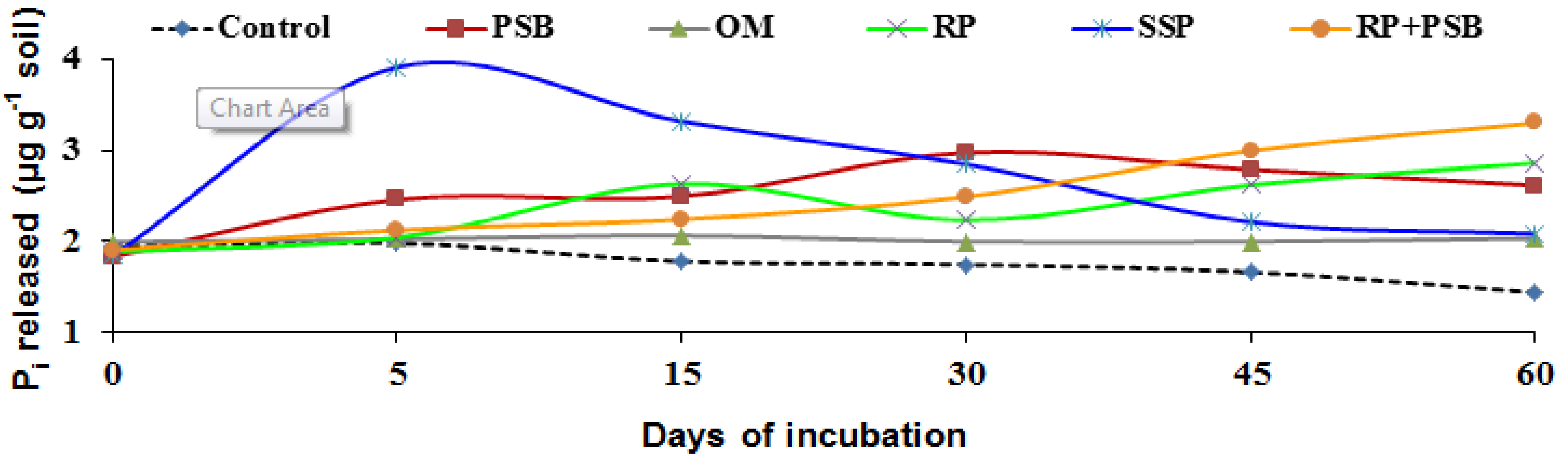


Fig. 4.10. Influence of phosphorus sources on phosphate release for profile 4. The repeated measures-ANOVA was performed to determine the significant difference among the derived marginal mean of phosphate released in different treatments considering different time points as replicate analysis. Values (marginal means) with different letters indicate statistically significant difference at P<0.05 using Tukey's honestly Significance Difference for multiple pair-wise comparisons.

	Marginal mean of P_i released ($\mu g\ g^{-1}$ soil)
Control	1.03a
PSB	1.87b
OM	1.93bc
RP	2.03c
SSP	1.85b
RP+PSB	2.37d

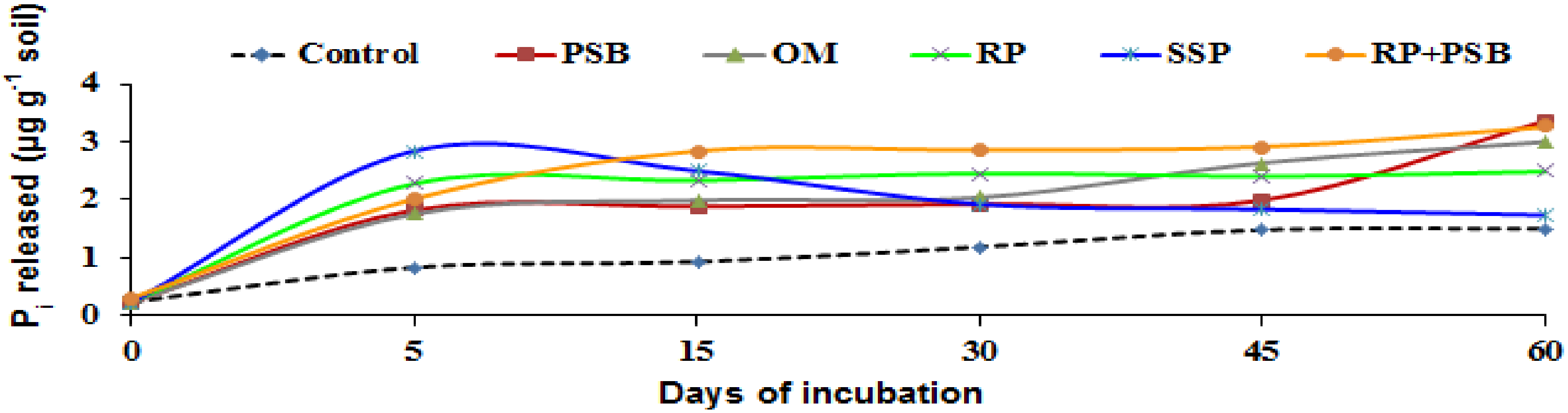


Fig. 4.11. Influence of phosphorus sources on phosphate release for profile 5. The repeated measures-ANOVA was performed to determine the significant difference among the derived marginal mean of phosphate released in different treatments considering different time points as replicate analysis. Values (marginal means) with different letters indicate statistically significant difference at $P<0.05$ using Tukey’s honestly Significance Difference for multiple pair-wise comparisons.

	Marginal mean of P_i released (µg g^{-1} soil).
Control	1.61a
PSB	2.34c
OM	1.98b
RP	2.07b
SSP	2.25c
RP+PSB	2.52d

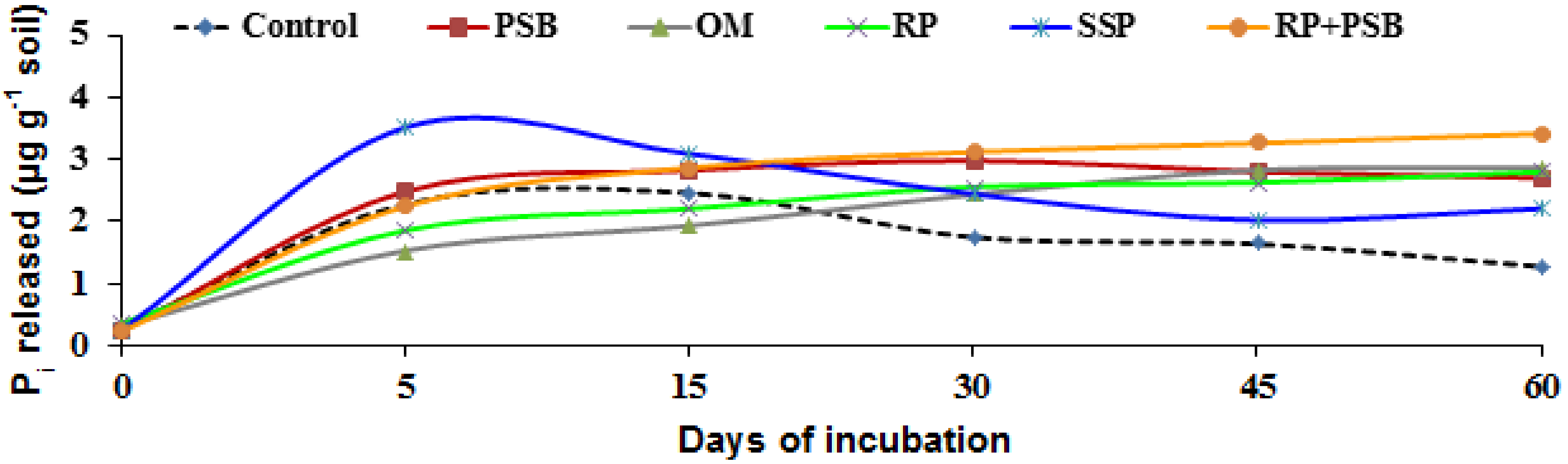


Fig. 4.12. Influence of phosphorus sources on phosphate release for profile 6. The repeated measures-ANOVA was performed to determine the significant difference among the derived marginal mean of phosphate released in different treatments considering different time points as replicate analysis. Values (marginal means) with different letters indicate statistically significant difference at $P<0.05$ using Tukey's honestly Significance Difference for multiple pair-wise comparisons.

4.3.3. The PRP of *Inceptisols* as influenced by P sources

The quantity of P released at different time points (0, 5, 15, 30, 45 and 60 days of incubation) by soils of 3 *Inceptisol* profiles are presented in Figure 4.13 to 4.15. The extent of P_i released due to addition of different P sources were significantly higher in each time point compared to that in no input control (Fig. 4.13 to 4.15). The maximum quantity of P_i released was attained within 7 days of incubation of P7, P8 and P9 soils with SSP and then P_i released was gradually decreased with the progression of time till 60 days. In comparison to SSP source, addition of PSB, OM and RP+PSB sources in P7 soils could able to release higher quantity of P_i from 15 days onwards, with exception of RP from 30 days onwards, indicating a gradual increase in quantity of P_i released from the start of incubation to till 60 days. Among OM, PSB, RP and RP+PSB applications, the combined application of RP+PSB and RP alone could released higher quantity of P_i during 45 to 60 days incubation as compared to PSB and OM sources (Fig. 4.13 to 4.15). In comparison to SSP source, addition of PSB and RP+PSB sources in P8 soils could release higher quantity of P_i from 15 days onwards to 60 days of incubation. The marginal means of P_i released across time points during the incubation period (0-60 days) differed significantly among P sources and higher quantity of P_i released was in order of RP+PSB > PSB > OM ~ SSP ~ RP > control for P7 soils, RP+PSB ~ PSB > SSP > OM > RP > control for P8 soil and SSP ~ PSB ~ OM > RP > RP+PSB > control for P9 soils ($P < 0.05$, as determined by repeated measures-ANOVA; Fig. 4.13 to 4.15).

	Marginal mean of P_i released ($\mu g\ g^{-1}$ soil)
Control	1.03a
PSB	2.31d
OM	2.15c
RP	2.04b
SSP	2.07bc
RP+PSB	2.49e

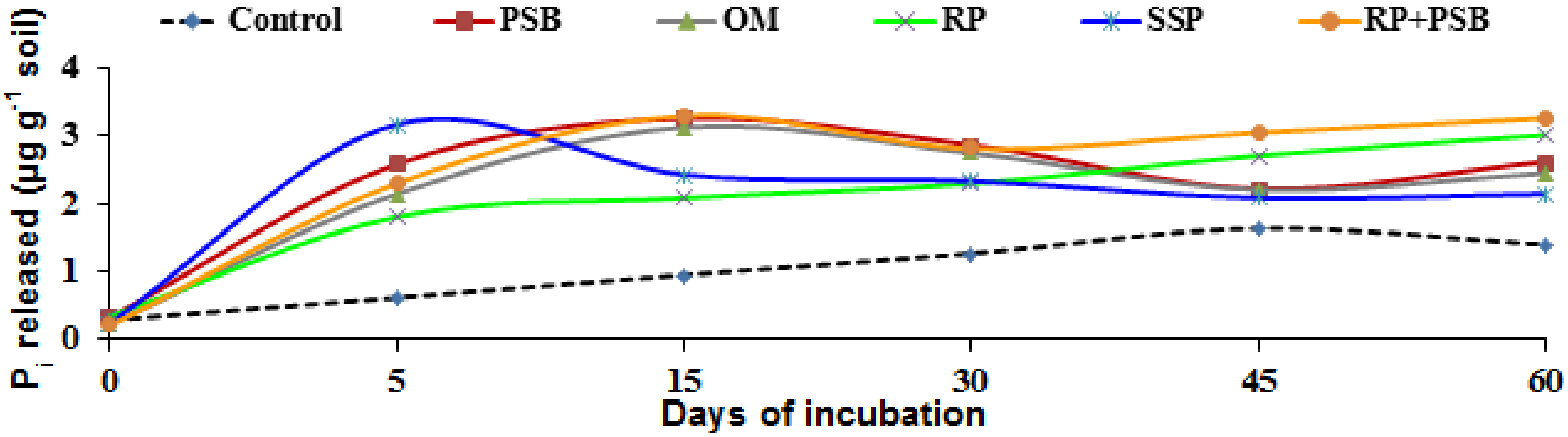


Fig. 4.13. Influence of phosphorus sources on phosphate release for profile 7. The repeated measures-ANOVA was performed to determine the significant difference among the derived marginal mean of phosphate released in different treatments considering different time points as replicate analysis. Values (marginal means) with different letters indicate statistically significant difference at P<0.05 using Tukey's honestly Significance Difference for multiple pair-wise comparisons.

	Marginal mean of P_i released (µg g^{-1} soil)
Control	1.03a
PSB	2.18e
OM	1.73c
RP	1.67b
SSP	1.90d
RP+PSB	2.19e

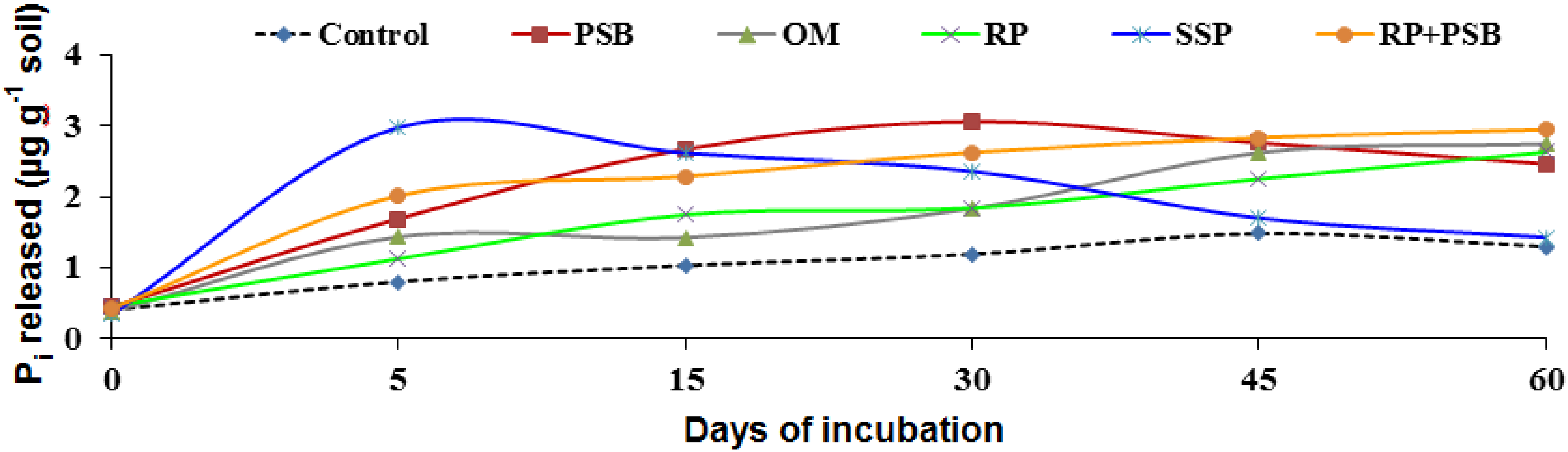


Fig. 4.14. Influence of phosphorus sources on phosphate release for profile 8. The repeated measures-ANOVA was performed to determine the significant difference among the derived marginal mean of phosphate released in different treatments considering different time points as replicate analysis. Values (marginal means) with different letters indicate statistically significant difference at P<0.05 using Tukey's honestly Significance Difference for multiple pair-wise comparisons.

	Marginal mean of P_i released (µg g^{-1} soil)
Control	1.26a
PSB	1.77cd
OM	1.73bcd
RP	1.68bc
SSP	1.82d
RP+PSB	1.66b

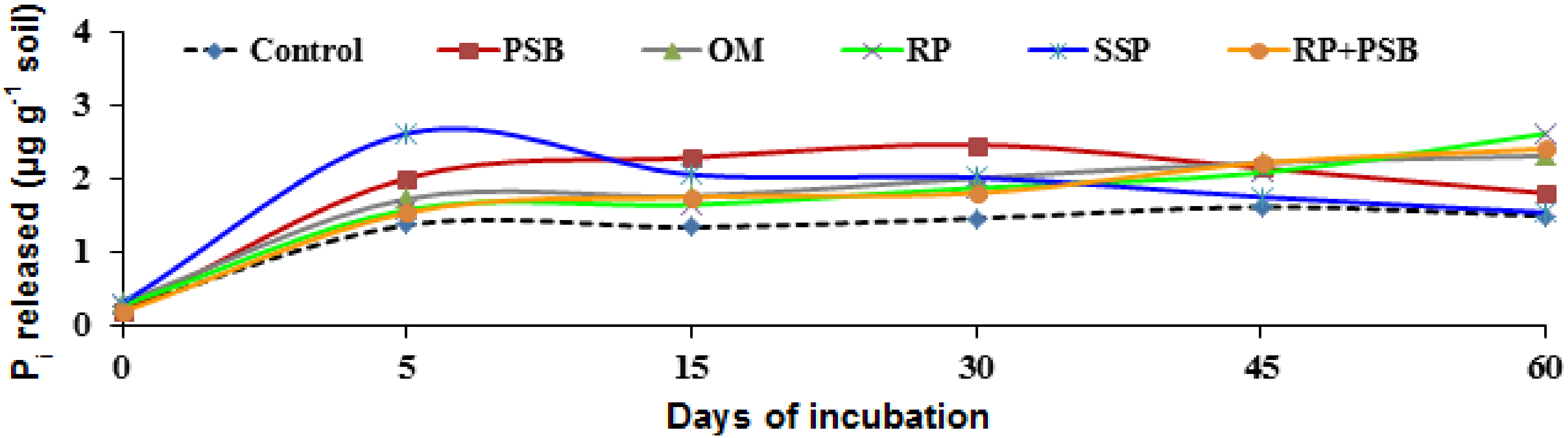


Fig. 4.15. Influence of phosphorus sources on phosphate release for profile 9. The repeated measures-ANOVA was performed to determine the significant difference among the derived marginal mean of phosphate released in different treatments considering different time points as replicate analysis. Values (marginal means) with different letters indicate statistically significant difference at $P<0.05$ using Tukey's honestly Significance Difference for multiple pair-wise comparisons.

4.3.4. The PRP of *Entisols* as influenced by P sources

The quantity of P released at different time points (0, 5, 15, 30, 45 and 60 days of incubation) by soils of 3 *Entisol* profiles are presented in Figure 4.16 to 4.18. The extent of P_i released due to addition of different P sources were significantly higher in each time point compared to that in no input control (Fig. 4.16 to 4.18). The maximum quantity of P_i released was attained within 7 days of incubation of P10, P11 and P12 soils with SSP and then P_i released was gradually decreased with progression of time till 60 days. In comparison to SSP, addition of PSB and PSB+RP sources in P10, P11 and P12 soils could release higher quantity of P_i at the later stages of incubation (between 30 to 60 days) indicating a gradual increase in quantity of P_i released from the start of incubation to till 60 days. Among OM, PSB, RP and RP+PSB applications, the combined application of RP+PSB could released higher quantity of P_i during incubation period 15 to 60 days (Fig. 4.16 to 4.18). The marginal means of P_i released across time points during the incubation period (0-60 days) differed significantly among P sources and higher quantity of P_i released was in order of RP+PSB ~ SSP > PSB > OM ~ RP > control for P10 soil, RP+PSB ~ PSB ~ SSP ~ OM > RP > control for P11 soil and RP+PSB > SSP ~ RP ~ PSB > OM > control for P12 soil (*P* <0.05, as determined by repeated measures-ANOVA; Fig. 4.16 to 4.18).

	Marginal mean of P_i released ($\mu g\ g^{-1}$ soil)
Control	1.34a
PSB	2.08c
OM	1.78b
RP	1.71b
SSP	2.22cd
RP+PSB	2.29d

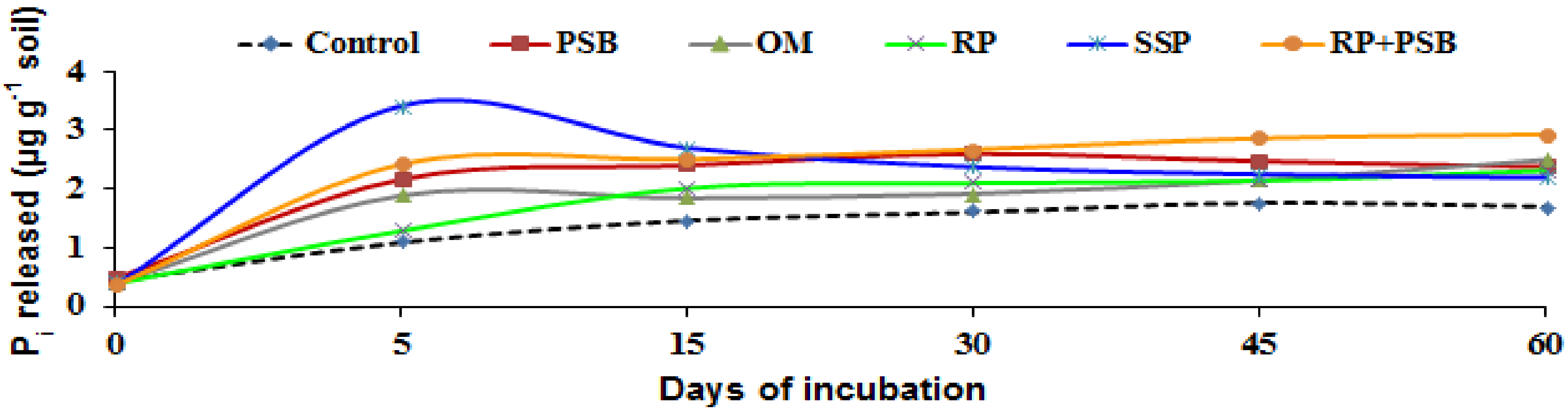


Fig. 4.16. Influence of phosphorus sources on phosphate release for profile 10. The repeated measures-ANOVA was performed to determine the significant difference among the derived marginal mean of phosphate released in different treatments considering different time points as replicate analysis. Values (marginal means) with different letters indicate statistically significant difference at P<0.05 using Tukey's honestly Significance Difference for multiple pair-wise comparisons.

	Marginal mean of P_i released ($\mu g\ g^{-1}$ soil).
Control	1.16a
PSB	1.91bc
OM	1.88bc
RP	1.70b
SSP	1.89bc
RP+PSB	2.13c

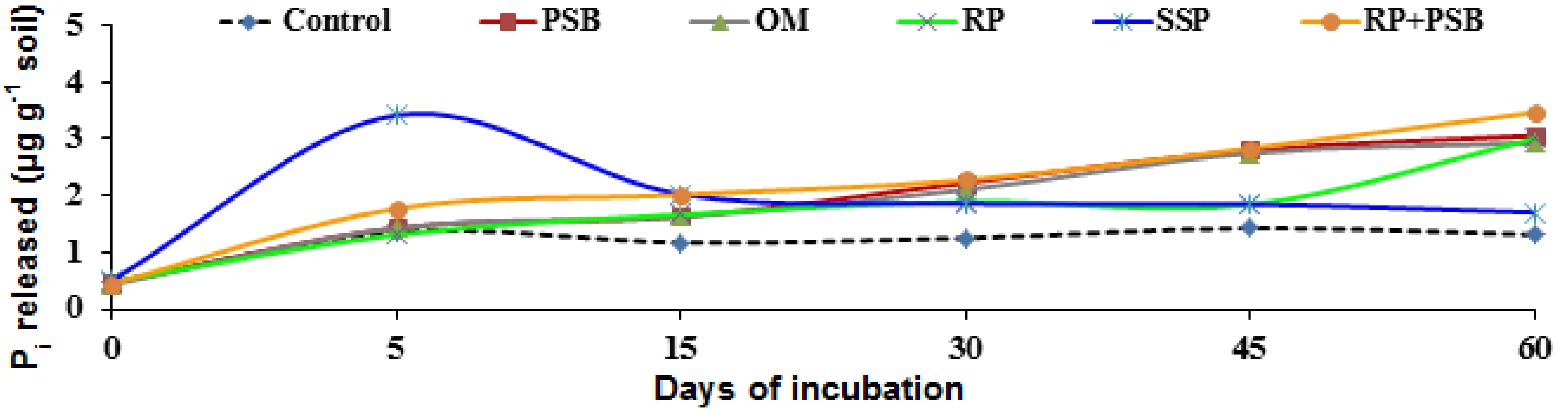


Fig. 4.17. Influence of phosphorus sources on phosphate release for profile 11. The repeated measures-ANOVA was performed to determine the significant difference among the derived marginal mean of phosphate released in different treatments considering different time points as replicate analysis. Values (marginal means) with different letters indicate statistically significant difference at $P<0.05$ using Tukey’s honestly Significance Difference for multiple pair-wise comparisons.

	Marginal mean of P_i released (µg g^{-1} soil).
Control	1.33a
PSB	2.09c
OM	1.87b
RP	2.11c
SSP	2.22c
RP+PSB	2.44d

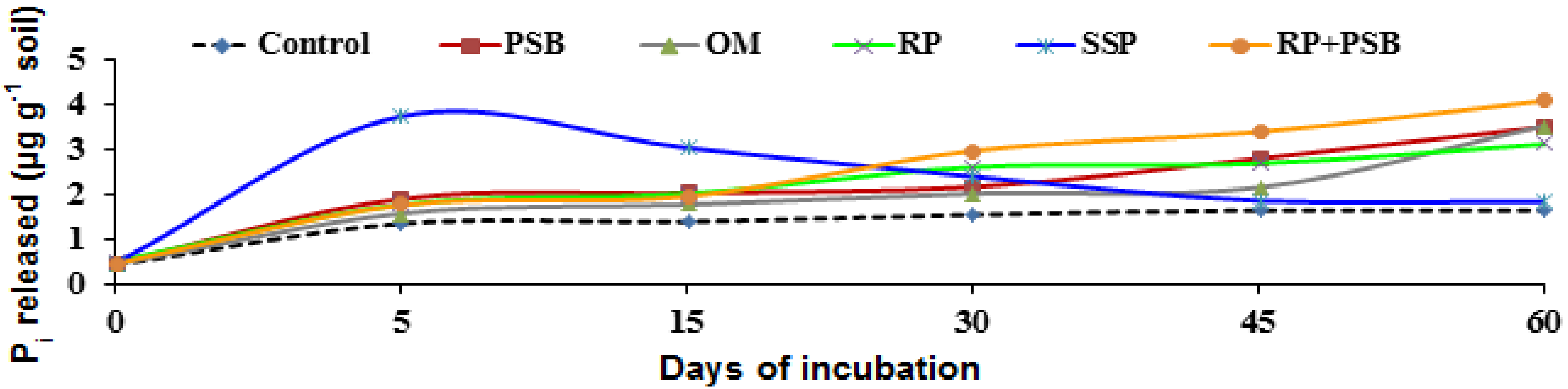


Fig. 4.18 Influence of phosphorus sources on phosphate release for profile 12. The repeated measures-ANOVA was performed to determine the significant difference among the derived marginal mean of phosphate released in different treatments considering different time points as replicate analysis. Values (marginal means) with different letters indicate statistically significant difference at $P<0.05$ using Tukey’s honestly Significance Difference for multiple pair-wise comparisons.

4.3.5. The comparative PRP among four soil orders

The marginal means of phosphate release capacity (µg P g^{-1} soil) differed significantly among four soil orders ($P < 0.05$, one way ANOVA) and the higher values were in order of *Ultisol* (1.38) > *Entisol* (1.28) > *Inceptisol* (1.11) > *Alfisol* (0.96) (Fig. 4.19). At 0, 5 and 15 days incubation time points, *Ultisol* released significant higher quantiry of P_i as compared to other 3 soil orders and the quantity of P_i released by *Alfisol, Inceptisol* and *Entisol* were comparable within 15 days of incubation (Fig. 4.20). Beyond 15 days of incubation, the quantity of PR in *Ultisol, Inceptisol* and *Entisol* were comparable and significantly higher than that in *Alfisol* (Fig.4.20).

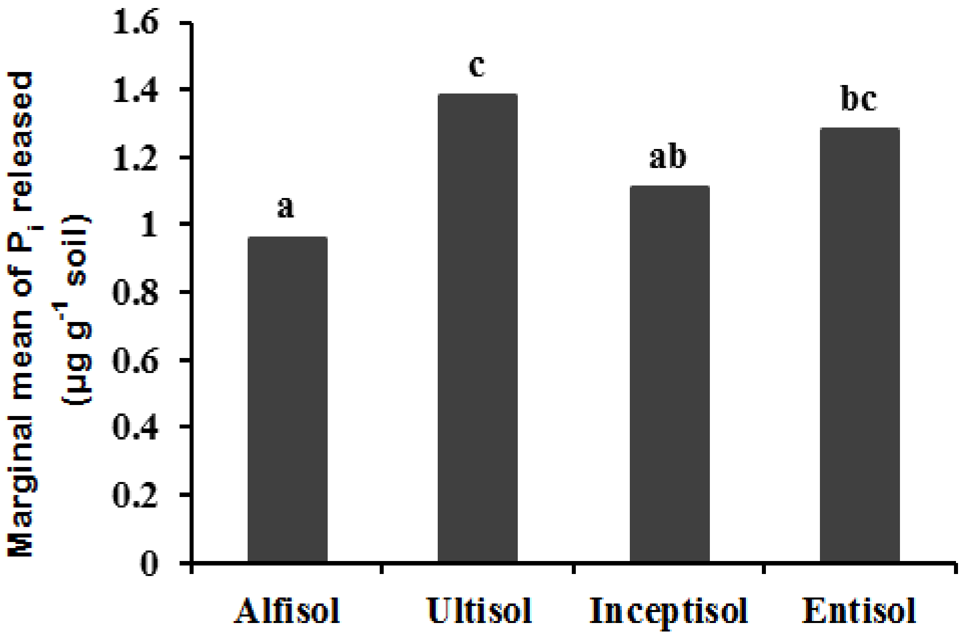


Fig. 4.19. Comparative phosphate release capacity of surface soils four dominant soil orders during laboratory incubation study. Each column represents marginal mean ± SEM, n= 9 (3 profiles per soil order and 3 replicate analysis per profile). Repeated measures-ANOVA was performed to test the significance difference among marginal means considering 6 time points measurements as replication and Tukey's HSD test was incorporated for pair-wise comparisons among marginal means.

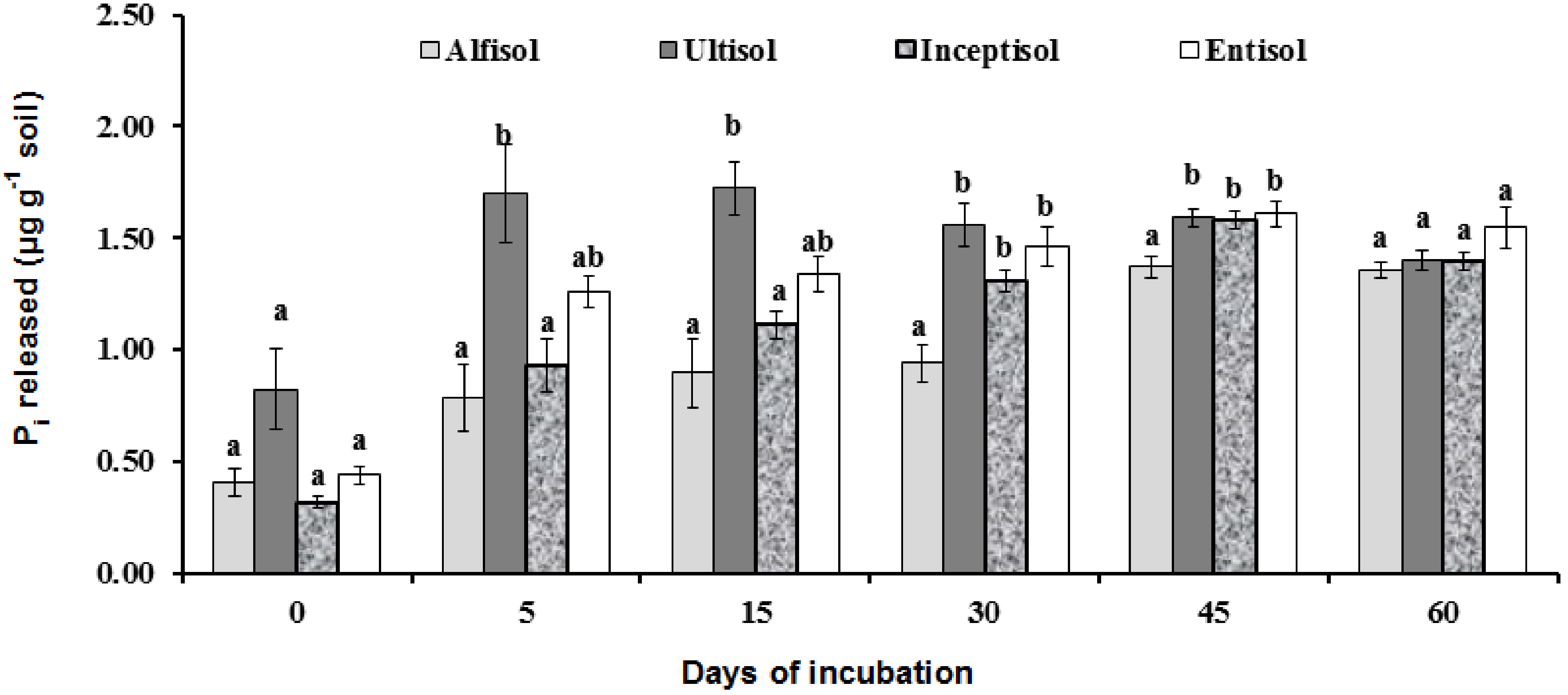


Fig. 4.20. Comparative phosphate release capacity of surface soil of four common soil orders at different time points during laboratory incubation study. Within a time point, each column represents mean ± SEM, n= 9 (3 profiles per soil order and 3 replicate analysis per profile). At each time point, one-way ANOVA was performed to test the significance difference among means and Tukey's HSD test was incorporated for pair-wise comparisons among means.

4.4. Objective-III: the phosphate fixation capacity and other soil attributes

The relationship of PFC of soils of 12 profiles belong to four dominant soil orders with other soil attributes are presented in Figure 4.21 and 4.22 and Table 4.4. The phosphate fixation capacity of soil decreased with increase in soil pH, which was evident from the significant negative correlation (r= - 0.58**) between soil pH and PFC of four soil orders. Againm the significant positive correlation (r = 0.57**) was noticed between the PFC of four soil orders and its SOC contents. The amount of P fixed at all levels of added P showed significant negative correlation with available P content of soils (r= -0.75**). Clay minerals are known to adsorb sufficient quantity of phosphates. More the clay content of soils, higher is the P fixation which was evident from the highly positive significant correlation (r = 0.73**) between PFC and clay content of soils. The rapid fixation of P by the clay minerals is attributed to its reaction with readily available Fe and Al in soils. High significant positive correlation (r = 0.85**) was noticed between PFC and readily soluble alumina content of soils. The amount of P fixed showed significant positive correlation with exchangeable alumina of soils (r = -0.59**). The P fixation capacity was also found to decrease with increase in exchangeable calcium plus magnesium. This was evident from the negative correlation (r = -0.62**) between them. The cation exchange capacity of soils also showed negative correlation (r= -0.49**) with PFC. Lime requirement also showed highly significant and positive correlation (r=0.81**) with PFC. The relationship between DTPA-Fe and PFC was non-significant (r=0.01). Significant and negative correlation (r = -0.48**) was noticed between PFC and base saturation of soils. The correlation between PFC and the soil physico-chemical properties is presented in Table 4.4 as correlation coefficient (r).

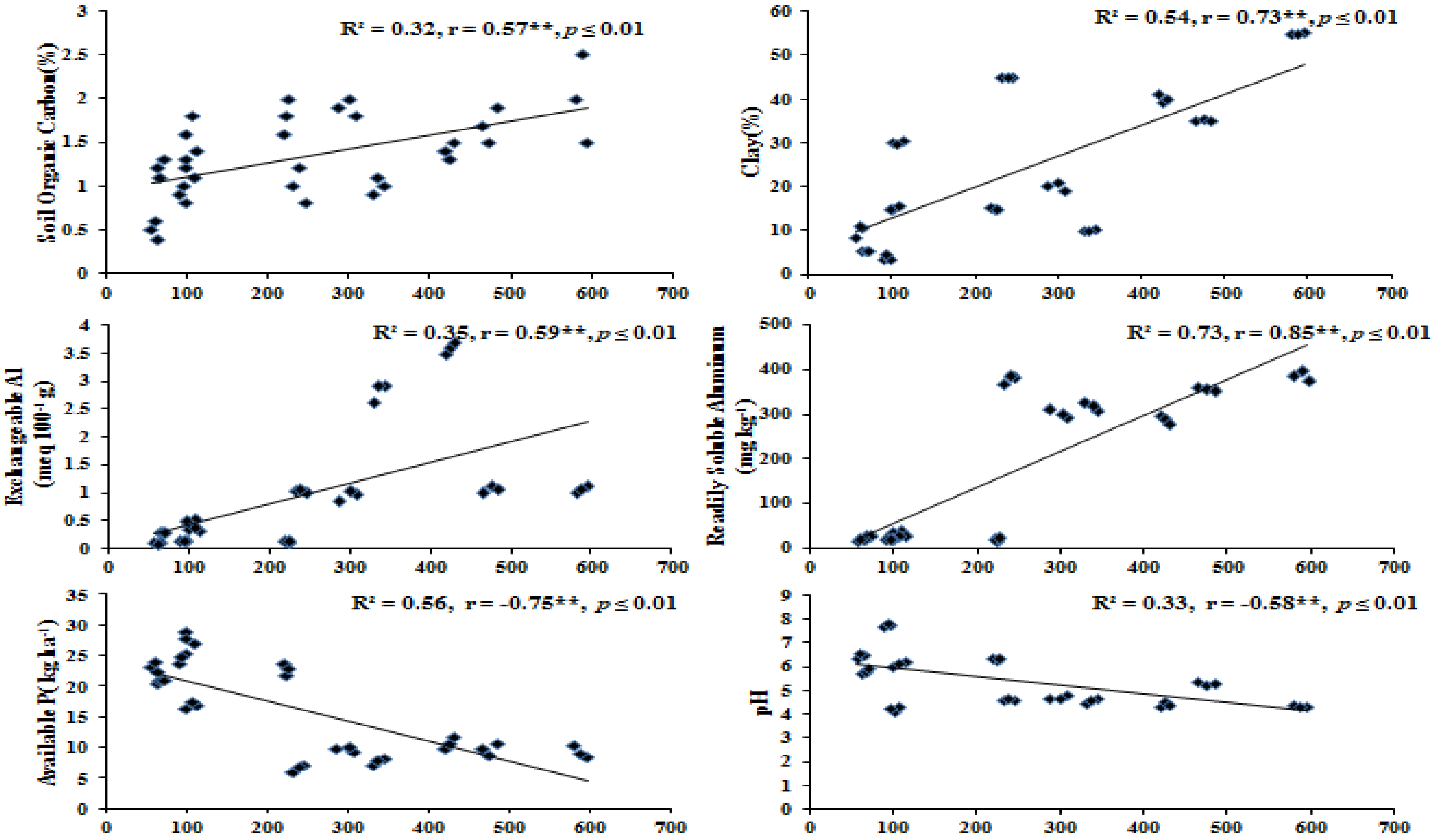


Fig. 4.21. Relationship between Phosphorus Fixation Capacity (µg P g^{-1} soil) and other soil attributes

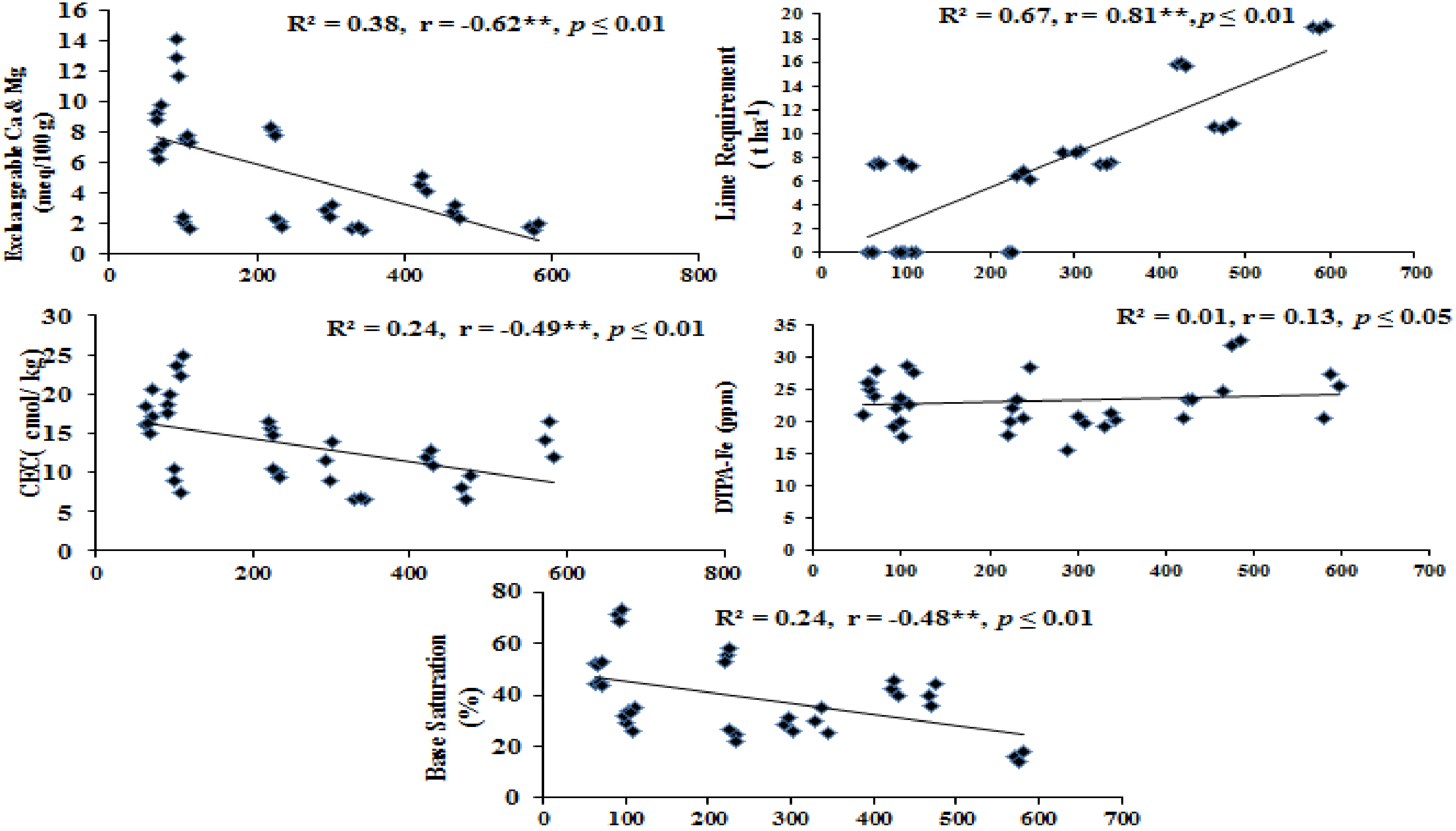


Fig. 4.22. Relationship between Phosphorus Fixation Capacity (µg P g^{-1} soil) and other soil attributes

Table 4.4. Relationship between Phosphorus Fixation Capacity (µg P g^{-1} soil) and other soil attributes

	MWHC	FC	SOC	Avl.N	Avl.K	Avl.P	Ex.Al	ExCaMg	CEC	Clay	RSA	DTPA-Fe	pH	PFC	BD	LR
MWHC																
FC	0.98**															
SOC	0.35*	0.34*														
Avl.N	0.10	0.10	0.53**													
Avl.K	0.57**	0.57**	0.61**	0.43**												
Avl.P	0.08	0.07	-0.31	-0.22	0.18											
Ex.Al	-0.02	-0.02	0.05	0.37*	-0.20	-0.64**										
ExCaMg	0.47**	0.48**	-0.32	-0.10	0.08	0.68**	-0.34*									
CEC	0.82**	0.83**	0.37*	0.09	0.38*	-0.02	-0.18	0.46**								
Clay	0.27	0.27	0.47**	0.46**	0.29	-0.66**	0.35*	-0.46**	0.36*							
RSA	-0.12	-0.12	0.33*	0.20	-0.07	-0.93**	0.62**	-0.77**	-0.11	0.71**						
DTPA-Fe	-0.21	-0.19	0.07	0.31	-0.09	-0.14	-0.10	-0.05	0.16	0.32	0.09					
pH	0.29	0.31	-0.30	-0.36*	-0.04	0.58**	-0.60**	0.80**	0.35*	-0.56**	-0.69**	0.03				
PFC	0.16	0.17	0.57**	0.46**	0.34*	-0.75**	0.59**	-0.60**	0.49**	0.73**	0.85**	0.13	-0.58**			
BD	-0.72**	-0.72**	-0.61**	-0.64**	0.57**	0.22	-0.23	-0.14	-0.60**	-0.53**	-0.20	-0.08	0.05	-0.48**		
LR	-0.01	-0.02	0.42**	0.43**	0.24	-0.60**	0.61**	-0.54**	0.02	0.66**	0.74**	0.12	-0.77**	0.82**	-0.28	

Correlation coefficient (r) = 0.33 and 0.42 at $P_{0.05}$ and $P_{0.01}$ 2-tailed significance, n-2 = 34

Chapter - 5

Discussion

Out of the 328 million hectares land in India, nearly 145 million hectares land is under cultivation. In India, acid soils cover about 49 million hectares, approximately 34% of cropped land (Maji *et al.,* 2012). According to Sharma and Sarkar (2005), out of total 48 to 49 million hectares of acidic soils, 23 million hectares has pH between 5.6 and 6.5 while about 25 million hectares shows pH less than 5.5. These soils can be categorized under problematic soils of India and the distribution of these acid soils mainly concentrated in North-Eastern region and Western Ghats, Jharkhand, Chhatisgarh, Uttarakhand with erratic distribution in Himachal Pradesh, Orissa and West Bengal, etc. (Panda, 1987). It is estimated that in the NE India, approximately 91% soils are acidic, and nearly 65% soils are suffering from strong acidity (pH<5.5) (Sharma *et al*., 2006). A multitude of acidity-related fertility constraints are the toxicities of aluminium (Al), iron (Fe) and Manganese (Mn), deficiency of phosphorus (P), molybdenum (Mo), low base saturation, impaired biological activity and other acidity-induced soil fertility and plant nutritional problems are associated with such soils (Patiram, 1991; Kumar *et al*., 2012). The existing phosphatic fertilizer doses in acid soils of NE India to rectify P deficiency is based on blanket recommendations and the recommended P doses for different crops grossly ignore the phosphate fixation capacity of soils and its release pattern. The problematic elements of acid soils namely Al, Fe and Mn responsible for P-fixation in soils are dependent on genesis and characteristics of secondary clay minerals, pH, organic matter content, etc. (Thakuria *et al*., 2016). The majority soils of NE India belong to four dominant soil orders *Alfisol, Ultisol, Inceptisol* and *Entisol* and their respective distribution is 3.6%, 15.1%, 49.6% and 22.2% of the total geographic area of NE India (Patiram and Ramesh, 2008). There is lack of scientific information on the comparative PFC of these four soil orders of NE India. It is general understanding that any recommended dose of phosphatic fertilizers must exceed the quantity of P required to satisfy the maximum PFC in order to obtain P application benefits to crops. Besides, the P release patterns of these four soil orders in response to different P sources are seldom reported or scientific data not available. Considering the above discussed research gaps, the present study addressed the 3 fundamentals aspects of acid soils of NE India were: (1) the PFC of soils of four dominant soil orders of NE India, (2) the P release pattern of soils of four dominant soil orders in response to different P sources and (3) the relationship of the PFC and other soil attributes. The objective-wise salient findings are discussed in this chapter.

5.1. Soil orders and the phosphate fixation capacity

Out of 4 soil orders, *Alfisol* ranked second in terms of the maximum quantity of applied P fixed (223 to 471 µg P g^{-1} soil) and % P fixed (74.4 to 94.1). The high amount of Ex.Al (95.4 to 323 mg kg^{-1} soil) and RS.Al (18.8 to 354 mg kg^{-1} soil) might be the responsible factor. About 1 meq exchangeable Al per 100 g soil when completely hydrolyzed can sorb up to 102 mg P L^{-1} in soil solution (Tisdale *et al.,* 1990) and the P adsorption is positively correlated with Ex.Al (r=0.84) (Syers *et al.,* 1971). Goundar *et al.* (2014) also reported the positive correlation between P fixation and Al and Fe content of soils (R = 0.65, p = 0.04). The higher P fixing capacity of *Alfisols* in the Chotanagpur plateau region of Eastern India was previously reported (Ghosal *et al.,* 2011). Thus, the higher P fixation capacity in *Alfisols* of NE India could be supported by the above past findings.

Most soils of the tropics (predominantly *Ultisols*) are acidic due to high weathering and high rainfall that results in loss of basic cations. In such soils, acidic cations such as Al and Fe predominate, and depending on soil pH, they fix the applied inorganic P (Adnan *et al.,* 2003). *Ultisols* are expected to show a high affinity for P since they are dominated by oxyhydroxides and kaolinite in soil. Our findings indicated that *Ultisol* order had the highest PFC which ranged from 103 to 577 µg P g^{-1} soil and % P fixed ranged from 85.1 to 96.1. In past, Syers *et al*. (1971) reported such higher PFC of highly weathered soils such as *Oxisols* and *Ultisols*. The pH of 3 soil profiles ranged from 4.22 to 4.56 and falls under very strongly acidic soils. In addition to very low soil pH, the high amount of Ex.Al (41.4 to 253 mg kg^{-1} soil) and RS.Al (34.6 to 384 mg kg^{-1} soil) might be the responsible factor for higher PFC values. The PFC of soils increased with decrease in soil pH, which was evident from the significant negative correlation (r= - 0.58**) between soil pH and PFC in this study. The similar relationship between PFC and soil pH was previously noticed (Kanwar and Grewal, 1990; Naidu *et al.,* 1990). The rapid fixation of P by clay minerals is attributed to its reaction with readily available Fe and Al in soils (Ayodele and Agboola, 1981; Tening *et al*., 2013; Goundar *et al.*, 2014;). The relatively lesser quantity of applied P fixed (103 µg P g^{-1} soil) and lesser % P fixed (51.4) by P4 (Table 4.2) soil in comparison to that in soils of P5 and P6 was an exception. The possible reason was that the Profile 4 falls within a commercial Tea garden (located in NorthWest, Jorhat) where inorganic fertilizers were applied regularly since last 50 years. The accumulation of P due to continuous application of inorganic P fertilizers in Peach orchard under humid subtropics of Eastern Hiamalays was recently report by Surchand-Singh *et al.* (2017). Because of build-up of inorganic P pools which could satisfy the P adsorption sites of clay minerals and Al and Fe oxides and hydroxides in P4 soils, the PFC was found lower (only 102 µg g^{-1} soil) as compared to the range (337 to 576 µg g^{-1} so) for P5 and P6 soils. This justification could be further supported by higher soil Avl.P content (62.1 kg ha^{-1}) for P4 soil as against the range of soil Avl.P content (7.6 to 9.2 kg ha^{-1}) for P5 and P6 soil. So, it can be mentioned that the right dose of P with suitable management practices (liming with organic manures) may offset the P deficiency problem in acid soils of tropics and subtropics (Franklin, 2012).

Results on PFC indicated that the maximum quantity of applied P fixed was approximately 2 times lesser in *Inceptisol* (ranged from 107 to 277 µg P g^{-1} soil) as compared to *Ultisol* (ranged from 337 to 577 µg P g^{-1} soil). Even Goundar *et al.* (2014) found the lowest P fixing power in case of *Inceptisol* having low amount of clay content. The moderate PFC of *Inceptisol* observed in this investigation might be associated with responsible factors like low pH, Ex.Al and RS.Al as discussed earlier for *Alfisol* and *Ultisol.* The PFC maintained a significant negative correlation with pH ($r = -0.58^{**}$, $p \leq 0.01$). Among 3 *Inceptisols,* P8 soil (pH 6.1) had the lowest PFC which was expected because P-fixation is minimal at pH 6.5 (Goundar *et al.*, 2014). The higher PFC of P7 and P9 soils were associated with low soil pH (4.72 and 4.62, respectively) as well as high Ex.Al and RS.Al. Our results corroborated the past findings of McBride (1994) and Guppy *et al.* (2005) that P fixation in acid soils is mainly by oxyhydroxides of iron and aluminium because of the formation of very insoluble Al and Fe phosphates. In slightly acid to neutral soils available P increases, due to reduction of this fixation by aluminum, iron and manganese.

The maximum quantity of applied P fixed in *Entisol* ranged from 67 to 92 µg P g^{-1} soil, which was the lowest among four dominant soil orders. The significant lesser PFC values and % P fixed (33.3 to 68.2) for *Entisols* could be explained by the relative higher soil pH (5.81 to 7.74), lower content of Ex.Al (8.1 to 25.2 mg kg^{-1} soil) and Rs.Al (18.4 to 22.6 mg kg^{-1} soil). Lopez-Hernandez and Burnham (1974a) also reported the lowest P adsorption capacity for *Entisols*. Because, *Entisols* are recently developed on river alluviums where water carried most of the clay particles and leaving behind only sand particles. This is evident from the fact that P fixation is strongly influenced by clay content of soil and is more specifically related to a large specific surface area for adsorption, where sand particles lacked (Rayment and Higginson, 1992; Sims and Pierzynski, 2005; Rayment and Lyons, 2011; Guppy *et al*., 2005). In this study, the lowest clay content (3.7 to 10%) was observed for *Entisols.*

This study revealed that higher % P fixed was in order of *Ultisol* (90.2) > *Alfisol* (84.5) > *Inceptisol* (74.2) > *Entisol* (49.2). Majumdar *et al*. (2005) studied the effect of liming on P adsorption and desorption behavior of acid *Alfisols* and *Entisols* of Meghalaya which revealed that the acid soils of the region had very high P adsorption and about 99% of added P was up to 150 µg P g^{-1} soil addition (Majumdar *et al*., 2005). The P desorption ability was very low in *Alfisols*, but was relatively more in *Entisols*. Again, Chatterjee *et al.* (2014) reported that phosphate fixation was higher in *Alfisol* as compared to *Inceptisol* and also stated that phosphorus fixation was positively correlated with different pools of iron and aluminum compounds. According to Bhat *et al.* (2017), higher soil pH was in order of *Entisols* > *Alfisols* > Inceptisols. Similarly, higher soil pH observed in this study was in order of *Entisols* (6.66) > *Inceptisols* (5.15) > *Alfisols* (4.85) > *Ultisols* (4.37).

5.2. Influence of phosphorus sources on phosphate release

Organic matter is an important influential factor for chemical, physical and biological soil properties. Negatively charged functional groups in organic substances (e.g., carboxyl, phenol) can interact with positively charged minerals such as iron oxides and alter phosphorus adsorption as a result (Liu *et al.,* 1999). Some studies have revealed that increasing the organic matter content of soil does not decrease P_{max} (Fink *et al.,* 2014 and 2016a); others, however, suggest that organic matter affects the binding energy of adsorbed P (Kreller *et al.,* 2003) and can therefore increase the efficiency of phosphatic fertilizer - possibly as a result of phosphate adsorption with little energy (e.g., via cation bridges; Guppy *et al.,* 2005). Recent studies in highly weathered Brazilian soils have shown that organic matter and various iron oxides have a direct effect on P adsorption/desorption and availability (Fink *et al.,* 2014; Bortoluzzi *et al*., 2015; Fink *et al.,* 2016b). Inorganic P fertilizer like SSP, a water soluble P fertilizer and can supply P during the initial part of crop growing period. But later on, its supply diminishes due to fixation mechanisms or leaching through the soil. Natural phosphate rocks (RP) have been recognized as a valuable alternative for P fertilizers. It is estimated that the rock phosphate deposits in India are almost 260 million tons and this material will provide a cheap source of phosphate fertilizer for crop production (FAI, 2002). Unfortunately, RP is not readily available to the plants in soils with a pH > 5.5 – 6.0. Because of this, extension services are reluctant to recommend it and farmers are hesitant to utilize RP directly. One approach for solubilization of RP in field conditions is the application of phosphate-solubilizing microorganisms (PSM). Phosphate solubilizing bacteria (PSB) has the ability to render unavailable form of P compounds into plant usable form. The active strains of PSB involved in this conversion are *Pseudomonas*, *Bacillus*, *Serratia, Mycobacterium*, *Flavobacterium*, *Micrococcus*, *Rhizobium*, *Mesorhizobium*, *Sinorhizobium, etc.* (Sharma *et al.,* 2013). Inoculation of PSB has been reported to modify P nutrition and increase its solubilization in soil through many process such as, they may decrease the pH of the soil by the producing organic (gluconic acid) and mineral acids (Chen *et al*., 2006), alkaline phosphatases (Rodriguez and Fraga, 1999), phytohormones and H+ protonation (Xiao *et al*., 2017), anion exchange, chelation and siderophores production which promote P solubilization in soil (Sugihara *et al*., 2010). Exploitation of these processes may prevent frequent addition of P into soil with inorganic P sources. Organic acids use their hydroxyl and carboxyl groups to chelate the cations (Ca, Al, Fe) bound to phosphorus and release the P (Taktek *et al*., 2017). Alori *et al.* (2017) found that PSB produce the enzyme phosphatase that plays a key role in the solubilization of P. The combine application of PSB and RP fertilization would be an appropriate substitute for chemical phosphate fertilizer application in sustainable agriculture systems (Akbari *et al*., 2010; Kaur and Reddy, 2015; Thakuria *et al*., 2016).

Application of various P forms *viz*. RP, SSP, OM, and PSB in strongly acid soil increased the content of soil Av.P to different extents. The increase in soil Avl.P content was more when PSB combined with RP compared to their individual application (Thakuria *et al*., 2009). Sundara *et al.* (2002) reported PSB application without any P fertilizer increased PSB population and soil available P status at different stages of the crop but effect on yield was observed much greater when PSB was inoculated with RP fertilizer. It has been observed that a 25% reduction in the amount of P applied is possible when P fertilizer like RP is used in combination with PSB (Kalidas-Singh *et al*., 2014). In this investigation, PSB+RP released significant higher soil P_i content compared to that in the recommended SSP throughout 60 days incubation period in all soil orders. Beyond 15 days of incubation, PSB, OM, RP and RP+PSB also released higher P_i compared to that in the recommended SSP during the incubation experiment. Application of OM, PSB, and RP in combination is able to maintain higher soil Avl.P pool in acidic soil by few possible ways: (1) organic manure induces microbiota population and activity, and thereby better nutrient cycling and maintenance of higher available pool of nutrients in soil (Manna *et al*., 2006, Yan *et al*., 2007), (2) reduction in activity of readily soluble-Al and exchangeable-Al in soil upon application of organic manures (Haynes *et al*., 2001; Thakuria *et al.,* 2016), (3) Slow release of orthophosphate from RP over the time due to the action of organic acids secreted by the test PSB isolate as well as the compost induced native microbiota. The soil Avl.P and pH maintained a positive correlation ($r=0.58^{**}$ at $p<0.01$, $n=36$), which was an indication that the application of PSB and RP in combination exerted a neutralizing activity against soil acidity. Organic anions can chelate Fe^{3+} and Al^{3+} in acidic soil (Haynes *et al.,* 2001). Thakuria *et al*. (2009) reported the strong positive correlation between soil pH and Avl.P content in acidic soil under rice-legume-rice rotation due to the continuous application of compost + *Rhizobium* + PSB + RP + MOP when compared with recommended SSP application. There are numerous reports that application of organic manures help maintaining higher Avl.P in P deficient acidic soils (Haynes *et al*., 2001; Havlin e*t al*., 2009). Such soil processes triggered by application of PSB and RP in combination might confer an advantage in releasing P_i in acidic soil as compared to that in application of SSP alone.

This study revealed that release of soil P_i increased consistently beyond 15 days of incubation and reached the highest peak towards later stages of incubation (45 – 60 days in this study) when PSB, OM, RP and PSB+RP were applied across soil orders. In contrast, the maximum quantity of soil P_i released within 15 days of incubation was observed for SSP sources across soil orders. Siddaramappa *et al*. (1991) conducted a study on release pattern from rock phosphate amended acidic lateritic soil (pH 5.0) and observed maximum P availability at 30DAT. Since, SSP contains much higher amount of water soluble P than RP and OM, the highest peak of P_i release in SSP application at initial stage of incubation was expected. However, high content of readily soluble Al and Fe in the soil fixed water soluble fraction of P as $AlPO_4$ and $FePO_4$. This fixation reaction caused drastic reduction in the content of soil Avl.P beyond 15 days incubation in SSP application. Soil Avl.P observed beyond 15 days of incubation was significantly lesser compared to the amount of soil Avl.P observed in PSB+RP applied soil. Application of OM led to the gradual increase in P_i release during the later stage of incubation. Perhaps due to decomposition of the amended organic matter gradually increases the deposition of organic anions and also gradual population build-up of native microbiota that secreted more amounts of organic acids and thereby chelation of Al and Fe oxides and hydroxides. This may be the cause for lesser P fixation or otherwise higher quantity of P released beyond 15 days of incubation in OM amended soil column. Such explanations have been made previously by many workers (Dalton *et al*., 1952; Moreno and Lindsay, 1960; Barrow, 1989). The introduction of efficient P solubilizers (PSB) has been found to increase the availability of P from both applied and native soil phosphorus. The microbial property of dissolving interlocked phosphates appears to have an important implication in agriculture and same has been documented by many investigators (Singh *et al*., 2005; Afzal, 2006; Arun, 2007). Thakuria *et al*. (2004) reported that application of PSB+RP in acidic rice soil increased grain yield of rice up to 21.6% over no input control. Further, Reddy and Raju (2006) found that application of PSB with RP produced rice yields statistically *at par* with that produced by SSP application at 30 kg ha^{-1}. In contrast, the other P treatments *viz*. RP and RP+PSB showed higher amount of released P_i. This might be due to addition of sparingly soluble RP along with PSB inoculation. Because RP is able to replenish the native P_i pool (soil solution P_i concentration) through PSB mediated slow dissolution of RP over the time. These results were supported the past finding that RP maintained higher amount of soil Avl.P in the long run than in SSP application (Mandal and Khan, 1972). Again, the combined application RP and PSB further increased soil Avl.P compared to their individual application (Panhwar *et al*., 2011). Overall, it was conclusive that the combined application of RP+PSB released significant higher quantity of P_i in soil solution at least beyond 15 to 30 days of incubation depending on soil orders.

5.3. Phosphorus fixation capacity and other soil properties

The PFC of soils decreased with increase in soil pH across soil orders tested. The significant negative correlation (r = -0.58**) between soil pH and PFC of soils observed in this study further consolidated the similar past findings (Kanwar and Grewal, 1990; Naidu *et al.,* 1990; Fageria and Baligar, 2008; Kumar, 2015). However, a few study also reported no correlation between P fixed and pH (Ayodele and Agboola, 1981; Dodor and Oya, 2000), while others reported a positive correlation between P fixed and pH of soils (Mukwange, 1975; Tening *et al.,* 2013). The significant positive correlation (r = 0.57**) was noticed between PFC and SOC content across soil orders. There was significant positive correlation observed between soil P availability and SOC content (Pandey *et al*., 2000). Previous studies on tropical savannah soils of Western Nigeria (Ayodele and Agboola, 1981) and the red and lateritic soils of West Bengal (Dolui and Gangopadhyay, 1984) also indicated positive correlation between organic carbon and P fixed. Higher P fixation capacity in soil with higher organic carbon content has also been reported by earlier researchers (Kanwar and Grewal, 1990; Venkatesh and Majumdar, 2001). The amount of P fixed at all levels of added P showed significant negative correlation (r= -0.75**) with soil Avl.P content, which corroborated the past findings (Venkatesh and Majumdar, 2001; Tening *et al.,* 2013). This was contrary to findings by Dodor and Oya (2000) who found no correlation between P fixed and available P. This could be associated to the fact that the fixation could mainly be due to adsorption which is a reversible process thus as fixation sites become saturated with P, less P is retained. Clay minerals are known to adsorb sufficient quantity of phosphates. More the clay content of soils, higher is the P fixation which was evident from the highly significant positive correlation (r = 0.73**) between PFC and clay content of soils observed in this study. The rapid fixation of P by clay minerals is attributed to its reaction with readily available Fe and Al in soils. Similar results were also observed by Ayodele and Agboola (1981), Goundar *et al.* (2014) and Tening *et al*. (2013). This indicates that fixation increased with increase in amount of clay. This could also be an indication that the soils are made up of aluminosilicate clays of the layered structure (phyllosilicates), which have sites for adsorption of P. As the amount of clay increases, the number of fixation sites increases. Fixation of phosphates by phyllosilicate clays could be viewed as surface reaction between exposed OH groups on the mineral crystal and the H_2PO4^- ion or removal of aluminium and iron ions from the edges of the silicate clay crystals for hydroxyl phosphates. The P fixation is strongly influenced by clay content of soil and is more specifically related to a large surface area for adsorption (Rayment and Higginson, 1992; Guppy *et al*., 2005; Sims and Pierzynski, 2005; Rayment and Lyons, 2011). Phosphorus retention will be minimal for soils containing higher percentage of silt and sand. The PFC and RS.Al maintained significant positive correlation (r = 0.85**) across soil orders observed in this study. The amount of P fixed showed significant positive correlation with Ex.Al in soils (r = 0.59**). Owusu-Bennoah and Acquaye (1989) studied the phosphate sorption characteristics of some Ghanaian soils and found that the phosphate sorption maxima were highly correlated with the soil properties in the order: Al_2O_3 and free Fe_2O_3. Goundar *et al.* (2014) reported positive correlation between P fixation and Al and Fe content of soils (R = 0.65, p = 0.04). Hence, there is strong association with phosphorus fixation in soil with increasing levels of Al and Fe in the soil. The PFC of soil was found to decrease with increase in soil Ex.Ca+Mg content. This was evident from the negative correlation (r = -0.62**) between them. Morel *et al.* (1989) evaluated the PFC of soils by the isotopic exchange techniques in north-east France and reported that there was a significant negative correlation between exchangeable cations. Cation exchange capacity also showed negative correlation (r= -0.49**) with PFC. The % P fixed also displayed negative relationship with CEC (Goundar *et al*., 2014). Lime requirement also showed highly significant positive correlation (r=0.81**) with PFC as well as with $Ex.Al^{3+}$ (Majumdar *et al.,* 2005; Chatterjee *et al.,* 2014). There was no co-relationship observed between DTPA-Fe and PFC (r=0.01). The PFC and BS of soils maintained a significant negative correlation (r = -0.48**) across soil orders.

Chapter - 6

Summary and Conclusions

Soil acidity is a major constraint to agriculture production globally. Soil acidity related constraints like toxicities of Al, Fe and Mn, deficiencies of P, Ca, Mg, B, Mo and meagre microbial activities are major management challenges. The North Eastern Indian soils are no exception to this where 26.22 million ha land are acidic in nature. The predominant soil orders prevailing in this region are *Inceptisol*s, *Entisol*s, *Ultisols* and *Alfisols.* The process of P fixation accelerates the problem leading to low PUE in soil. Since, there lies spatial variability of P availability in soils, single blanket recommendation is not appropriate, instead site-specific nutrient management is the need of the hour. The PUE can be enhanced by the application of different P sources *viz*., OM, PSB, RP and SSP to these soils. Therefore, the present study was conducted to find out the P fixation capacity of twelve soil profiles representing four dominate soil orders of NE India and the release pattern of P_i was evaluated by soil column study in response to amendment with OM, PSB, RP, SSP and RP+PSB as P sources. Keeping the above facts in mind, the objective-wise salient findings are summarized hereunder:

- The BD, MWHC and clay content ranged from 0.91 to 1.37 g cc^{-1}, 32.7 to 55.5% and 3.7 to 55%, respectively among 12 soil profiles.
- The content of SOC, Avl.N, Avl.P and Avl.K ranged from 0.50 to 2.00%, 122 to 301 kg ha^{-1}, 6.6 to 62.1 kg ha^{-1} and 108 to 220 kg ha^{-1}, respectively.
- Soil pH, Ex.Al, RS.Al, Ex.Ca+Mg and BS ranged from 4.22 to 7.74, 0.09 to 3.5 meq 100 g^{-1} soil, 18.4 to 384 mg kg^{-1} soil, 1.7 to 12.9 meq 100 g^{-1}soil, 16.2 to 71%, respectively.
- The PFC (µg P g^{-1} soil) ranged from 223 to 471 for *Alfisol*, 337 to 577 for *Ultisol,* 107 to 277 for *Inceptisol* and 67 to 92 for *Entisol*.
- The maximum PFC was found at the P application dose (µg g^{-1} soil) at 500 for *Alfisol*, 600 for *Ultisol*, 300 for *Inceptisol* and 200 for *Entisol.*
- The highest percent P fixed for *Alfisol* (84.5), *Ultisol* (90.2), *Inceptisol* (74.2) and *Entisol* (49.2).

- The low PFC (102 µg g^{-1} soil) of P4 soil (*Ultisol* belongs to Tea Garden) was an exception. The cause of this low PFC in *Ultisol* was due to long-term application of inorganic P fertilizer that lead to accumulation of P in soil which might partially saturated the P fixation sites and as a result higher content of soil Avl.P content i.e. 62.1 kg ha^{-1}.
- The quantity of P_i released was soil order dependent; where as the pattern of P_i released over the incubation duration was highly influenced by the source of applied P across soil orders.
- The highest amount of P_i released was observed in SSP application at the initial stage of incubation (within 15 days of incubation) and thereafter, amount of released P_i decreases gradually.
- On the other hand, higher amount of released P_i was increasing gradually with the progressive incubation duration in PSB, OM, RP and RP+PSB sources indicating more released P_i beyond 15 or 30 days onwards depending on soil orders.
- Among P sources other than SSP, application of RP+PSB could release significant higher quantity of P_i as compared to their single application throughout the incubation period.
- Among 4 soil orders, *Ultisol* exhibited the significant higher amount of phosphate release (PR) compared to other 3 soil orders and the quantity of PR of *Alfisol, Inceptisol* and *Entisol* were comparable within 15 days of incubation.
- Beyond 15 days of incubation, the quantity of PR in *Ultisol, Inceptisol* and *Entisol* were comparable and significantly higher than that in *Alfisol.*
- The marginal means of P_i released values indicated that higher PR capacity was in order of *Ultisol* > *Entisol* > *Inceptisol* > *Alfisol*

In conclusion, out of four major soil orders of NE India, *Ultisol, Alfisol* and *Inceptisol* possess very high PFC and *Entisol* possesses relatively the lowest PFC. The higher percent P fixed was in the order *Ultisol* (90.6) > *Inceptisol* (87.5) > *Alfisol* (84.6) > *Entisol* (61). So, the PFC findings of this study calls for an urgent need to correct the existing blanket recommended dose of phosphatic fertilizer. The significant higher correlation of PFC with RSA, Clay, Ex.Al, Av.P, Ex.Ca+Mg, pH, BS and SOC indicated the need for formulation of suitable nutrient management practice that can improve the status of these soil attributes so as to reduce the PFC and enhancing the PUE of soil. The application of OM, RP and PSB showed significant positive effects on the phosphate release capacity of soils. So, it can be suggested that PFC and PRP behaviours of acid soils of NE India are important factors to be considered while formulating P nutrition management practices. A starter dose of SSP along with PSB+RP as P fertilizer sources seems to be the most suitable P management option for maintaining consistently more pool of solution P in all four dominant soil orders. Findings of this investigation revealed the fundamental understanding on PFC and PRP of dominant soil orders and based on which efficient P management practice needs to be formulated and tested for effectiveness against the existing blanket recommendation of P fertilizer through future trials in farmers' fields.

BIBLIOGRAPHY

Abedin, M.J. and Saleque, M.A. (1998). Effects of phosphorus fertilizer management on phosphorus sorption characteristics of lowland rice soil. *Thai J. of Agril. Sci.,ISSN*: 0049-3589.

Adnan, A., Mavinic, D.S., and Koch, F.A. (2003). Pilot-scale study of phosphorus recovery through struvite crystallization-examining to process feasibility. *J. Environ. Eng. Sci.,* 2: 315–24.

Afif, E., Baron, V., and Torrent, J. (1995). Organic matter delays but does not prevent phosphate sorption by Cerrado soil from Brazil. *Soil Sci.*, 159: 207-2011.

Afzal, M. (2006). Effect of Rhizobium, PSB with different fertility levels on green gram under temperate conditions of Kashmir. M. Sc. Thesis. Thesis Submitted to SKUAT,Kashmir.

Afzal, A. and Bano, A. (2008). Rhizobium and phosphate solubilizing bacteria improve the yield and phosphorus uptake in wheat (*Triticumaestivum L.*). *Int. J. Agri. Biol.,* 10: 85-88.

Agbenin, O.J. (2003). Extractable iron and aluminum effects on phosphate sorption in asavanna *Alfisol*. *Soil Sci. Soc. Am. J.*, 67: 589–595.

Agbenin, J.O. and Tiessen, H. (1995). Phosphorus sorption at field capacity and soil ionic strength: Kinetics and Transformation. *Soil Sci. Soc. of Am. J.,* 59: 998-1005.

Akbari, G.A., Eftekhari, G., and Allahdadi, I. (2010). Evaluationof rock and super phosphates effects on yield and yield components of rice (*Oriza sativa* L.) with and without phosphate solubilizing bacteria. *Am. Eurasian J. Agron.,* 3: 51–58.

Akhtar, M.S., Brian K.R., Pedro, A.M., Maarten de, G., and Tammo, S.S. (2003). Dissolved phosphorus from undisturbed soil cores. *Soil Sci. Soc. Am. J.*, 67: 458–470.

Alam, S., Khalil, S., Ayub, N., and Rashid, M. (2002). *In-vitro* solubilization of inorganic phosphate by phosphate solubilizing microorganism (PSM) from maize rhizosphere. *Intl. J. Agric. Biol.,* 4: 454-458.

Alori, E.T., Glick, B.R., and Babalola, O.O. (2017). Microbial phosphorus solubilization and its potential for use in sustainable agriculture. *Front. Microbiol.*, 8: 971.

Arun, K.S. (2007). Bio-fertilizers for sustainable agriculture.Sixth edition, Agribios publishers, Jodhpur, India.

Ayodele, O. and Agboola, A.A. (1981). Evaluation of phosphorus fixation capacity of tropical savannah soils of Western Nigeria. *Soil Sci. Soc. Am. J*. 45: 462 – 464.

Ayoub, A.T. (1999). Fertilizers and the environment. *Nutr. Cycl. Agroecosys*., 55: 17-121.

Baifan, J. and Yichu, G. (1989). A suggested fractionation scheme of inorganic phosphorus in calcareous soils. *Fert. Res.,* 20: 159-165.

Bansal, S.K. and Sekhon, G.S. (1994). Soil phosphorus in some *Vertisols* and crop response to phosphorus in these soils. *Fertilizer News,* 39: 13-17.

Barrow, N.J. (1967). Relationship between uptake of phosphorus by plants and the phosphorus potential and buffering capacity of the soil-An attempt to test Schofield's hypothesis.*Soil Sci.,* 104 (2): 99-106.

Barrow, N.J. (1989). Testing a mechanistic model-IX. Comparison between anions for sorption by soil. *Soil Sci.,* 40: 415-425.

Bartholdy, B.A., Berreck, M., and Haselwandter, K. (2001). Hydroxamatesiderophore synthesis by *Phialocephalafortinii*, a typical dark septate fungal root endophyte. *Bio. Met.*, 14: 33-42.

Baruah, T.C. and Borthakur, H.P. (1999). A Text Book of soil analysis, Vikas Publishers, New Delhi, pp. 334.

Batjes, N.H. (2011). Global distribution of soil phosphorus retention potential (No. 2011/06) International Soil Reference and Information Centre (ISRIC)-World Soil Information.

Beckett, P.H.T. and White, R.E. (1964). Studies on the phosphate potentials of soils: The pool of labile inorganic phosphate*. Plant soil,* 21: 253-282.

Bhat, J.A., Chandra M.K., Mandal, B., and Hazra, G.C. (2017). Nature of Acidity in *Alfisols*, *Entisols* and *Inceptisols* in relation to soil properties. *Comm. Soil Sci. Plant Anal.*, *48*(4): 395-404.

Bhattacharyya, P. and Ghosh G. (2001). Phosphorus use efficiency in brinjal with FYM and S. *J. Indian Soc. Soil. Sci*., 49 (2): 456-462.

Bolan, N.S., Naidu, R., Mahimairaja, S., and Baskaran, N. (1994). Influence of low molecular weight organic acids on the stabilization of phosphates. *Biol. Fertil. Soils,* 18: 311-319.

Bolland, M.D.A. and Gilkes, R.J. (1998). The relative effectiveness of superphosphate and rock phosphate for soils where vertical and lateral leaching of phosphorus occurs. *Nutr. Cycl. Agroecosyst.,* 51: 139-153.

Bolland, M.D.A., Lewis, D.C., Gilkes, R.J., and Hamilton, L.J. (1997). Review of Australian phosphate rock research. *Aust. J. of Exp. Agric.,* 37: 845-859.

Bortoluzzi, E.C., Pérez, C.A., Ardisson, J.D., Tiecher, T., and Caner, L., (2015). Occurrence of iron and aluminumsesquioxides and their implications for the P sorption in subtropical soils. *Appl. Clay Sci.*, *104:* 196-204.

Brady, N.C. and R.R. Weil (2002). The nature and properties of soils (13th ed). Pearson Education Ltd., USA, p. 960.

Brady, N.C. and Weil, R.R. (2008). The Nature and Properties of Soils, (14thed). Prentice Hall, Upper Saddle River, NJ, USA, p. 230.

Bray, R.H. and Kurtz, L.T. (1945). Determination of total, organic and available forms of phosphorus in soils. *Soil Sci*., 59: 39-45.

Bromfield, S.M. (1965). Studies on the relative importance of Fe and Al in the sorption of phosphate by some Australian soils. *Aus. J. soil Res.,* 3: 31 – 44.

Buresh, R.J., Smithson, P.C., and Hellumus, D.T. (1997). Building soil P in Sub- Saharan Africa. In: Buresh, *et al.* (ed.) Replenishing soil fertility in Africa. *Soil Sci. Soc. Am.* Special publication number 51, Madison, West Indies, pp. 1-46.

Burkitt, L.L., small, D.R., McDonald, J.W., Wales, W.J., and Jenin, M.L. (2007). Comparing irrigated biodynamic and conventionally managed dairy farm. Soil and pasture properties. *Aust. J. Exp. Agric*., 47: 479-488.

Burnham, C.P. (1982) Phosphate retention in different soil Taxonomic classes.*Soil Sci*., 134: 376-380.

Cabello, M., Irrazabal, G., Bucsinszky, A.M., Saparrat, M., and Schalamuck, S. (2005). Effect of an arbuscularmycorrhizal fungus, *G. mosseae* and a rock-phosphate-solubilizing fungus, *Penicilliumthomii* on *Menthapiperita* growth in a soilless medium. *J. Basic Microbiol.,* 45: 182-189.

Cabrera, F., Arambarri, P. D., Madrid, L., and Toca, C.G. (1981). Desorption of phosphatefrom iron oxides in relation to equilibrium pH and porosity. *Geoderma*, 26: 203–216.

Campbell, L.B. and Racz, G.J. (1975). Organic and inorganic phosphorus content, movement and mineralization of phosphorus in soil beneath a feedlot. *Can. J. of Soil Sci.*, 55: 457-466.

Chakravarti, S.N. and Talibudeen, O. (1962). Phosphate equilibria in acid soils. *J. Soil Sci*., 13: 231-240.

Chatterjee, D., Datta, S.C., and Manjaiah, K.M. (2014). Fractions, uptake and fixation capacity of phosphorus and potassium in three contrasting soil orders. *J. Soil Sci. Plant Nutr.,* 14 (3): 640-656.

Chen, Y.P., Rekha, P.D., Arunshen, A.B., Lai, W.A., and Young, C.C. (2006). Phosphate solubilizing bacteria from subtropical soil and their tricalcium phosphate solubilizing abilities. *Appl. Soil Ecol.,* 34: 33-41.

Cordell, D. (2010). The story of phosphorus: Sustainability implications of global phosphorus scarcity for food security, Ph.D. Thesis, Submitted to Linkoping University, Sweden.

Cordell, D. and White, S. (2011). Peak phosphorus: clarifying the key issues of a vigorous debate about long-term phosphorus security. *Sustainability,* 3(10): 2027–2049.

Cordell, D., Drangert, J.O., White. S. (2009). The story of phosphorus: global food security and food for thought*. Global Environ*. *Chang*., 19: 292-305.

Dalton, J.D., Russell, G.C., and Sieling, D.H. (1952). Effect of organic matter on phosphate availability.*Soil Sci.,* 73: 173-181.

deRidder, M., de Jong, S., Polchar, J., and Lingemann, S. (2012). Risks and opportunities in the global phosphate rock market: Robust strategies in times of uncertainty. Hague Centre for Strategic Studies, Netherlands, pp. 1-76.

Dhir, R.P. (1956). Phosphorus status of major Indian soils. M.Sc. Thesis, Submitted to IARI, New Delhi.

Dodor, D.E. and Oya, K. (2000). Phosphate sorption characteristics of major soils in Okinawa, Japan. *Commun. Soil Sci. Plant. Anal.,* 31: 277-288.

Dolui, A.K. and Gangopadhyay, S.K. (1984). Fixation of phosphate in relation to properties of some red and lateritic soils of West Bengal. *Indian J. Agric. Chem*., 17: 177 - 182.

Doula, M., Ioannou, A., and Dimirkou, A. (1996). Thermodynamics of phosphate adsorption-desorption by *Alfisols, Entisols*, *Vertisols*, and *Inceptisols*. *Commun. Soil Sci. Plant Anal*. 27: 1749–1764.

Ellis, R.M., Quader, M.A., and Truog, E. (1955). Rock phosphate availability as influenced by soil pH. *Soil Sci. Soc. Am*. *J*., 19(4): 484-487.

El-Swaify, S.A., Pathak, P., Rego, T.J., and Singh, S. (1985). Soil management for optimized productivity under rainfed conditions in the semi-arid tropics. *Adv. Soil Sci*., 1:1-64.

Erich, M.S., Fitzgerald, C.B., and Porter, G.A. (2002). The effect of organic amendments on phosphorus chemistry in a potato cropping system. *Agric. Ecosyst. Environ*, 88(1): 79-88.

Eswaran, H., Reich P., and Beinroth, F. (1997). Global distribution of soils with acidity. In: Moniz,A.C. (ed.), Plant-soil interactions at low pH. Sao Paulo, Brazil, pp. 159-164.

Fageria, N.K. and Baligar, V.C. (2008). Ameliorating soil acidity of tropical *Oxisols* by liming for sustainable crop production. *Adv. Agron.,* 99: 345–431.

Fankem, H., Nwaga, D., Deubel, A.L., Dieng, W., Merbach, W., and Etoa, F.X. (2006). Occurrence and functioning of phosphate solubilizing microorganisms from oil palm tree (*Elaeisguineensis*) rhizosphere in Cameroon. *African J. Biotech*., 5(24): 2450-2460.

Fertilizer Association of India (FAI) (2002). Fertilizer statistics: 2001–2002. New Delhi, India, pp. 39–47.

Fink, J.R., Inda, A.V., Bayer, C., Torrent, J. and Barrón, V. (2014). Mineralogy and phosphorus adsorption in soils of south and central-west Brazil under conventional and no-tillage systems. *Acta Scientiarum. Agronomy*, *36*(3): 379-387.

Fink, J.R., Inda, A.V., Bavaresco, J., Barrón, V., Torrent, J., and Bayer, C. (2016a). Adsorption and desorption of phosphorus in subtropical soils as affected by management system and mineralogy. *Soil Tillage Res.,* 155: 62-68.

Fink, J.R., Inda, A.V., Bavaresco, J., Sánchez-Rodríguez, A.R., Barrón, V., Torrent, J. and Bayer, C. (2016b).Diffusion and uptake of phosphorus, and root development of corn seedlings, in three contrasting subtropical soils under conventional tillage or no-tillage. *Biol. Fertil. Soils*, 52(2): 203-210.

Fitter, A., 2002. Characteristics and functions of root systems. In *Plant roots*. CRC Press. pp. 49-78.

Fixen, P.E. and Grove, J.H. (1990). Testing soils for phosphorus. *Testing soils for phosphorus*, pp.141-180.

Franklin, O.N. (2012). Ameliorating soil acidity in Ghana: A concise review of approaches. *J. Sci. Technol*., 2: 1-9.

Garden, D.L., Ward, G.N., Sale, P.W.G., Tannakoon, S., Hindell, R.P., and Gardiner, B. (1997). The agronomic effectiveness of reactive phosphate rocks. A comparison of application strategies for soluble phosphorus and reactive phosphate rock fertilisers. *Aust. J. Exp. Agric.,* 37(8): 947-956.

Garg, A.K. and Mikha, S.A. (2010). Effect of long term fertilizer management and crop rotation on accumulation and downward movement of phosphorous in semi-arid subtropical irrigated soil. *Comm. Soil Sci. Plant Anal*., 41: 848-864.

Ghosal, P., Chakraborty, T., and Banik, P. (2011). Phosphorus fixing capacity of the OxicRhodustalf— *Alfisol* soil in the Chotanagpur plateau region of Eastern India. *Agricul. Sci.,* 2(4): 487-490.

Gichangi, E.M., Mnkeni, P.N.S., and Brookes, P.C. (2009). Effects of goat manure and inorganic phosphate addition on soil inorganic and microbial biomass phosphorus fractions under laboratory incubation conditions. *Soil Sci. Plant Nutr.,* 55(6): 764-771.

Goenadi, D.H. and Sugiarto, Y. (2000). Bioactivation of poorly soluble phosphate rocks with a phosphorus-solubilizing fungus. *Soil Sci. Soc. Am. J.,* 64(3): 927 932.

Goldstein, A.H. (1986). Bacterial mineral phosphate solubilization: historical perspectives and future prospects. *Am. J. Altern. Agric.,* 1: 57-65.

Goldstein, A.H. (1994). Involvment of quinoprotein glucose dehydrogenase in the solubilization of exogenous phosphates by gram-negative bacteria. In: Torriani-Gorini, A., Yagil, E., and Silver, S. (ed). Phosphate in microorganisms: Cellular and molecular biology. Washington, DC: ASM Press, pp. 197-203.

Goldstein, A.H. and Rogers, R.D. (1999).Biomediated continuous release phosphate fertilizer. U.S. *Patent*, Lockheed Martin Idaho Technologies Co., U.S., 5: 912-398.

Goswami, N.N. and Sahrawat, K.L. (1982). Nutrient transformations in soils: Macronutrients.In: Review of Soil Research in India. Proceedings of the 12th International Congress of Soil Science. Pp. 123-145, February 8-16, 1998. New Delhi, India.

Goundar, M.S., Morrison, R.J., and Togamana, C. (2014). Phosphorus requirements of some selected soil types in the Fiji sugarcanebelt. *South Pacific J. Nat. Applied Sci.,* 32 (1): 1-10.

Guppy, C.N., Menzies, N.W., Blamey, F.P.C., and Moody, P.W. (2005). Do decomposing organic matter residues reduce phosphorus sorption in highly weathered soils?. *Soil Sci. Soc. America J.,* 69: 1405-1411.

Gupta, P.K. (2007). Soil, Plant and Water Fertilizer analysis, second edition.

Gupta, R.K., Singh, T.A., and Ghildyal, B.P. (1972). Fate of native and applied phosphorus under saturated and unsaturated soil moisture conditions. *Agro. Chem.,* 16: 548-54.

Gupta, R.K., Singh, M., and Shukla, U.C. (1977). Characterization of added and soil P in some soils of Haryana. *J. Indian Soc. Soil Sci*., 25: 134-140.

Hanway, J.J. and Heidel, H. (1952). Soil analysis methods as used in Iowa State College Soil Testing Laboratory. *Iowa Agric*., 57: 1-31.

Haug, A. (1983). Molecular aspects of aluminum toxicity. *Crit. Rev. Plant Sci.,* 1(4): 345-373.

Havlin, J.L., Beaton, J.D., Tisdale, S.L., and Nelson, W.L. (2009). Soil fertility and fertilizers. In:An introduction to nutrient management, 7th edn. Prentice- Hall of India Private Limited, New Delhi.

Haynes, R.J. and Mokolobate, M.S. (2001). Amelioration of Al toxicity and P deficiency in acid soils by additions of organic residues: a critical review of the phenomenon and the mechanisms involved. *Nutrient Cycl. Agro ecosystem.* 59(1): 47-63.

He, Z.L., Bian, W., and Zhu, J. (2002). Screening and identification of microorganisms capable of utilizing phosphate adsorbed by goethite.*Comm. Soil Sci. Plant Anal.,* 33(5-6): 647-663.

Hemwall, J.B. (1957). The fixation of phosphorus by soils. *Adv. Agron*., 9: 95-112.

Holford, I.C.R. (1976). Effects of phosphate buffer capacity of soil on the phosphate requirements of plants. *Plant soil*, 45: 433-444.

Holford, I.C.R. (1989). Phosphorous behaviour in soils. *Agri. Sci*., 12: 15- 20.

Holford, I.C.R. (1997). Soil Phosphorus: Its measurement and its uptake by plants. *Aust. J. Soil Res*., 35: 227-239.

Holford, I.C.R. and Mattingly, G.E.G. (1976). A model for the behaviour of labile phosphates in soil. *Plant Soil*, 44: 219–229.

Horta, C., Monteiro, F., Madeira, M., and Torrent, J. (2013). Phosphorus sorption and desorption properties of soils developed on basic rocks under a sub-humid Mediterranean climate. *Soil Use Management*, 29: 15-23.

Hoyt, P.B. and Webber, M.D. (1974). Rapid measurement of plant available aluminium and manganese in acid Canadian soils. *Can. J. Soil Sci*., 54: 53-61.

Hue, N.V. (1991). Effect of organic acids/ anions on P sortion and phyto availability in soils with different mineralogies. *Soil Sci*., 152: 463-471.

Igual, J., Valverde, A., Cervantes, E., and Velazquez, E. (2001). Phosphate-solubilizing bacteria as inoculants for agriculture: use of updated molecular techniques in their study. *Agronomy*, 21(6-7): 561-568.

International Society of Soil Science (ISSS) (1929). Minutes of the first commission meetings, International Congress of Soil Science, Washington, 1927, *Proc. Inter. Soc. Soil Sci*., 4: 215-220.

Iyamuremye, F. and Dick, R.P. (1996). Organic amendments and phosphorus sorption by soils. *Adv. Agron.,* 56: 139-185.

Jackson, M.L. (1973). Soil Chemical Analysis. Prentice Hall of India Pvt. Ltd., New Delhi.

Jaggi, T.N. (2000). Rock phosphate resource in India: An overview. In: Ghose, A.K. (ed) Mining-Challenges of the 21st century, L.P.H. publisher, New Delhi, pp. 465-467.

Jain, S.C. (1997). Available macro and micro nutrient status in relation to their physico-chemical properties of I.G.K.V.V. Raipur (Chhattisgarh). M.Sc. Thesis, Submitted to I.G.K.V.V. Raipur, Chhattisgarh.

Jalali, M. and Ranjbar, F. (2009). Ageing effects on phosphorus transformation rate and fractionation in some calcareous soils. *Geoderma*, 155: 101-106.

Jasinski, S.M. (2013). Annual publication: Mineral commodity summaries: Phosphate rock (1996-2013). US Geological Survey.Web.http://minerals.usgs.gov/minerals/pubs/commodity/phosphate_rock . Accessed 26 July 2015.

Jilani, G., Akram, A., Ali, R.M., Hafeez, F.Y., Shamsi, I.H., Chaudhry, A.N., and Chaudhry, A.G. (2007). Enhancing crop growth, nutrients availability, economics and beneficial rhizospheremicroflora through organic and biofertilizers. *Ann. Microbiol.*, 57(2): 177-183.

Juo, A.S.R. and Fox, R.L. (1977). Phosphate sorption characteristics of some bench mark soils of West Africa. *Soil Sci*., 124: 370-376.

Kafkafi, U., Bar-Yosef, B., Rosenburg, R., and Sposito, G. (1998). Phosphorus adsorption by kaolinite and montmorillonite: II. Organic anion competition. *Soil Sci. Soc. Am.*, 52: 1585-1589.

Kalidas-Singh, S., Thakuria, D., and Hazarika, S. (2014). Rhizosphere-based phosphorus management for rice in acidic inceptisols. In: Proceedings of the 9th International Soil Science congress on “The Soul of Soil and Civilization” organized by Soil Science Society of Turkey cooperation with Federation of Euroasian Soil Science Societies to be held 14-16 October, 2014, Side, Turkey.

Kaistha, B.P., Sharma, P.K., and Sharma, R.P. (1997). Influence of soil components on phosphorus fixing capacity of some Alfisols in Himachal Pradesh. *J. Indian Soc. Soil Sci*., 4: 261-264.

Kamprath, E.J. and Watson, M.E. (1980). Conventional soil and tissue test for assessing the phosphorus status of soils. In: F.E. Khawsaneh *et al.* (Ed) The role of Phosphorus in Agriculture. *Soil Sci. Soc. Am*. *J*., Madison, WI., USA, pp. 433-469.

Kanwar, J.S. (1986). Crop production techniques and fertilizer management with special reference to phosphate fertilizer in rainfed areas. ICRISAT experience. Proceedings of the IMPHOS meeting on crop production techniques and fertilizer management in rainfed agriculture in southern Asia, InstitutMondial Du Phosphate (IMPHOS) and Fertilizer Association of India, Pp. 1-44, 23-25 January, 1986, New Delhi, India.

Kanwar, J.S. and Grewal, J. (1990). Phosphorus fixation in Indian soils.Second edition.Indian Council of Agricultural Research,New Delhi, India.

Kanwar, J.S. and Reddy, D.D. (2003). Phosphorus Fixation and Management in Indian soils, First edition, IARI, Krishi Anusandhan Bhavan, New Delhi, pp. 30-40.

Kaur, G. and Reddy, M.S. (2015). Effects of phosphate-solubilizing bacteria, rock phosphate and chemical fertilizers on maize-wheat cropping cycle and economics.*Pedosphere*, 25(3): 428–437.

Kennedy, W.C., Newman, S., Kumpf, H., and Laing, J.A. (2001). Decomposition responses to phosphorus enrichment in an Everglades (USA) slough. Biogeochem., 54(3): 229–250.

Khalil, M.I., Schmidhalter, U., Gutser, R., and Heuwinkel, H. (2011). Comparative efficiency of urea fertilization via super granules versus prills on nitrogen distribution, yield response and nitrogen use efficiency of spring wheat. *J. Plant Nutr.,* 34: 779-797.

Khan, K.S. and Joergensen, R.G. (2009). Changes in microbial biomass and P fractions in biogenic household waste compost amended with inorganic P fertilizers. *Bioresour. Technol.,* 100(1): 303-309.

Khan, M.S., Zaidi, A., and Wani, P.A. (2007). Role of phosphate-solubilizing microorganisms in sustainable agriculture—a review. *Agron. Sustain. Develop.,* 27(1): 29-43.

Kreller, D.I., Gibson, G., Novak, W., Van Loon, G.W., and Horton, J.H. (2003). Competitive adsorption of phosphate and carboxylate with natural organic matter on hydrous iron oxides as investigated by chemical force microscopy. *Colloids Surf. Physicochem. Eng. Aspects*, 212(2-3): 249-264.

Kucey, R.M.N., Janzen, H.H., and Legget, M.E. (1989). Microbial mediated increases in plant available phosphorus. *Adv. Agron.,* 42: 199-228.

Kumar, M. (2015). Phosphate requirement of acidic soils in Northeast India: a reappraisal based on phosphate sorption isotherms. *Natl. Acad. Sci. Lett.,* 38(5): 383-386.

Kumar, M., Hazarika, S., Choudhury, B.U., Ramesh, T., Verma, B.C., and Bordoloi, L.J. (2012). Liming and integrated nutrient management for enhancing maize productivity on acid soils of Northeast India. *Indian J. Hill Farming*, 25(1): 35-37.

Kumari, S.R., Subramanium, R., and Reddy, A.N. (2005). Evaluation of fertility status of the cotton growing soils of Guntur district of Andhra Pradesh. *J. Cotton Res. Dev*., 19: 202-206.

Lajtha, K. and Bloomer, S.H. (1988). Factors affecting phosphate sorption and phosphate retention in a desert ecosystem. *Soil Sci*., 146: 160-167.

Lakshminaarayana, K. (2007). Distribution of inorganic phosphorus fractions and critical limit of available P in rice soils of Mizoram. *J. Indian Soc. Soil Sci.*, 55: 481-487.

Le Mare, P.H. (1991). Rock Phosphate in Agriculture.*Exp. Agric.,* 27: 413-422.

Leinweber, P., Turner, B.L., and Meissner, R. (2002). Phosphorus. In: Haygarth, P.M. and Jarvis, S.C. (eds.), Agriculture, Hydrology and Water Quality. CABI, Wallingford, U.K., pp. 29-55.

Lindsay, W.L. (1999). Chemical equilibrial in soil. John Wiley and Sons, New York.

Lindsay, W.L. and Norwell, W.A. (1978). Development of DTPA soil test for zinc, iron, manganese and copper. *Soil Sci. Soc. Am.J.*, 42: 421-428.

Liu, F., He, J., and Colombo, C. (1999). Competitive adsorption of sulfate and oxalate on goethite in the absence or presence of phosphate. *Soil Sci*., 164: 180-189.

Lopez-Hernandez, D. and Burnham, C.P. (1974a). The effect of pH on phosphate adsorption in soils. *Soil Sci*., 25: 207-216.

Lopez-Hernandez, D., and Burnham, C.P. (1974b). The covariance of phosphate sorption with other soil properties in some British and tropical soils. *Soil Sci*., 25: 196-206.

Lynch, J. (1995). Root architecture and plant productivity. *Plant Physiology,* 109: 7–13.

Mahidi, S.S., Hassan, G.I., Hussain, A., and Faisul-ur-Rasoo. (2011). Phosphorus availability issue-Its fixation and role of phosphate solubilizing bacteria in phosphate solubilization-Case study. *Res. J. Agric. Sci.,* 2(1): 174-179.

Mahmood-Soltani, S. and Samadi, A. (2003). Determination of phosphorus fraction in some calcareous soil in Fars province and their relationships with soil physico-chemical properties. *J. Sci. Technol. Agric. Natural Resour*., 7(3): 119-114.

Maida, J.H.A. (1980). Phosphate availability indices related to fractions in selected Malawi soils. *J. Sci. Food Agri*., 29: 423- 428.

Maji, A.K., Obi-Reddy, G.P., and Sarkar, D. (2012). Acid soils of India–Their extent and spatial distribution. *NBSSLUP Bull.*, 145: 1-138.

Majumdar, B., Venkatesh, M.S., Kumar K., and Patiram. (2004) Effect of different farming systems on phosphorus fractions in an acid *Alfisols* of Meghalaya. *J. Indian Soc. Soil Sci.,* 52(1): 29-34.

Majumdar, B., Kumar, K., Venkatesh, M.S., and Patiram (2005). Effect of liming on phosphorus adsorption and desorption behaviour of acidic Alfisols and Entisol of Meghalaya. *J. Indian Soc. Soil Sci.*, 53 (2): 188-193.

Malik, M.A., Marschner, P., and Khan, K.S. (2012). Addition of organic and inorganic P sources to soil - Effects on P pools and microorganisms. *Soil Biol. Biochem.,* 49: 106-113.

Mallikarjuna, G., Sudhir, K., Srikanth, K., and Srinivasamurthy, C.A. (2003). Phosphorus fixation capacity and its relationship with the soil characterstics in laterite soils of Karnataka.*J. Indian Soc. Soil Sci.*, 51(1): 23-25.

Mandal, S.C. (1997). Introduction and Historical Overview. In: Mahapatra, I.C., Mandal, S.C. Misra, C., Mitra, G.N., and Panda N., (ed) Acid Soils of India, ICAR, New Delhi, India, pp. 3-24.

Mandal, L.N. and Khan, S.K. (1972). Release of phosphorus from insoluble phosphatic materials in acidic lowland rice soils. *J. Indian Soc. Soil Sci.,* 20(1): 19-25.

Manikandan, P. and Sastry, T.G. (1988). Role of different soil components in phosphate adsorption in some soils of Mysore plateau. *J. Indian Soc. Soil Sci.*, 36: 228-234.

Manna, M.C., Swarup, A., Wanjari, R.H., Singh, Y.V., Ghosh, R.K., Singh, K.N., Tripathi, A.K., and Saha, M.N. (2006). Soil organic matter in a West Bengal *Inceptisol* after 30 years of multiple cropping and fertilization. *Soil Sci. Soc. Am. J.,* 70: 121-129.

Marschner, H. (1995). Mineral Nutrition of Higher Plants. Academic Press, San Diego, CA.

Marshall, S.K. and Laboski, C.A.M. (2006). Sorption of inorganic and total phosphorus from dairy and swine slurries to soil. *Environ. Quality*, 35(5): 1836-1843.

McBride, M.B. (1994). Environmental chemistry of soils, Oxford University Press, New York.

McDowell, R.W. and Sharpley, A.N. (2003). Phosphorus solubility and release kinetics as a function of soil test P concentration. *Geoderma,* 112: 143-154.

McLaughlin, J.R., Ryden, J.C., and Syers, J.K. (1981). Sorption of inorganic phosphate by iron and aluminium containing components. *Soil Sci.,* 32: 365-377.

McLaughlin, M.J., Fillery, I.R., and Till, A.R. (1991). Operation of the phosphorus, sulphur and nitrogen cycles. In 'Australia's renewable resources: sustainability ad global change. Bureau of Rural Resources Proceedings No. 14'. (Eds RM Gifford, MM Barson). Australian Government Printing Services, Canberra, pp. 67-116.

McLean, E.O. (1965). In methods of soil analysis, part II, (C.A. Black, Ed.), *Am. Soc. of Agron. Inc*., Madison, Wisconsin, USA, pp. 978-998.

Medhi, B.K., Ruhal, D.S., Singh, C.P., Groover, D., and Sarma, A. (2012) Effect of levels of phosphate and organic manures on phosphate supplying capacity and P kinetics in wheat grown in a TypicHaplustept soil. *Crop Res*., 44: 21-25.

Mehrvarz, S., Chaichi, M.R., and Alikhani, H.A. (2008). Effect of phosphate solubilizing microorganisms and phosphorus chemical fertilizer on forage and grain quality of barely (*Hordeumvulgare*L.). *Agric. Environ. Sci.*, *3*(6): 855-860.

Morel, J.L., Fardeau, J.C., Beruff, M.A., and Guckert, A. (1989). Phosphate fixing capacity of soils: a survey using the isotopic exchange technique of soils from north-eastern France. *Fert. Res.,* 19: 103 -111.

Moreno, E.C. and. Lindsay, W.L., (I960). Phosphate phase equilibria in soils. *Soil Sci. Soc. Am. J.*, 24: 177-182.

Morgan, M.A. (1997). The behaviour of soil and fertilizer phosphorus, In: Tunney, H., Carton, O. T., Bookes, P.C., and Johnston, A.E. (ed) Phosphorus loss from soil to water. CAB International, Wallinford, pp.137-149.

Mukwange, U. (1975). The Influence of pH on the adsorption of phosphate by soils from the Guinea and Sudan Savannah zones of Nigeria. *Soil Sci. Soc. Am. Proc*., 39: 1100-1102.

Muralidhar, M., Gupta, B.P., and Jayanthi, M. (2005). Quantity-intensity relationship and fixation of phosphorus in soils from shrimp farming areas of coastal India, Central Institute of Brackish water Aquaculture. *Indian J. Fish.,* 52(41): 421-431.

Muralidharudu, Y., Reddy, K.S, Mandal, B.N., Subba-Rao, A., Singh, K.N., and Sonekar, S. (2011). GIS based soil fertility maps of different states of India, AICRP-STCR, IISS, Bhopal, pp. 224.

Nad, B.K. and Goswami, N.N. (1984). Effect of long-term application of phosphate on soil phosphorus status in a rice-wheat rotation. *J. Indian Soc. Soil Sci.,* 32*:* 288-291.

Naidu, R., Syers, J.K., Tillman, R.W., and Kirkman, J.H. (1990). Effect of liming on phosphate soption by acid soils. *Soil Sci*., 41: 163 -175.

Nair, K.P.P. and Mengel, K. (1984). Importance of phosphate buffer capacity on phosphate uptake by rye. *Soil Sci. Soc. Am. J.*, 48: 92-95.

Oehl, F., Oberson, A., Probst, M., Andreas-Fleissbach, A., Roth, H.R., and Frossard, E. (2001). Kinetics of microbial phosphorus uptake in in cultivated soils. *Biol. Fertil. Soils*, 34: 31-41.

Oehl, F., Oberson, A., Tagmann, H.U. Besson, J.M. Dubois, D., Mader, P., Roth, H.R., and Frossard, E. (2002). Phosphorus budget and phosphorus availability in soils under organic and conventional farming. *Nutr. Cycl. Agroecosyst*., 62: 25-35.

Olsen, S.R. and Wantanabe, F.S. (1963). Diffusion of phosphorus as related to soil texture and plant uptake. *Soil Sci. Soc. Am. J.,* 27(6): 648-653.

Olsen,R.J., Hesler, R.F., and Attoe, O.J. (1970). Effect of manure application, aeration and soil pH on nitrogen transformation and on contain soil test values. *Soil Sci. Soc. Am. J*., 34: 222-225.

Owusu-Bennoah, E. and Acquaye, D.K., (1989). Phosphate sorption characteristics of selected major Ghanaian soils. *Soil Sci.*, *148*(2): 114-123.

Ozanne, P.G. and Shaw, T.C. (1967). Phosphate sorption by soils as a measure of the phosphate requirement for pasture growth. *Aus. J. Agric. Res*., 18: 601-612.

Paliyal, S.S. and Verma, T.S. (2002). Adsorption of added phosphorus as influence by the application of lime and gypsum in an acidic *Alfisols* of Himlayan region. *J. Indian Soc. Sci.,* 50(2): 163-167.

Panda, N. (1987). Acid soils of Eastern India - Their chemistry and management. *J. Indian Soc.Soil Sci.,* 35: 568−581.

Pandey, S.P., Singh, R.S., and Mishra, S.K. (2000). Availability of phosphorus and sulphur in *Inceptisols* of Central Uttar Pradesh. *J. Indian Soc. Soil Sci.*, 48(1): 118-121.

Panhwar, Q.A., Radziah, O., Zaharah, A.R., Sariah, M., and Razi, M.I. (2011). Role of phosphate solubilizing bacteria on rock phosphate solubility and growth of aerobic rice.*J. Environ. Biol.,* 32: 607-612.

Patiram (1991). Liming of acid soils and crop production in Sikkim. *J. Hill Res.,* 4: 6-12.

Patiram and Ramesh, T. (2008). Technologies for soil and soil fertility management of north eastern region, ICAR research complex for NEH Region, Umroi Road, Umiam-793103, Meghalaya, pp. 20.

Patiram, R.N., Raj, M.M. and Prashad, R.N. (1990). Forms of phosphorus and suitable extractants for available phosphorus in acid soils of Sikkim. *J. Indian Soc. Soil Sci.*, 38: 237-242.

Paul, E.A. and Clark, F.E. (1996). Soil microbiology and biochemistry.Academy press, San Diego.

Pierzynski, G.M. and McDowell, R.W. (2005). Chemistry, cycling, and potential movement of inorganic phosphorus in soils. *Phosphorus: agriculture and the environment*, (phosphorusagric), pp.53-86.

Pierzynski, G.M., Logan, T.J., Traina, S.J., and Bigham, J.M. (1990). Phosphorus chemistry and mineralogy in excessively fertilized soils: Quantitative analysis of phosphorus-rich particles. *Soil Sci. Soc. Am. J.,* 54: 1576-1583.

Ponmurugan, P. and Gopi, C. (2006). Distribution pattern and screening of phosphate solubilizing bacteria isolated from different food and forage crops. *J. Agron.,* 5(4): 600-604.

Pradhan, N. and Sukla, L.B. (2005). Solubilization of inorganic phosphate by fungi isolated from agriculture soil. *African. J. Biotechnol.,* 5: 850-854.

Probert, M.E. (1983). The sorption of phosphate by soils.Soils: an Australian viewpoint.Commonwealth Scientific and Industrial Research Organisation (CSIRO) Melbourne Academic Press, London, pp. 427-435.

Prochnow, L.I., Chien, S.H., Carmona, G., Dillard, E.F., Henao, J., and Austin, E.R. (2008). Plant availability of phosphorus in four superphosphate fertilizers varying in water-insoluble phosphate compounds. *Soil sci. Soc. Am J.,* 72(2): 462-470.

Quang, V.D., Thai, V.C., Linh, T.T.T., and Dufey, J.E. (1996). Phosphorus sorption in soils of the Mekong Delta (Vietnam) as described by the Langmuir equation. *Eur. J. Soil Sci*., 47: 113–123.

Rajan, S.S.S. (1973). Phosphorus adsorption characteristics of Hawaiian soils and their relationships to equilibrium phosphorus concentrations required for maximum growth of millet. *Plant Soil*, *39*(3): 519-532.

Rajni, A.V., Patil, D.V., Shobhana, H.K., Naria, J.N., and Golakiya, B.A. (2010). Dynamics of phosphorus fractions in a calcareous VerticHaplustepts under AICRP-LTFE soils, *Asian J. Soil Sci.,* 5(1): 83-89.

Rajput, A., Panhwar, Q. A., Naher, U.A, Rajput, S. Hossain, E. and Shamshuddin, J. (2014). Influence of incubation period, temperature and different phosphate levels on phosphate in soil. *Am. J. Agri. Biol. Sci.*, 9(2): 251-260.

Ram, M., Prasad, R.N., and Patiram. (1987). Adsorption and phosphate fixation in occurring in different altitudes. *J. India Soc. Soil Sci.*, 35: 207-216.

Rao, T*.S.,* Ahmed, N., and Rao, H.K. (1972). Fractionation of the residual phosphorus compounds in black and red soils treated with phosphatic fertilizers. *J. Indian Soc. Soil Sci.,* 20(4): 323-326.

Rao, S.C., Venkateswarlu, B., Lal, R., Singh, A.K., and Sumanta, K. (2013). Sustainable management of soils of dryland ecosystems of India for enhancing agronomic productivity and sequestering carbon. *Adv. Agron*., 121: 254-329.

Rao, C.S., Lal, R., Prasad, J.V.N.S., Gopinath, K.A., Singh, R., Jakkula, V.S., Sahrawat, K.L., Venkateswarlu, B., Sikka, A.K., and Virmani, S.M. (2015). Potential and challenges of rainfed farming in India. *Adv. Agron.*, 133: 9-11.

Rasmussen, J., Soegaard, K., Pirhofer-Walzl, K., and Eriksen, J. (2012). N_2 fixation and residual N effect of four companion legume grass species. *Eur. J. Agron.*, 36: 66-74.

Rayment, G.E. and Higginson, F.R. (1992). Australian laboratory handbook of soil and water chemical methods. Inkata Press, Australia, pp. 188-253.

Rayment, G.E. and Lyons, D.J. (2011). *Phosphorus soil chemical methods- Australasia*.CSIRO Publications, Collingwood, Victoria.

Reddy, P.R. and Raju, A.P. (2006). Integrated nutrient management for rice.Proceedings of the 18th World Congress of Soil Science. Pp. 166-20, July 9-15, 2006. Philadelphia, Pennsylvania, USA.

Reddy, D.D., RaoSuba, A., and Rupa, T.R. (2000). Effect of continuous use of cattle manure and fertilizer phosphorus on crop yields and soil organic phosphorus in a *Vertisol. Bioresour. Technol.,* 75: 113-18.

Reddy, D.D., Rao, S.A., and Singh, M. (2005). Changes in P fractions and sorptions in an *Alfisols* following crop residue application. *J. Plant Nutr. Soil Sci.,* 168: 241-247.

Richardson, A.E. (1994). Soil microorganisms and phosphorus availability. *Soil Biota*, 8: 50–62.

Richardson, E.R., Hocking P.J., Simpson, R.J., and George, T.S. (2009). Plant mechanisms to optimise access to soil phosphorus.*Crop Pasture Sci.,* 60(2): 124-143.

Rodriguez, H. and Fraga, R. (1999). Phosphate solubilizing bacteria and their role in plant growth promotion. *Biotechnol. Adv.,* 17(4): 319-339.

Rousk, J., Brookes, P.C., and Baath, E. (2009). Contrasting soil pH effects on fungal and bacterial growth suggests functional redundancy in carbon mineralisation. *Appl. Environ. Microbiol.*, 75: 1589–1596.

Rowell, D.L., Martin, M.W., and Nye, P.H. (1967). Fundamentals of soil plant interactions as derived from nutrient diffusion in soil, uptake kinetics and morphology of roots. *Soil Sci.,* 204 – 222.

Rubaek, G.H. and Sibbessen, E. (1993). Resin extraction of labile soil organic phosphorus*. Soil Sci.*, 44: 467–478.

Sahrawat, K.L. (1997). EDTA extractable P in soil as related to available and inorganic phosphorus forms. *Comm. Soil Sci. Plant Anal.*, 8(4): 281-287.

Sahu, G.C. and Mishra, K.N. (1997). Morphology, characteristics and classification of soil of an irrigated river flood plain in the eastern coastal region. *J. Indian Soc. Soil Sci.*, 44(1): 176-177.

Sanchez, P.A. (1976). Properties and management of soils in the tropics.John Wiley & Sons. New York, USA.

Sanchez, P.A., Palm, C.A., and Buol, S.W. (2003). Fertility capability of soil classification: a tool to help assess quality in the tropics. *Geoderma*, 114 (3-4): 157-185.

Sarkar, A.K. (2015). Soil acidity and liming. In: Rattan, R.K., Katyal, J.C., Dwivedi, B.S., Sarkar, A.K., Bhattacharyya, T., Tarafdar, J.C., and Kukal, S.S. (eds), Soil Science: An Introduction. Indian Society of Soil Science, New Delhi, pp. 329-352.

Sarkar, D., Haldar, A., and Mandal, D. (2014). Forms of phosphorus in relation to soil maturity along a toposequence under hot, dry, subhumid agro-ecological subregion of West Bengal. *J. Indian Soc. Soil Sci.*, 62(1): 29-37.

Schmitt S.K., Nemergut D.R., Miller, A.E., Freeman, K.R., King, A.J., and Seimon, A. (2009). Microbial activity and diversity during extreme freeze-thaw cycles in periglacial soils, 5400m elevation cordillera vilcanota, Peru. *Extremophiles,* 13: 807-816.

Schofield, R.K. (1955). Can a precise meaning be given to available soil phosphorus? *Soil Fertilizers,* 18: 373-375.

Shariatmadari, H., Shirvani, M., and Jafari, A., (2006). Phosphorus release kinetics and availability in calcareous soils of selected arid and semiarid toposequences. *Geoderma*, 132(3-4): 261-272.

Sharma, P.D. and Sarkar, A.K. (2005). Managing acid soils for enhancing productivity technical bulletin. Indian Council of Agricultural Research, NRM Division, Krishi Anusandhan Bhavan - II, New Delhi, pp. 23.

Sharma, U.C. and Singh, R.P. (2002). Acid soils of India: their distribution, management and future strategies for higher productivity. *Fertilizer News*, 47(3): 45-52.

Sharma, P.D., Baruah, T.C., Maji, A.K., and Patiram (2006). Management of acid soils of NEH Region. Indian Council of Agricultural Research, Krishi Anusandhan Bhavan, Pusa Campus, New Delhi, pp. 45-60.

Sharma, K., Dak, G., Agrawal, A., Bhatnagar, M., and Sharma, R. (2007). Effect of phosphate solubilizing bacteria on the germination of *Cicerarietinum* seeds and seedling growth.*J. Herb. Med. Toxicol*., 1(1): 61-63.

Sharma, S.B., Sayyed, R.Z., Trivedi, M.H., and Gobi, T.A. (2013). Phosphate solubilizing microbes: sustainable approach for managing phosphorus deficiency in agricultural soils. *Springer Plus*, 2: 587.

Shen, J., Li, R., Zhang, F., Fan, J., Tang, C., and Rengel, Z. (2004). Crop yields, soil fertility and phorphorus fractions in response to long term fertilization under the rice monoculture system on a calcareous soil. *Field Crops Res.,* 86: 225-238.

Shivaprasad, C.R., Reddy, R.S., and Velayutham, M.M. (1998). Land resource management. NBSS and LUP, Nagpur, 47: 65-68.

Sibbesen, E. (1983). Phosphate soil tests and their *suitability to assess* the phosphate status of soil. *J. Sci. Food Agril.*, 34: 1368-1374.

Siddaramappa, R., Jagadish, N.R., and Srinivasamurthy, C.A. (1991). Efficiency of rock phosphate as phosphatic fertilizer to rice in acid soil of Karnataka, India. *Dev. Plant Soil Sci.*, 45: 307-312.

Siemens, J., Ilg, K., Lang, F., and Kaupenjohann, M. (2004). Adsorption controls mobilization of colloids and leaching of dissolved phosphorus. *Euro. J. Soil Sci.*, 55(2): 253-263.

Sims, J.T. and Pierzynski, G.M. (2005). Chemistry of phosphorus in soils. *Chem. processes soils*, 4: 151-192.

Singh, C.P. and Amberger, A. (1998). Solubilization of rock phosphate by humic and fulvic acids extracted from straw compost. *Agrochimica,* 41: 221-228.

Singh, R. and Brar, S.P.S. (1973). Correlation of different soil tests with maize response for nitrogen and phosphorus at different fertility levels of the soils*. J. Indian Soc. Soil Sci*., 2: 213-17.

Singh, K.P. and Singpuri, M.K. (1986). Sorption of phosphorus as related to properties of soils of Bihar*. J. Indian Soc. Soil Sci*., 34: 603-604.

Singh, D.K., Chand, L., and Singh, K.N. (2005). Evaluation and sustainability of bio-fertilizers in combination with inorganic fertilizer in field pea for temperate conditions of Kashmir. *Research Council Meet Report*.

Singh, U.V., Raj, D., Chand, T., and Tomar, N.K. (2011). Effect of calcium carbonate and clay on phosphate sorption by soils. *J. India Soc. Soil Sci*., 59(1): 43-47.

Smith, S.E. and Read, D.J. (1997). Mycorrhizal Symbiosis, Second Edition. Academic Press, San Diego.

Son, T.T.N., Diep, C.N., and Giang, T.T.M. (2006). Effect of bradyrhizobia and phosphate solubilizing bacteria application on soyabean in rotational system in the Mekong delta. *Omonrice*., 14: 48-57.

Sood, A., Patel, L.B., and Patel, P.K. (2003). N, P, K Status of sub mountainous tract of Punjab. *J. Indian Soc. Soil Sci.*, 19: 33-40.

Subbiah, B.V. and Asija, G.L. (1956). A rapid procedure for the determination of available nitrogen in soils. *Curr. Sci*., 25: 259-260.

Sugihara, S., Funakawa, S., Kilasara, M., and Kosaki, T. (2010). Dynamics of microbial biomass nitrogen in relation to plant nitrogen uptake during the crop growth period in a dry tropical cropland in Tanzania. *Soil Sci. Plant Nut.,* 56: 105–114.

Sundara, B., Natarajan, V., and Hari, K. (2002). Influence of phosphorus solubilizing bacteria on the changes in soil available phosphorus and sugarcane yields. *Field Crops Res.,* 77(1): 43-49.

Surchand-Singh, K., Hazarika, S., Thakuria, D., Bordoloi, L.J., and Deka, B.C. (2017). Long-term management impact on soil quality under Peach (*Prunispersica*L.) orchard in humid subtropics of Eastern Himalayas. *J. Indian Soc. Soil Sci.,* 65(4): 401-409.

Syers, J.K., Browman, G.W., and Corey, R.B. (1977). Phosphate sorption by soils evaluated by the Langmuir adsorption equation. *Soil Sci. Soc. Am. J.*, 37: 358-363.

Syers, J.K., Evans, T.D., Williams, D.H., and Murdock, J.T. (1971). Phosphate sorption parameters of representative soils from Rio Grande do sul, Brazil. *Soil Sci.*, 112: 267-275.

Sylvia, D.M, Hartel, P.G., Fuhrmann, J.J., and Zuberer, D.A. (2005). Principles and applications of soil microbiology. Pearson Education Inc, Prentice hall, New Jersey, pp. 263-282.

Taktek, S., St-Arnaud, M., Piche, Y., Fortin, J.A., and Antoun, H. (2017). Igneous phosphate rock solubilization by biofilm-forming mycorrhizo-bacteria and hyphobacteria associated with *Rhizoglomusirregulare* DAOM 197198. *Mycorrhiza,* 27: 13–22.

Tate, K.R. (1984). The biological transformation of P in soil. In: *Biological Processes and Soil Fertility*, Springer, Dordrecht, pp. 245-256.

Taylor, A.W. and Gurley, E.L. (1964). Solubility of variscite. *Soil Sci.,* 98: 9-13

Tening, A.S., Foba-Tendo, J.N., Yakum-Ntaw, S.Y., and Tchuenteu, F. (2013). Phosphorus fixing capacity of a volcanic soil on the slope of mount Cameroon. *Agric. Biol. J. N. Am*., 4(3): 166-174.

Thakur, R.S., Bisen, D.C., and Dubey, S.M. (1975). Transformations of applied phosphorus under waterlogged conditions in rice culture. *J. Indian Soc. Soil Sci.,* 13: 423-27.

Thakuria D., Hazarika S., and Krishnappa R. (2016). Soil acidity and management options. *Indian J. Fertilizers,* 12: 40-56.

Thakuria, D., Talukdar, N.C., Goswami, C., Hazarika, S., Boro, R.C., and Khan, M.R. (2004). Characterization and screening of bacteria from rhizosphere of rice grown in acidic soils of Assam. *Curr. Sci.*, 86: 978-995.

Thakuria, D., Talukdar, N.C., Goswami C., Hazarika, S., Kalita, M.C., and Bending, G.D. (2009). Evaluation of rice-legume-rice cropping system on grain yield, nutrient uptake, nitrogen fixation, and chemical, physical, and biological properties of soil. *Biol. Fertil. Soils*, 45: 237-251.

Tiessen, H.J., Stewart, W.B, and Cole, C.V. (1984). Pathways of phosphorus transformations in soils of differing pedogenesis*. Soil Sci. Soc. Am. J.,* 48: 853-858.

Tinker, P.B. and Nye, P.H. (2000).Solute movement in the Rhizosphere. Oxford university press, New York.

Tisdale, S.L., Nelson, W.L., and Beaton, J.D. (1985). Soil fertility and fertilizers. 4th ed., Macmillan Publishing Co, New York, p. 754.

Tisdale, S.L., Nelson, W.L., and Beaton, J.D. (1990). Soil and fertilizer phosphorus. In: Soil fertility and fertilizer, 4th edn, Macmillan, Singapore, pp. 189-237.

Tiwari, K.N. (2012). Fundamentals of soil science.Second edition. Rattan, R.K., Indian Society of Soil Science, New Delhi.

Tomar, N.K. (2000). Dynamics of phosphorus in soils. *J. Indian Soc. Soil Sci*., 48: 640-73.

Tomar, N.K. (2001). Response in crops to applied phosphate. IMPOMOS-IFFCO Discussionheld at the Fertilizer Management and Development Institute. IFFCO, Gurgaon.

Turner, B.L., Richardson, A.E., and Mullaney, E.J. (2007). Inositol phosphates in soil: amounts, forms and significance of the phosphorylated inositol stereoisomers. Inositol Phosphates: Linking Agriculture and the Environment. CABI, Wallingford, UK, pp. 186–206.

Turner, B.L., Driessen, J.P., Haygarth, P.M., and Mckelvie, I.D. (2003). Potential contribution of lysed bacterial cells to phosphorus solubilisation in two rewetted Australian pasture soils. *Soil Biol. Biochem.*, *35*(1): 187-189.

Vaccari, D.A. (2009). Phosphorus: a looming crisis. *Soil Sci. Soc. Am. J.*, 300(6): 54-59.

Van-Kauwenbergh, S.J. (1991). Overview of phosphate deposits in East and Southern Africa. *Fert. Res.,* 30: 127-150.

Van-Straaten, P. (2002). Rocks for crops: agrominerals of sub-Saharan Africa. ICRAF, Nairobi, Kenya, pp. 338.

Vassilev, N., Vassileva, M., and Nikolaeva, I. (2006). Simultaneous P-solubilizing and biocontrol activity of microorganisms: potentials and future trends. *Appl. Microbiol. Biotechnol*., 61: 435-440.

Vassilev, N., Vassileva, M., Fenice, M., and Federici, F. (2001). Immobilized cell technology applied in solubilization of insoluble inorganic (rock) phosphates and P plant acquisition. *Bioresour. Technol.,* 79: 263-271.

Velayutham, M. and Bhattacharya, T. (2000). Soil resource management. In: Yadav, J.S.P. and Singh, G.B., (ed)Natural resource management for agricultural production in India. Indian Society of Soil Science, pp.133-135.

Venkatesh, M.M., Majumdar, B., Kumar, K., and Patiram (2002). Effect of phosphorus, FYM and limestone on yield, P uptake by maize and forms of soil acidity in typichaliudalf of Meghalaya. *J. Indian Soc. Sci*., 50(3): 254:258.

Venkatesh, M.S. and Majumdar, B. (2001).Phosphorus fixation capacity in acid Alfisols of Meghalaya.*Indian J. Hill Farm.*, 14(1): 136 – 140.

Verma, L.N. (1993). Biofertiliser in agriculture. In: Thampan, P.K. (ed.) Organics in soil health and crop production. Peekay Tree Crops Development Foundation, Cochin, India. pp. 152-183.

Verma, S. (2002). Studies on long-term effects of chemical fertilizers and amendments on phosphorus dynamics and its budgeting in wet temperate zone soils of Western Himalayas. M.Sc. Thesis, Submitted to CSK Himachal Pradesh Krishi Vishvavidyalaya, Palampur, India.

Verma, S., Subehia, S.K., and Sharma, S.P. (2005). Phosphorus fractions in an acid soil continuously fertilized with mineral and organic fertilizers. *Biol. Fertil. Soils*, 41(4): 295-300.

Von-Uexküll, H.R., and Mutert, E. (1995). Global extent, development and economic impact of acid soils. *Plant Soil,* 171: 1-15.

Walkley, A., and Black, I.A. (1934). An examination of the Degtjareff method for determining soil organic matter, and proposed modification of the chromic acid titration method. *Soil Sci*., 34: 29-38.

Wani, P.A., Khan, M.S., and Zaidi, A. (2007). Co-inoculation of nitrogen fixing and phosphate solubilizing bacteria to promote growth, yield and nutrient uptake in chickpea. *Acta. Agron. Hung.,* 55(3): 315-323.

Webber, M.D. and Mattingly, G.E.G. (1970). Inorganic soil phosphorus. I. Changes in monocalcium phosphate potentials on cropping*. Soil Sci.*, 21: 111- 120.

White, E. and Payne, G., (1980). Distribution and biological availability of reactive high molecular weight phosphorus in natural waters in New Zealand. *Can. J. fisheries aquatic Sci.*, *37*(4): 664-669.

Whitelaw, M.A. (2000). Growth promotion of plants inoculated with phosphate solubilizing fungi. *Adv. Agron*., 69: 99-151.

Wild, A. (1988). Plant Nutrients in Soil: Phosphate. In: Russells Soils Conditions and Plant Growth. *Longman Scientific J. Soil Res.*, 9: 95-106.

Xiao, C.Q., Chi, R.A., He, H., Qiu, G.Z., Wang, D.Z., and Zhang, W.X. (2009). Isolation of phosphate solubilizing fungi from phosphate mines and their effect on wheat seedling growth. *Appl. Biochem. Biotechnol*., 159(2): 330-342.

Xiao, Y., Wang, X., Chen, W., and Huang, Q. (2017). Isolation and identification of three potassium-solubilizing bacteria from rape rhizospheric soil and their effects on ryegrass. *Geomicrobiol. J.*, *34*(10): 873-880.

Yan, D., Wang, D., and Yang (2007).Long-term effect of chemical fertilizer, straw, and manure on labile organic matter fractions in a paddy soil. *Biol. Fertil. Soils*, 44: 93-101.

Yazdani, M., Bahmanyar, M.A., Pirdashti H., and Esmaili, M.A. (2009). Effect of Phosphate solubilization microorganisms (PSM) and plant growth promoting rhizobacteria (PGPR) on yield and yield components of Corn (*Zea mays* L.). *Proc*. *World Acad. Sci. Eng. Technol*., 37: 90-92.

Zaidi, A. (1999). Synergistic interactions of nitrogen fixing microorganisms with phosphate mobilizing microorganisms. Ph.D. Thesis, Submitted to Aligarh Muslim University, Aligarh, India.

Zaidi, A. and Khan, M.S. (2006). Co-inoculation effects of phosphate solubilizing microorganisms and *Glomusfasciculatumon* on green gram-*Brady rhizobium* symbiosis. *Turk. J. Agric*., 30(3): 223-230.

Zhang Z., Simard, R.R., Lafond, J., and Parent, L.E. (2001). Changes in phosphorus fraction of a humicgelisol as influenced by cropping system and fertilization.World congress of soil science, Philadelphia, USA, pp. 9-16.

Zhang, J., Li, M., Liu, S., Liu, Y., Zhang, L., Cao, Q., and Sun, D. (2011). Seasonal variations and bioavailability of inorganic phosphorus in soils of Yeyahu Wetland in Beijing, China. *Sediment Res*., 26(2): 181-192.

Zhang, T.Q., MacKenzie, A.F., Liang, B.C., and Drury, C.F. (2004). Soil test phosphorus and phosphorus fractions with long-term phosphorus addition and depletion. *Soil Sci. Soc. Am. J*., 68: 519–528.

APPENDIX

Appendix 1: Soil colour notation by using Munsellcolour chart

Profile	Soil colour			
	Dry		Moist	
P1	10YR 4/4	Dark yellowish brown	10 YR 3/4	Dark yellowish brown
P2	7.5YR 4/6	Strong brown	2.5YR 3/6	Dark red
P3	10YR 5/6	Yellowish brown	5YR 3/3	Dark reddish brown
P4	2.5 YR 6/4	Light yellowish brown	2.5 Y 4/4	Olive brown
P5	10YR 5/4	Yellowish brown	7.5 YR 3/4	Dark brown
P6	2.5Y 5/4	Light olive brown	10YR 3/3	Dark brown
P7	10YR 2/4	Yellowish brown	10 YR 3/4	Dark yellowish brown
P8	2.5Y 5/4	Light olive brown	10YR 4/2	Dark greyish brown
P9	2.5Y 7/4	Pale yellow	2.5 Y 5/4	Light olive brown
P10	10YR 5/3	Brown	5 YR 3/2	Dark reddish brown
P11	2.5Y 6/2	Light brownish gray	5Y 4/1	Dark grey
P12	2.5YR 6/8	Olive yellow	10 YR 4/6	Dark yellowish brown

Appendix 2: Descriptive - ANOVA soil physico-chemical properties

		Sum of Squares	df	Mean Square	F	Sig.
MWHC	Between Groups	2739.116	11	249.011	104.590	0.000
	Within Groups	57.140	24	2.381		
	Total	2796.256	35			
FC	Between Groups	1599.268	11	145.388	546.914	0.000
	Within Groups	6.380	24	0.266		
	Total	1605.648	35			
SOC	Between Groups	6.990	11	0.635	15.886	0.000
	Within Groups	0.960	24	0.040		
	Total	7.950	35			
Avl.N	Between Groups	98005.982	11	8909.635	105.527	0.000
	Within Groups	2026.313	24	84.430		
	Total	100032.296	35			
Avl.K	Between Groups	156112.063	11	14192.006	696.854	0.000
	Within Groups	488.780	24	20.366		
	Total	156600.843	35			
Avl.P	Between Groups	1943.712	11	176.701	303.205	0.000
	Within Groups	13.987	24	0.583		
	Total	1957.699	35			
Ex.Al	Between Groups	40.817	11	3.711	751.568	0.000
	Within Groups	0.118	24	0.005		
	Total	40.936	35			
Ex.CaMg	Between Groups	444.097	11	40.372	158.194	0.000
	Within Groups	61.125	24	0.255		
	Total	450.222	35			
CEC	Between Groups	846.790	11	76.981	34.811	0.000
	Within Groups	53.073	24	2.211		
	Total	899.864	35			
Clay	Between Groups	9462.813	11	860.256	2204.465	0.000
	Within Groups	9.366	24	0.390		
	Total	9472.179	35			
RS.Al	Between Groups	912661.278	11	82969.207	1826.463	0.000
	Within Groups	1090.228	24	45.426		
	Total	913751.506	35			
DTPA-Fe	Between Groups	351.061	11	31.915	4.066	0.002
	Within Groups	188.367	24	7.849		
	Total	539.428	35			
pH	Between Groups	40.275	11	3.661	490.360	0.000
	Within Groups	0.179	24	0.007		
	Total	40.454	35			
BS	Between Groups	7660.476	11	696.407		0.000
	Within Groups	181.682	24	7.570		
	Total	7842.159	35			
BD	Between Groups	0.626	11	0.057	325.234	0.000
	Within Groups	0.004	24	0.000		
	Total	0.630	35			