EFFECT OF ORGANIC MATTER ON PHOSPHORUS TRANSFORMATION AND UPTAKE BY RICE IN ACIDIC SOILS OF WEST BENGAL

A Thesis

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Of

MASTER OF SCIENCE (Agriculture)

In

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By

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This is to certify that the work recorded in the thesis entitled **"Effect of organic matter on phosphorus transformation and uptake by rice in acidic soils of West Bengal"** submitted by Mr. Sourav Saha for the award of the degree of master of science (Agriculture) in soil science and agricultural chemistry of the Uttar Banga Krishi Viswavidyalaya, is the faithful and Bonafede research work carried out under my direct supervision and guidance. The results of the investigation reported in the thesis have not so far been submitted for any other degree or diploma. The assistance and help received from various sources during the course of investigation have been duly acknowledged.

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EFFECT OF ORGANIC MATTER ON PHOSPHORUS TRANSFORMATION AND UPTAKE BY RICE IN ACIDIC SOILS OF WEST BENGAL

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Abstract

Phosphorus (P) is a vital component of ATP, DNA, RNA, phospholipids, etc. and is extremely important to human and crop physiology. Phosphorus plays an important role in metabolic pathways, root development, tillering, early flowering, and crop ripening. It is 2nd most important nutrient for rice. Among the plant nutrients, P has the most limiting bioavailability. Even P applied through fertilizers or organic sources tends to get fixed in the soil, especially in acidic soil in various insoluble and sparingly soluble fractions. Even, the higher application of P could be detrimental to crops and may lead to eutrophication. Mere measuring available P in the soil could not assess the P supplying power of soil in long run. Therefore, it is required to assess the P releasing power of soilbefore applying P from external sources. The soils of northern part of West Bengal are acidic in nature and known to have P deficiency. Hence, this study was undertaken to examine (i) P fractions in acidic soils of two distinct agroclimatic zones of the northern part of West Bengal, (ii) effect of organic matter on P release kinetics and (iii) effect of organic matter on the yield of rice and P fractions in rice soils. The current study was conducted on Uttar Ganga variety in the Rabi season (2023-24) in Pundibari, Cooch Behar. Soils were collected from Samsing (Kalimpong district) and Pundibari (Cooch Behar district). Farm yard manure was applied as the organic source at 0, 5 and 10 t ha^{-1}. The laboratory study includes fractionation of soil P and its release kinetic study with or without organic sources, pot culture experiment with rice and fractionation of P at harvest f rice. The data obtained were analysed using available SPSS software applying completely randomized design.

The results of the release kinetic study showed that P release increased with time and the P release was dependent on the native P status of soil and the presence of P in different forms. Higher available P containing Pundibari soil (14.36 mg kg^{-1}) released more P. Increased doses of FYM increased P release progressively. It was also observed that there was a rapid increase in P released at 3rd and 4th extraction (240 and 336 hr) in both soils and after that, the release came to a stationary phase. It was also observed that the power function equation (R^2=0.984,0.982; SE=0.164,0.176) and parabolic diffusion equation (R^2=0.982,0.981; SE=1.30,1.31) was best fit for the P release data.

The pot culture experiment showed that the significantly highest value of plant yield (straw and grain), plant dry matter (straw and grain) and phosphorus uptake (straw and grain) was obtained in a high FYM application rate at 10 t ha^{-1}. The release of P by application of FYM could have contributed to the higher availability of P in pot soil for rice and increased the yield and P uptake. The results of P fractionation showed that the dominance of P fractions followed the order Fe-P > Reductant soluble P>Al-P>Ca-P>occluded P> Saloid P in Pundibari soils and Al-P > Reductant soluble P>Fe-P>occluded P>Ca-P> Saloid P in Kalimpong soil. The FYM amendment increased P in different fractions.

Key words: Phosphorus fractionation, kinetic study, release kinetics, plant parameters.

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ABBREVIATIONS

Notations	**Full form**
SE	Standard error of mean
FYM	Farm yard manure
%	Percentage
N	Nitrogen
P	Phosphorus
K	Potassium
SOM	Soil organic matter
R^2	Coefficient of Determination
dSm^{-1}	Desi siemens per meter
kg ha^{-1}	Kilogram per hectare
g	Gram
t ha^{-1}	Tonne per hectare
mg kg^{-1}	Milligram per kilogram
g pot^{-1}	Gram per pot
mg pot^{-1}	Milligram per pot
hr.	Hour
ppm	Parts per million
Fig.	Figure

INTRODUCTION

CHAPTER 1 INTRODUCTION

Phosphorus (P), the fifteenth element in Period 3 and Group 15 of the periodic table, has a molecular weight of 30.98 u. Phosphorus atoms can exist in oxidation states ranging from -3 to +5. It is a highly reactive non-metal found in numerous minerals as a phosphate compound rather than in a free state in nature. The German alchemist Hennig Barnard is credited for being the first to isolate P elementally in 1669 while searching the philosopher's stone. Its presence as a vital component of ATP, DNA, RNA, and phospholipids made it extremely important to human and crop physiology (Isidra-Arellano *et al.*, 2021). In plants, P serves as a crucial nutrient that enhances metabolic pathways, promotes root development, facilitates tillering, stimulates early flowering, and supports crop ripening (Liu, 2021). Its role extends to virtually all biochemical processes in plants that involve energy transfer (Khan *et al.*, 2023).

Phosphorus is a critical nutrient necessary for fundamental component of genes and chromosomes in all living organisms. ATP, which function as the primary energy carrier within plants highlights its pivotal role. Conversion of a mole of ATP to ADP results in release of 32 kJ of energy. Moreover, P is important for helping the growth and development of reproductive organs such as fruits and seeds, as well as promoting good root growth (Havlin *et al.*, 1984).

In many natural environments, P availability is limited, posing challenges for plants despite their diverse biological activities. Several studies show that P is a limiting nutrient in more than 40% of arable land worldwide (Dey *et al.*, 2017). In India 49.3% of the districts and union territories are low, 48.8% medium, and 1.9% high in available P (Hasan, 1996). Plant roots primarily absorb two forms of Phosphorus from the soil solution: primary orthophosphate ions ($H_2PO_4^-$) and secondary orthophosphate ions (HPO_4^{2-}). Another form is also there which is a trivalent inorganic anion PO_4^{3-}. Deficiency of P can lead to stunted growth, reduced quality, imbalanced shoot-to-root ratio, and poor seed or fruit setting. Visual deficiency symptoms appear as unusual dark green pigmentation on older leaves (Rattan *et al.*,2012). It is predicted that P deficiency will remain a significant constraint on agricultural productivity (Lynch and Brown, 2008).

The total P content in Indian soils ranges widely from 44 to 3580 mg kg^{-1}. The P content in agricultural crops typically ranges from 0.1% to 0.5%. Soils vary widely in their ability to supply P to crops because only a fraction of the total P in soil is in a form that plants can readily use. Therefore, without adequate plant-available P in soil only P addition through fertilizers crop growth will be hampered. Much of the P applied to soils in fertilizer form is fixed by the soil or removed by intensive cropping systems and may not be effectively utilized by plants (Dey *et al.*, 2017). Crop P recovery ranges from 10% to 15%, it is incredibly wasteful in terms of plant usage (Edwards *et al.*, 2015).

According to Brady (2008), P is found to be mobile within plants but immobile in soil, limiting its movement and availability for root absorption. Phosphorus is known for its poor solubility in soils and exists in very low concentrations in soil solutions, necessitating diffusion (development of concentration gradient) as an alternatemechanism for plant uptake. The availability of P to plants is influenced by total P content, solubility of P containing compounds and fixation of soluble sources to unavailable forms as well as biological processes like immobilization and mineralization.Phosphorus availability varies with time and is explained by the ideas of P equilibria in soils, which is why the rate of Phosphorus release needs to be closely monitored (Sanyal*et al.*, 1991).

Soil P occurs in organic and inorganic forms, frequently linked to calcium, iron, and aluminium, which greatly affect its plant availability (Tan,1998). Phosphorus is present in three primary apatite minerals, namely fluorapatite, chlorapatite, and hydroxyapatite. In soil the dominant P form depends on parent material and soil physico-chemical properties (Nishigaki *et al.*, 2018). The soil physicochemical properties include pH, texture, and organic matter content which affect the P sorption and dissolution process in soil and thus determine the forms and availability of P (Bouray *et al.*, 2021). Phosphorus is present in soil as organic as well as inorganic compounds in association with aluminium (Al-P), iron (Fe-P), and calcium (Ca-P). According to Walker and Syers (1976) Al-P and Fe-P are the dominant forms of P in highly weathered soils of the tropics while Ca-P is dominant in relatively younger soil. It is essential to comprehend the various P forms in soils for effective fertilizer management and enhanced Phosphorus Use Efficiency (PUE) in soil-plant systems. These pools include P in soil solution, P adsorbed on surfaces, strongly bonded P, and P in mineral or precipitated forms that is very strongly bonded or inaccessible. Understanding how each of these pools contributes to plant Phosphorus nutrition is very crucial (Syers *et al.*, 2008).

Chemical fractionation is a method for identifying the main forms of inorganic P in soils. It categorizes P into fractions including the most easily soluble P, active forms of inorganic P (such as P adsorbed on Al and Fe oxide surfaces and P associated with Ca), and inactive forms of P (including P occluded within Al and Fe oxides and reductant soluble iron-P). These fractions differ significantly in their mobility, bioavailability, and chemical behaviour in soils, and can transform between forms under certain conditions.

The effect of organic matter application in soil P fractionation is important as the organic manure application increase soil organic matter content and influences dissolution and subsequent desorption of P from various forms in soil by changing soil pH (Nobile *et al.,* 2020). In acidic soils the increase in pH promotes P desorption from Fe/Al oxides whereas in alkaline calcareous soil decrease of pH by organic matter promotes the release of P from Ca-P compounds (Yan *et al.*, 2018).

The availability of P fluctuates over time, which is governed by P equilibria in soils. Therefore, monitoring the rate of P release is important (Sanyal *et al.*, 1991). The uptake of P by plants results in a depletion of soluble P in the soil solution, causing a net release of P from solid soil phases into the liquid phase. Therefore, in addition to the total P content in the soil, the availability of soluble P at any given time largely depends on the rate at which P is released from soil particles into the soil solution (Shariatmadari *et al.*, 2006). Understanding the kinetics of P release in soils is essential for assessing soil P availability in agricultural systems. Detailed studies on P desorption kinetics can provide insights into the mechanisms of P adsorption and desorption in soils (Pavlatou and Polyzopoulos, 1988). These insights are crucial for optimizing P management practices to improve crop productivity sustainably.

Chemical kinetics, the study of reaction rates and mechanisms, is fundamental to understanding how chemical processes occur. Various kinetic equations have been developed to describe the behaviour of different types of reactions. The most basic is the zero-order kinetic equation, where the reaction rate is independent of reactant concentration (Atkins & de Paula, 2014). In addition to the classical models, several other kinetic equations are important in specific contexts such as (i) The power function equation **(**$\ln q = \ln a + b \ln t$) is often used to describe adsorption kinetics, where q is the amount adsorbed, t is time, and a and b are constants (Ho, 2006), (2). the parabolic diffusion equation ($q = a + bt^{1/2}$) is commonly applied in diffusion-controlled processes, particularly in soil science (Sparks, 1989), (3) the first-order equation [$\ln(q_0-q_t)=a-bt$] describes many adsorption and desorption processes, q_t is the cumulative P released up to time t, t denotes the time of release, q_0 is the maximum P released, and a and b are constants (Lagergren, 1898) and (4) the Elovich equation ($q=a+b \ln t$) where a and b are constants, is often used for chemisorption processes and heterogeneous systems (Low, 1960). Understanding these kinetic equations and their applications is essential for predicting reaction behaviour, release pattern of P in soil for effective P management. The kinetic study of P release pattern is more important than just measuring available P because a part of applied P gets fixed in soil and the plant uptake P for a long period (Hosseinpur and Pashamokhtari, 2008).

There are strong linear correlations between rice grain yield and total P absorption, encompassing both immediate and residual P sources. This suggests that simple models based on P uptake can effectively estimate plant P requirements. Such insights are valuable for optimizing Phosphorus management strategies to enhance agricultural productivity sustainably (Sahrawat, 2008),

Phosphorus is second most crucial nutrient for rice both in aerobic and anaerobic conditions. Regular recommendation of P fertilizers is necessary for maintaining soil fertility as well as rice yield (Wei *et al.*, 2022). The uptake of P by rice depends on genotype, environment and tillage practices but in general, an uptake of 1.8- 4.2 kg P is required to produce one ton of grain yield in the Asian countries. Such amount of P availability depends on the P forms present in soils and the capacity of soil to release P from fixed sources. Ignoring the P supply capacity of soil the farmers often blindly apply excess P fertilizer which in turn may cause serious environmental pollution like eutrophication. Excess P fertilization through inorganic and organic sources may lead to accumulation of excess amount of P in soil which is known as Legacy P. The release of such Legacy P in depleted condition is important to maintain the equilibrium P in soil solution. therefore, the understanding of P forms in rice soil and its release pattern is crucial for effective management of P and also to improve the use efficiency of applied

P. The prevalence of different forms of P in rice soil is important for determining P availability to rice (Nishigaki *et al.*, 2019).

Phosphorus availability for rice in acidic soil can be enhanced by regulating or increasing soil organic carbon content by applying organic matter in soil. Organic matter application may also influence different P fractions in rice soil and also enhance P mobilization by altering soil physicochemical properties and/or microbial activity, such as pH and phosphatase enzyme (Qaswar *et al.*, 2020). Hawkins *et al.* (2022) showed that the accumulated or legacy P in the soil can be made bioavailable to crops for several years to decades by mobilization with soil organic matter.

The soils of northern part of West Bengal are acidic with relatively high Fe/Al content (Paramanik *et al.*, 2012) and rice-based cropping sequence is predominated. The soils are reported as deficient in available P contents in several studies (Dutta and Mukhopadhyay, 2007). However, there is lack of information regarding the effect of organic matter in P release kinetics and P forms in rice soils. Estimation of P release capacity of the soils of this zone is important for effective P management for crops.

Therefore, in view of the above considerations the present study entitled, "**Effect of organic matter on phosphorus transformation and uptake by rice in acidic soils of West Bengal**" was undertaken to meet the following objectives:

1. Assessment of phosphorus fractions in acidic soils of two distinct agroclimatic zones of the northern part of West Bengal
2. Estimation of the effect of organic matter on phosphorus release kinetics in acidic soils of two distinct agroclimatic zones of the northern part of West Bengal
3. Evaluation of the effect of organic matter on the yield of rice and phosphorus fractions in rice soils

REVIEW OF LITERATURE

The review of literature on various aspects related to “Effect of organic matter on Phosphorus transformation and uptake by rice in acidic soils of West Bengal” has been presented in this chapter under the following headings:

2.1 Phosphorus in relation to soil-plant nutrition

2.2 Different forms of phosphorus in soil

2.3 Sorption-desorption of phosphorus

2.4 Release kinetics of phosphorus

2.5 Effect of phosphorus on rice yield

2.6 Phosphorus fractionation in rice growing soils

2.1 Phosphorus in relation to soil plant nutrition:

Richardson(2001) found that microorganisms play a crucial role in soil by facilitating the acquisition and transfer of nutrients, particularly Phosphorus (P). They participate in various processes that impact P transformation, influencing its availability as phosphate (HPO_4^{2-}, $H_2PO_4^-$) to plant roots. Microorganisms can solubilize and mineralize P from both inorganic and organic pools of soil P. Furthermore, they may enhance root surface area and contain a substantial pool of immobilized P within their biomass, potentially accessible to plants. Given the widespread deficiency of plant-available P in soils and the significant cost of P fertilizers in global agricultural production, there is growing interest in utilizing soil microorganisms as inoculants to mobilize P from less accessible soil sources.

Sahrawat and Sika (2002) examined the long-term P fertilizer needs for upland rice in Ultisol during both the P build-up and residual phases, using Bray-I P as a measure. They found that the relationship between applied fertilizer P and soil Bray-I P levels was linear and significant during the build-up phase but not in the residual phase. Linear regression equations were employed to describe how Bray-I P availability changed over time with different P treatments in Ultisol. The study also noted that available P in Ultisols decreased rapidly due to chemical interactions with iron and aluminium oxides.

Kovar and Claassen (2005) found that several interrelated soil processes govern the acquisition of soil P by plant roots. Contact between the plant root and soil P must occur for uptake of P by roots. This contact takes place when plant roots grow into soil where P is located or the P in the soil is transported to the root surface. Movement of P from the soil surrounding a root to the root surface occurs as a result of two processes: mass flow and diffusion.

Purnomo *et al.* (2005) found that rhizospheric bacteria enhance rice's Phosphorus absorption. Indonesian farmers have long cultivated native rice varieties in acidic soils without P fertilization. It was also observed that in these soils *Harbor burkholderia* sp., a type of rhizospheric bacteria, which might decompose tricalcium phosphate [$Ca_3(PO_4)_2$] and aluminium phosphate [$AlPO_4$], thereby improving P uptake by rice.

Kudeyarova (2010) emphasized that excessive phosphatic fertilizers in acidic soils result in the chemisorption of phosphate anions. This process leads to the breakdownof metal-humus sorbents, producing soluble P-containing compounds and reducing the soil's sorption capacity due to the formation of complex metal phosphate anions.

Panhwar *et al.* (2013) demonstrated that adding organic acids to phosphate-solubilizing bacteria (PSB) increased the amount of soluble P in the soil solution without affecting soil pH. This addition also promoted better root development and increased plant biomass in aerobic rice seedlings.

Fageria *et al.* (2013) investigated the P absorption and utilization efficiency of upland rice, dry beans, corn, and soybeans grown in rotation on a Brazilian Oxisol. They observed that as plants aged, the concentration of P per unit dry matter decreased significantly. However, P uptake in the shoots increased substantially with plant growth. At harvest, P absorption was higher in grains compared to shoots, highlighting its higher mobility in plant body and the crucial role for enhancing crop yields.

Roberts and Johnston (2015) demonstrated that crops typically recover only 10-15% of P from Phosphorus containing fertilizer in the year following its application, highlighting the inefficiency of P fertilizers. This inefficiency is mainly due to leaching and P fixation in soil in forms that are unavailable to plants.

Nayak *et al.* (2016) observed that plants can only absorb dissolved phosphate ions. Generally, agricultural soils contain less than 1 mg kg^{-1} of dissolved phosphate, except in recently fertilized soils. The overall soil P content ranges from 200 to 2,000 ppm, depending on the soil's parent material.

Wen *et al.* (2017) studied the effect of root morphology on P nutrition by maize and observed that maize biomass attained its peak at 2.7 mg g^{-1} shoot P concentration. The maize root morphology increased at lower P concentrations but decreased at extremely low levels. Whereas, increasing the shoot P concentration results in decreased root morphology but enhanced physiological responses highlighting the importance of the root morphology in P uptake and utilization.

Irfan *et al.* (2020) observed that P allocation pattern and tissue specific biomass were responsible for P use efficiency in rice. In their study, they have observed that the rice cultivars with higher P uptake, acquisition efficiency, utilization efficiency were lower P-tolerant and more desirable for adaptation to soils with low available P.

2.2 Different forms of phosphorus in soil

Majumdar *et al.* (2004) observed that the distribution of inorganic P fractions followed the order: Red-P > Al-P > Fe-P > occluded-P > Ca-P > saloid-P in surface soil samples of an agricultural watershed-based farming system where rice, groundnut, and pea were grown for 17 years.

Dutta and Mukhopadhyay (2007) reported varying concentrations of different P fractions in four soil series of the terai region of West Bengal. In these soils the saloid P ranged from 2.1 to 8.2 mg kg^{-1}, Fe-P from 22.5 to 81.8 mg kg^{-1}, Ca-P from 11.3 to 40.1 mg kg^{-1}, reductant soluble P from 18.5 to 67.5 mg kg^{-1}, and occluded P from 6.82 to 30 mg kg^{-1}. The study highlighted that Balarampur soil had the lowest amount of saloid P, indicating lower organic matter content. Binnaguri soil, with higher levels of aluminium across all forms, exhibited the highest concentration of Al-P. Gopalpur soil showed relatively elevated levels of Fe-P, reductant soluble P, and occluded P, possibly due to its higher Fe_2O_3 content. Overall, the Phosphorus fractions generally decreased in the order: Al-P > Fe-P > Reductant soluble P > Ca-P > occluded P > saloid P.

Sharma *et al.* (2007) investigated how ongoing nitrogen, Phosphorus, and potassium application affected maize-wheat crops. Their physico-chemical analysis of Phosphorus availability revealed that wheat required less energy to absorb P from Saloid P and Fe-P sources compared to Ca-P sources. The study found that released P undergoes refixation at various wheat growth stages: like Al-P during tillering, Fe-P at ear initiation, and once more as Al-P at harvest time.

Setia *et al.* (2007) observed that in a maize-wheat cropping sequence, the relative abundance of inorganic P fractions followed the order: saloid-P < Fe-P < Al-P < Ca-P. They noted that the various inorganic P fractions tended to decrease with the age of the crop. Specifically, the inorganic P forms, excluding saloid-P, decreased after wheat harvest compared to their initial levels.

Trivedi *et al.* (2010) noted that Ca-P was the most predominant P fraction in soil profiles, followed by Red-P, Al-P, and Fe-P. This pattern was observed in Inceptisols with a soil pH range of 9.1 to 9.2, and in Alfisols with a pH range of 6.8 to 8.5, specifically at depths of 0-15 cm.

Sarkar *et al.* (2013) reported that in soil samples collected from four pedons of a paddy field, namely rolling uplands, moderately sloping uplands, gently sloping uplands, and gently sloping plain, the abundance of P fractions followed this order: Red-P > Fe-P > Ca-P > occluded-P > Al-P.

According to Saha *et al.* (2013), among different inorganic P fractions, Ca-P was the dominant fraction (78.7%), followed by Al-P (10.1%), Fe-P (7.9%), and saloid-P (3.3%) in the soil under long term field experiment on pearl millet-wheat cropping sequence. They found that increasing levels of P application significantly increased saloid-P, Al-P, Fe-P, and Ca-P compared to lower levels of P application in a pearl millet-wheat cropping sequence in Hissar, Haryana.

Devra *et al.* (2014) observed that among all the inorganic P fractions in strongly alkaline soils, Ca-P was the dominant fraction, following the order Ca-P > Fe-P > saloid-P > Red-P in plains of Rajasthan. The high concentration of Ca-P was attributed to the presence of high $CaCO_3$ content, indicating greater availability of Ca-P in calcareous soils.

Devra *et al.* (2015) observed that among the different P fractions in moderately to strongly alkaline soils, Ca-P was the dominant fraction, followed by organic-P, Fe-P, and saloid-P.

Srilatha *et al.* (2015) reported that the inorganic fractions of Phosphorus followed the order: Ca-P > Al-P > Fe-P > saloid-P. They observed that all inorganic fractions of

Phosphorus (saloid-P, Al-P, Fe-P, and Ca-P) increased from their initial values after ten years under a rice-rice cropping system. The highest values were obtained in the 100% NPK + FYM treatment, followed by the 150% NPK treatment (116%), compared to all other treatments.

Chandrakala *et al.* (2017) reported that among soil P fractions, the content of total-P (1218.90 to 3383.08 mg kg^{-1}), organic-P (624.95 to 3461.85 mg kg^{-1}), reductant soluble-P (132.56 to 364.55 mg kg^{-1}), occluded-P (7.38 to 49.69 mg kg^{-1}), and Ca-P (6.21 to 38.76 mg kg^{-1}) increased with increasing soil P fertility. In contrast, saloid-P (38.31 to 63.23 mg kg^{-1}), Al-P (61.49 to 164.31 mg kg^{-1}), and Fe-P (35.23 to 109.87 mg kg^{-1}) fractions showed a decreasing trend.

Kadam *et al.* (2017) stated that in all studied soil series (Entisols, Inceptisols, and Vertisols), the distribution of inorganic P fractions followed this order: Ca-P > Red-P > Al-P > Fe-P > occluded-P > saloid-P. They found higher levels of saloid-P in the surface layer, which decreased with depth. In Entisols and Inceptisols, higher concentrations of Red-P, Fe-P, and occluded-P were observed, while Vertisols showed higher levels of Ca-P. The content of Ca-P increased with depth in Entisols, Inceptisols, and Vertisols due to rising $CaCO_3$ levels.

Sowjanya *et al.* (2017) observed that the distribution of inorganic P fractions followed the sequence Ca-P > Al-P > Fe-P > saloid-P. They noted varying ranges for saloid-P, Al-P, Fe-P, and Ca-P across different landscapes: 1.25 to 12.50 mg kg^{-1} in uplands, 1.50 to 45.00 mg kg^{-1} in midlands, and 10.50 to 71.50 mg kg^{-1} in lowlands. The concentrations of all P fractions were highest in lowlands, followed by midlands and uplands.

Bhavsar *et al.* (2018) found that among all forms of Phosphorus at the Agricultural Botany Research Farm in Nagpur, Ca-P was the most dominant, followed by Al-P, Red-P, Fe-P, Occluded-P, and saloid-P. Ca-P ranged from 182.09 ppm to 208.45 ppm, accounting for 41.11% of the total Phosphorus present.

Watham *et al.* (2018) reported that in strongly acidic soils, the average content of inorganic P fractions followed this order: Red-P > Fe-P > Al-P > occluded-P > Ca-P > saloid-P. The average concentrations (in ppm) were 82.54 for Red-P, 73.38 for Fe-P, 50.83 for Al-P, 29.00 for occluded-P, 22.17 for Ca-P, and 8.70 for saloid-P.

Rai *et al.* (2020) found that P fraction in neutral to slightly alkaline soils of Varanasi was as Saloid-P (23.43 to 44.62 mg kg^{-1}), Al-P(10.75 to 20.02 mg kg^{-1}), Fe-P (6.96 to 13.4 mg kg^{-1}), Ca-P (80.97 to 115.78 mg kg^{-1}), reductant soluble-P (10.68 to 27.70 mg kg^{-1}), occluded-Al-Fe-P (13.02 to 26.75 mg kg^{-1}), organic-P (81.41 to 172.32 mg kg^{-1}) and the total Phosphorus(270.75 to 383.84 mg kg^{-1}).

Nai-yu *et al.* (2022) examined the inorganic P fraction in three non-acidic soils of northeastern China under the long-term field experiment. They have observed that the proportion of Ca_{10}-P in the sum of total inorganic P fractions was highest in all the three soils and accounted for 33.5% in black soil, 48.8% in fluvo-aquic soil, and 44.8% in loess soil.

2.3 Sorption-desorption of phosphorus

In much of the research establishing phosphate adsorption relationships, various equations including Langmuir, modified Freundlich, Temkin and mechanistic models have been utilized to depict P adsorption (Huang, 1998).

Muralidharan *et al.* (1999) reported that P adsorption and desorption exhibited a linear relationship with varying Phosphorus sorption capacity in soils.

Pierzynski *et al.* (2005) highlight that when soluble P compounds are introduced into soil, their availability diminishes due to reactions such as precipitation and adsorption onto solid particle surfaces. Adsorption is identified as a primary mechanism for Phosphorus retention.

Roy and Pal (2018) discovered that larger size aggregates exhibited a lower bonding energy coefficient and buffering capability for a given amount of sorbed P.

2.3.1. Effect of phosphorus sorption-desorption in plant

According to Reddy *et al.* (1999), Phosphorus sorption is higher in fertilized soil and decreases gradually as the fertilizer P rate increases, both in manured and unmanured soils.

Nyborg *et al.* (1999) suggested that when the soil contains a substantial amount of plant-available P, it can adequately supply the Phosphorus needed by plants to achieve maximum crop yield at a reasonable cost.

Rashmi *et al.* (2014) reported that phosphate fertilizers, when applied to soils, undergo transformations that involve reactions with soil particles and calcium compounds. These processes, including adsorption and precipitation, reduce the availability of Phosphorus to the plant system. The efficiency of Phosphorus uses by crops through adsorption into the soil ranges from 10% to 25%.

2.3.2. Sorption-desorption isotherms

According to studies by Pardo *et al.* (1992), Marchi *et al.* (2006), Anda *et al.* (2008), Eberhardt *et al.* (2008), and Negassa *et al.* (2008), highly weathered tropical soils exhibit a higher zero-point charge (ZPC) value. This characteristic makes the soils more electropositive, resulting in a greater capacity to adsorb anions such as phosphate.

P sorption isotherms, as noted by Ozanne and Shaw (1968) and Fox and Kang (1978), offer distinct advantages over extraction methods for assessing the efficiency of plants in utilizing available P. However, the time-consuming nature of creating these isotherms renders them less suitable for soil-test operations where rapid responses are typically required (Hue and Fox, 2010).

According to Khan *et al.* (2010), adsorption isotherms are defined as quantitative equilibrium relationships between the amounts of dissolved phosphate species and the amounts adsorbed onto surfaces at a constant temperature.

According to Jia *et al.* (2010), the Langmuir, Freundlich, and Temkin equations are suitable for describing the adsorption of both organic and inorganic Phosphorus. For the best fit of inorganic and organic P adsorption, the Langmuir-Temkin equation was utilized. They found that P adsorption correlates exponentially with both organic and inorganic desorption. Additionally, the adsorption of Phosphorus was influenced by the ionic strength of the sorption solutions.

Correa *et al.* (2011) observed that the processes and factors involved in soil formation control the amount of labile Phosphorus in soil. These processes contribute to varying chemical, physical, and biological characteristics that influence changes in the Maximum Phosphorus Adsorption Capacity (MPAC) and the energy levels between Phosphorus bonds and colloids.

According to Njoyim *et al.* (2016), phosphate adsorption isotherms are utilized to measure the soil's adsorption capacity and are crucial parameters for studying how ions interact with oxides and the soil. Adsorption is typically characterized by fitting adsorption isotherms and describing them mathematically using one or more adsorption equations.

Jamal *et al.* (2018) suggest that adsorption isotherm models can effectively predict the Phosphorus requirements of soil for achieving optimal yields. This is crucial because Phosphorus requirements for optimal crop yields vary significantly under field conditions, depending on soil type and crop species.

Yang *et al.* (2019) showed that the effect of SOM on P adsorption/desorption data well fitted in both Freundlich and Langmuir isotherms. The maximum adsorption capacity of P increased with the increase in SOM, but the P bonding energy and maximum buffering capacity first decreased, and then increased, with the lowest values obtained with a SOM content of 75.3 mg kg^{-1}. But in black soil the maximum desorption capacity of P was the greatest when the SOM content reached 75.3 g kg^{-1}.

2.3.2.1 Absorption isotherm

Cornell and Schwertmann (1996) noted that several equilibrium-based models are commonly employed to illustrate adsorption on mineral surfaces, including the Stern model, the diffuse double-layer model, the Freundlich equation, and the Langmuir equation. However, among these models, the Langmuir and Freundlich equations are the most frequently utilized in subsequent studies.

These equations are not only used to summarize and compare adsorption data but also to predict adsorption behavior in non-experimental settings. It's important to emphasize that these isotherms do not provide specific details on the speciation of surface complexes or the exact sorption mechanisms responsible for adsorption.

Langmuir equation:

Sparks (1995) explains that the Langmuir equation, originally developed for gas adsorption on metal surfaces, has been adapted to describe solid-solution interactions based on similar assumptions. It posits the existence of an adsorption maximum, or monolayer coverage, on surfaces with a fixed number of identical binding sites capable of holding one molecule each. The process is reversible, allowing for desorption of adsorbed molecules, and assumes no lateral movement of molecules on the substrate's surface. Notably, adsorbate molecules do not interact with each other regardless of surface coverage, and the adsorption energy remains constant across all sites.

Hussain *et al.* (2003) emphasize that one of the benefits of the Langmuir equation is its ability to determine both the adsorption maximum and the relative binding energy for Phosphorus sorption. This makes it a valuable tool for predicting and understanding adsorption behaviors in diverse soil and environmental conditions.

In numerous investigations, such as those by Syer *et al.* (1973), Ryden and Syers (1975), and Tomar and Gautam (1996), plotting phosphate sorption data across a wide range of solution -P concentrations often resulted in a curved rather than linear isotherm when using the traditional Langmuir equation. This deviation can be attributed to several factors: the surface not being energetically homogeneous, migration of sorbed Phosphorus to the surface layer and crystalline hydrous oxides resulting in phosphate compounds with varied compositions and solubilities, especially at higher Phosphorus concentrations (Hundal, 1988; Sanyal and De Datta, 1991). Additionally, a decrease in surface charge and potential can lead to increased phosphate sorption in the soil system (Sposito, 1981). These factors likely contribute to the observed deviations from ideal Langmuir behavior.

To address these issues, many studies have extensively utilized modifications of the Langmuir equation with multiple surfaces (Syer *et al.*, 1973). This approach allows for a more accurate representation of the complex sorption processes occurring in soils under varying Phosphorus concentrations.

Freundlich equation:

This model is particularly effective for describing the energetically heterogeneous sorption of Phosphorus on solid surfaces, where the interaction energy between the adsorbate and sites fluctuates with fractional surface coverage. Consequently, the Freundlich equation often provides a better fit for phosphate sorption data across a wide range of equilibrium solution Phosphorus concentrations in soils compared to the Langmuir equation (Gunary, 1970; Tomar and Gautam, 1996).

Unlike the Langmuir equation, the Freundlich equation is considered empirical and does not assume a fixed adsorption maximum. Instead, it accounts for varying adsorption energies with changes in surface coverage (Sparks, 1995).

The Freundlich equation, initially an empirical model to describe gas and solute adsorption, has been widely utilized in soil science to characterize phosphate adsorption (Aslam *et al.*, 2000; Arshad *et al.*, 2000).

Temkin equation:

According to Surchi (2011) and Tan (2008), the Temkin equation assumes that the binding energy of adsorption decreases linearly with increasing surface coverage, contrary to the Freundlich equation (Thomas and Thomas, 1967), which suggests otherwise. This model, proposed by Temkin and Pyzhev, considers both adsorbate-adsorbate interactions and indirect adsorbate effects on adsorption isotherms. It predicts that the heat of adsorption of each molecule in the layer will decrease linearly with coverage.

When plotting sorbed Phosphorus versus log C (concentration), the Temkin equation typically produces a curved rather than a straight line (Fox and Kamprath, 1970; Bache and Williams, 1971; Roy and De Datta, 1985; Sanyal *et al.*, 1993). Despite this deviation from linearity, experimental data generally fit the Temkin model better than the Langmuir plot across a wider concentration range (Sanyal and De Datta, 1991).

Further supporting its applicability, Ioanou *et al.* (1998) found that the Temkin equation also effectively describes Phosphorus sorption by Goethite and Kaolinite-Goethite systems. This highlights the Temkin model's utility in capturing the complexities of Phosphorus sorption dynamics in various soil and mineral systems.

2.4 Release kinetics of phosphorus

Hosseinpur and Pashamokhtari (2008) compared soils treated with sewage sludge to control soils and found that the modified soils released P at a higher rate. This phenomenon was attributed to the high P and organic matter content in the treated sewage sludge. They tested six kinetic equation models to explain Phosphorus release dynamics in both control and modified soils, identifying power function equations and the Elovich and first-order models as potentially suitable for describing Phosphorus release data.

Analyzing the correlation between P release rate parameters and specific soil characteristics in control soils, they discovered a strong relationship between calcium carbonate equivalent and Olsen-extractable P. However, clay content, cation exchange capacity, and organic matter did not exhibit strong associations with P release parameters in these soils.

In soils treated with sewage sludge, Hosseinpur and Pashamokhtari (2007) demonstrated a significant association between P desorption rate parameters and organic matter, cation exchange capacity, Olsen-extractable Phosphorus, and calcium carbonate equivalent.

Islas-Espinoza *et al.* (2013) found that in soils treated with biosolid and vermicompost, P release initially occurred rapidly but then slowed down, corresponding to a quick initial and prolonged fertilizing effect. They observed that low soil pH facilitated Phosphorus binding to aluminum and iron, thus enhancing P retention, with inorganic orthophosphates playing a crucial role in plant growth. Similar kinetics were observed in other soils and amendments regarding P release over time, with the parabolic diffusion law appearing to be the most suitable model, suggesting diffusion as a likely limiting step in Phosphorus liberation.

Vermicompost added more available P and released less compared to biosolids. Additionally, earthworm bio-indicators suggested that vermicomposted biosolids were relatively benign. The modifications studied were deemed significant for Phosphorus replenishment and easy release, potentially mitigating surface and groundwater contamination within specified dose limits.

Wang *et al.* (2015) indicated that the acid strength of solutions containing low molecular weight organic acids potentially contributed to higher phosphate (Pi) release. They observed that organic acids played a role in the kinetic release of organic Phosphorus (Po). Interestingly, chelation by organic acid ligands did not significantly influence the kinetic release of organic Phosphorus (Po) in short-term experiments. This finding enhances understanding of the mechanisms involved in organic Phosphorus release facilitated by low molecular weight organic acids.

According to Yang *et al.* (2019), Phosphorus applied to black soil undergoes rapid adsorption onto particle surfaces, quickly converting water-soluble phosphate into non-extractable forms within a short period. This initial adsorption phase is followed by a gradual transformation into less accessible forms over time. The time-dependent release of Phosphorus was effectively described by an Elovich equation.

The addition of oxalic and citric acids was found to increase the solubility of aluminum-phosphate (Al-P), iron-phosphate (Fe-P), and calcium-phosphate (Ca-P). Among these phosphate fractions, Al-P exhibited the highest solubility. Through simple correlation and path analyses, Al-P solubility emerged as the most significant direct causal factor influencing the solubility of phosphate. Therefore, the Al-P fraction is identified as a critical potential source of Phosphorus in black soil ecosystems.

2.4.1. Models of isotherm:

Release isotherm

Phosphorus release isotherms are mathematical representations that illustrate how the amount of Phosphorus released from soil or sediment changes in response to factors like soil pH, organic matter levels, and microbial activity. These models are crucial in agricultural and environmental studies, providing valuable insights into Phosphorus availability, soil fertility management, and potential environmental impacts. By quantifying Phosphorus release under varying conditions, these models support informed decision-making regarding nutrient management and protection of water quality. This introduction explores the essential concepts, applications, and importance of Phosphorus release isotherms in comprehending and controlling Phosphorus dynamics across different ecosystems.

Using solubility diagrams and Phosphorus (P) fractionation data, McDowell *et al.* (2003) showed that the release of soil P into solution appears to be influenced by complexes involving Al (variscite), Fe (strengite), and Ca (hydroxyapatite). The kinetics of P release from the soil were accurately described ($P<0.01$) using a power-function equation ($\text{release}=\alpha t\beta$, where t=time). The initial release rate (α) ranged from 0.3 to 34.9, and the rate of release over time (β) decreased from 0.405 to 0.079 as Olsen P or $CaCl_2$–P levels (9–55 mg kg^{-1} and 0.201–3.491 mg l^{-1}, respectively) in the soils increased. Relative to the release of $CaCl_2$–P (used to estimate P in soil solution and subsurface flow), two concurrent processes were identified: rapid P release from soil directly in contact with the solution and slower diffusion of P from within soil particles. These processes should be considered when interpreting the dynamics of P release to surface runoff and subsurface flow in soils with different P concentrations.

Hansen *et al.* (2003) studied phosphate release kinetics from soil that had received solid-dairy manure applications over a period exceeding a decade. They conducted experiments to simulate leaching conditions, continuously replenishing the solution until phosphate concentrations stabilized (sequential desorption experiment). Their measurements showed that 80% of soluble phosphate was released within 24 hours, followed by a slower release that continued for up to 504 hours. Several mathematical models were applied to describe the experimental data, including a reversible first-order model, the Elovich model, and a modified version of the Elovich model empirically correlated to soil organic matter and percent clay. The Elovich model provided the best fit to the data. In the sequential desorption experiments, total phosphate released from the manure-amended soil amounted to 29% from the surface soil (0–10 cm) and 8% from the subsurface soil (45–65 cm). These findings suggest that phosphate release from manure-amended soils is primarily controlled by the dissolution rate of meta-stable calcium-phosphate mineral phases.

2.4.1.1. FIRST ORDER EQUATION

Chien and Clayton (1980) emphasized that phosphate release and sorption processes in soils often involve a combination of simultaneous first-order reactions, rather than being adequately described by a single first-order kinetic reaction alone.

Soriano *et al.* (2019) proposed that Phosphorus release rates can be effectively described using multiple first-order equations, each representing different stages of the release process

First order equation: $\ln (q_0 - q_t) = a - bt$

2.4.1.2. Power function

Abdu (2009) demonstrated that the desorption rates of Phosphorus from anion-exchange resins can be effectively described using empirical kinetic models, including the fractional power equation.

Fekri *et al.* (2011) investigated Phosphorus desorption kinetics in calcareous soils and found that a power function equation provided an accurate description, highlighting how soil characteristics influence Phosphorus release.

Regarding the application of manure, Vadas *et al.* (2004) observed that the release of inorganic Phosphorus from dairy manure was well-captured by a power function equation. Wang *et al.* (2017) studied the release of both organic and inorganic Phosphorus from Mollisols induced by low molecular weight organic acids. Their study underscored the diverse mechanisms involved in Phosphorus release and their implications for Phosphorus availability to plants in soil.

Power function equation: $\ln q = \ln a + b \ln t$

2.4.1.3. Parabolic diffusion model

Parabolic diffusion equations are frequently employed to characterize the kinetics of Phosphorus desorption across different types of soils. Studies have demonstrated the effectiveness of the parabolic diffusion equation in modeling the release of Phosphorus from soils under diverse conditions.

For example, research by Abdu (2009) and Fekri *et al.* (2011) illustrated that the parabolic diffusion equation, alongside other kinetic models, accurately described Phosphorus desorption rates from soils. Additionally, Mihoub *et al.* (2018) found that the parabolic diffusion equation provided a good fit to experimental data on Phosphorus release kinetics in calcareous conditions.

Moreover, parabolic diffusion equations are not limited to Phosphorus studies alone. Hu *et al.* (2018) utilized a modified Langmuir equation incorporating advection-diffusion equations to simulate the interaction between Phosphorus and sediment in water systems. This demonstrates the versatility of parabolic diffusion equations in modeling a wide range of diffusion processes.

Parabolic diffusion: $q = a + bt^{1/2}$

2.4.1.4. Elovich equation

The Elovich equation has been extensively utilized in various studies to accurately describe the release kinetics of diverse substances in both soils and aqueous solutions. Researchers have successfully applied the simple Elovich equation to examine the release kinetics of substances such as Phosphorus (Soriano *et al.*, 2019) and phosphate (Wang *et al.*, 2013). Furthermore, it has been observed that the simple Elovich equation provides a good fit for phosphate sorption kinetic data (Zeng *et al.*, 2003).

Moreover, this equation has been employed to model kinetic data across different contexts, including the desorption kinetics of Phosphorus from soils (Fekri *et al.*, 2011). Additionally, researchers have found it effective in describing the kinetics of chemisorption processes involving heterogeneous active sites (Khalifa *et al.*, 2019). The simple Elovich equation is also widely acknowledged as a suitable model for describing chemisorption kinetics on solid surfaces (Wolfe & Lind, 2008).

Furthermore, in studies concerning soil treatments, the simple Elovich kinetic equation has been identified as the most effective model for fitting P retention ("The Feasibility of Using Unconventional Fertilizers on P Availability in Soil", 2013).

Elovich equation: $\mathbf{q = a + b \ln t}$

2.5 Effect of phosphorus on rice yield

Applying 90 kg P_2O_5 per hectare increased grain yield by 14% and 6% compared to applying 30 kg and 60 kg P_2O_5 per hectare, respectively, on the red soils of Meerut, Uttar Pradesh (Katyal *et al.*, 2000).

Tripathi *et al.* (2001) discovered that using split doses of P at 60 kg per hectare produced higher grain and straw yields than a single basal application on lowland alluvial soils.

Studies by Babu *et al.* (2008) in P-accumulated vertisols showed that paddy yield in soil with higher initial available P (62 kg P_2O_5 ha^{-1}) was higher even without P application compared to soil with medium available P (40 kg P_2O_5 ha^{-1}), despite the latter being supplied with 75% of the recommended dose of P (RDP). While this suggests a potential saving of P fertilizer in soils with higher initial available P, the mean yield in medium P soil was 32% lower. This indicates that higher available P may help achieve maximum yield, possibly due to reduced fixation and increased utilization of applied P in soils with higher initial P levels.

Islam *et al.* (2008) demonstrated that the P content in rice plants increased steadily with higher P levels at different growth stages. Varietal differences in P content were minimal. Initially, there was a negative correlation between P and nitrogen (N) uptake during tillering, but by harvest, a significant positive correlation between P and N uptake was observed. Throughout all stages, the crop consistently showed a positive correlation between N and potassium (K) uptake.

According to Sahrawat (2008), there are strong linear correlations between rice grain yield and total P absorption, which includes both immediate and residual P sources.

This indicates that simple models based on P uptake can be used effectively to estimate plant P requirements.

According to Sharma *et al.* (2009), applying P at rates up to 35 kg h^{-1} a generally resulted in higher rice production, growth, yield parameters, gross and net returns. They also observed that incorporating crop residues improved the recovery of applied P and the availability of P in the soil, although it did not significantly affect grain yield.

The highest grain yield (7.10 t ha^{-1}) was achieved with the application of 62.5 kg P_2O_5 ha^{-1} compared to its lower levels (Shekara *et al.*, 2011).

Srujana *et al.* (2011) conducted a field experiment at Agricultural College Farm, Bapatla, and found that the highest number of tillers (485), number of filled grains per panicle (141), grain yield (5249 kg ha^{-1}), and straw yield (6232 kg ha^{-1}) were obtained with two splits of P applied through DAP.

In their study, Lan *et al.* (2012) investigated the influence of soil P availability on rice yield in paddy fields. They found that applying fertilizers (N, P, and K) had a positive effect on rice grain yield. The most significant improvements occurred when chemical fertilizers were combined with rice straw or cow dung. In the control treatment (CK), soil inorganic P fractions (Pi) decreased due to uptake by rice plants, while in the fertilizer treatments, Pi generally increased owing to consistent P supply. Soil organic P fractions (Po) increased over time regardless of fertilizer application, attributed to stubble preservation and biological processes. This long-term transformation of Pi to Po resulted in reduced soil P availability, potentially impacting rice yield.

Yoseftabar (2012) found that on application of nitrogen and P fertilizer on growth and yield in rice cultivar Tarom Hashemi, tiller number, fertile tiller, total grain, 1000-grain weight and yield increased significantly with nitrogen and P fertilizer.

Hasanuzzamen *et al.* (2012) conducted a field experiment on silt loam soil to study the response of hybrid rice to different levels of P (0, 30, 50, and 70 kg P_2O_5 ha^{-1}). The results indicated that grain yield, straw yield, biological yield, and harvest index were not significantly affected by the different levels of P. However, the numerically highest grain yield (7.58 t ha^{-1}) was observed with 50 kg P_2O_5 ha^{-1}, the highest straw yield (9.61 t ha^{-1}) at 30 kg P_2O_5 ha^{-1}, the highest biological yield (16.92 t ha^{-1}) at 50 kg P_2O_5 ha^{-1}, followed by 30 kg P_2O_5 ha^{-1} (16.72 t ha^{-1}), and straw yield at 50 kg P_2O_5 ha^{-1}.

Results from the field trial conducted by Imrul *et al.* (2016) showed that applying 35 kg P_2O_5 per hectare significantly increased the yield and yield-attributing characteristics, such as the number of effective tillers per hill, panicle length, number of filled grains per panicle, 1000-grain weight, grain yield, straw yield, and total biological yield of rice on clay loam soil in Dhaka.

Paramasivan *et al.* (2016) conducted a two-year experiment at the Agricultural College and Research Institute, Killikulam, and found that applying 75 kg P_2O_5 per hectare significantly increased the number of productive tillers per plant (18.3), the number of grains per panicle (212), test weight (26 g), grain yield (7043 kg ha^{-1}), and straw yield (8581 kg ha^{-1}) of rice compared to other treatments (0 and 50 kg ha^{-1}) on clay loam soils.

2.6. Phosphorus fractionation in rice growing soils

Laxminarayana (2007) investigated the distribution of various inorganic P fractions (saloid-P, Al-P, Fe-P, and Ca-P) in rice soils of Kolasib district, Mizoram. The study revealed varying concentrations: saloid-P ranged from 3.25 to 90.23 mg kg^{-1}, Al-P from 29.6 to 46.8 mg kg^{-1}, Fe-P from 18.2 to 33.7 mg kg^{-1}, and Ca-P from 22.4 to 39.1 mg kg^{-1}. Total-P in these soils ranged from 132.3 to 365.8 ppm. The fractions Al-P, Fe-P, and Ca-P predominantly contributed to the available P pool. In terms of their contribution to total-P, these soils followed the order Fe-P (15.8%) > Ca-P (12.0%) > Al-P (19.6%) > saloid-P (2.46%).

Laxminarayana (2011) examined different forms of P in soils within rice-growing regions of Meghalaya. According to the study, the sequence of P forms varied across different areas: in Ri-Bhoi, Jaintia hills, and Khasi hills, the order of occurrence was RS-P > Fe-P > Al-P > Ca-P > Sal-P. Conversely, in Garo hills, the order observed was RS-P > Ca-P > Fe-P > Al-P > S-P. The higher levels of Ca-P in Garo hills might result from the conversion of insoluble tricalcium phosphate into more soluble dicalcium phosphate.

According to Lungmuana *et al.* (2012), in surface soils of rice-growing areas in the red and lateritic zones of West Bengal, the proportions of different inorganic P fractions relative to total P were as follows: RS-P (28.2%), Al-P (7.9%), Ca-P (5.8%), Fe-P (18.5%), and saloid-P (0.8%).

Sarkar *et al.* (2013) found that in soil samples collected from four pedons of paddy fields—specifically, rolling uplands, moderately sloping uplands, gently sloping uplands, and gently sloping plain—the abundance of P fractions followed this order: red-P > Fe-P > Ca-P > occluded-P > Al-P.

According to Srilatha *et al.* (2015), the inorganic fractions of P followed this order: Ca-P > Al-P > Fe-P > saloid-P. Over a period of ten years under a rice-rice cropping system, all inorganic fractions of Phosphorus (saloid-P, Al-P, Fe-P, and Ca-P) increased from their initial values. The highest values were observed in the treatment with 100% NPK + FYM, followed by a 116% increase with 150% NPK, compared to all other treatments

Majumdar *et al.* (2016) collected soil samples from a micro-watershed in the northern transition zone of Karnataka, previously utilized for paddy cultivation. They observed that the average percentage of inorganic P fractions in surface soils exhibited the following sequence: Red-P > Fe-P > Al-P > Ca-P > occluded-P > saloid-P.

MATERIALS AND METHODS

CHAPTER 3 MATERIALS AND METHODS

The current study examines various forms of phosphorus (P) and their release pattern in soil samples collected from two distinct locations in West Bengal, representing different agro-climatic zones: the Hill region and the Terai region. The investigation involved the use of multiple materials and the execution of several laboratory experiments to accomplish the study's objectives. A concise overview of these materials and the analytical methods employed in this research is provided below.

3.1. Materials:

3.1.1 Soil sample:

Surface soil samples (0-15 cm depth) for this study were gathered from two locations representing two distinct agro-climatic zones in West Bengal: Samsing, Kalimpong (26.9952º N, 88.8064º E, altitude 576m) of the hill region and Pundibari, Cooch Behar (26.3938º N, 89.383º E, altitude 47m) of the terai region. The Pundibari soil was collected from a seasonal fallow land under cultivation for long time and the Kalimpong soil was collected from the forest of Samsing area. The collected soils were carefully broken by hand to avoid damaging plant roots, then air-dried at 35°C until reaching a constant weight in the laboratory. Coarse litter and plant debris were removed to minimize soil loss, and the soil samples were sieved through a 2-mm brass sieve. Subsequently, the samples were labelled and stored in paper bags for further analysis.

3.1.2. Water: Singly distilled water was used for nitrogen and potassium analysis, while double distilled water was employed for Phosphorus analysis and cleaning glassware and plasticware.

3.1.3. Glassware: Borosilicate glassware, containers, and plastic bottles were exclusively used for sample analysis and storage throughout the study.

3.1.4. Whatman Filter Paper: Whatman Filter No. 42 was used for Phosphorus estimation.

3.1.5. Chemicals: Analytical Reagent (AR) and Guaranteed Reagent (GR) grade chemicals were used in different chemical analysis.

3.1.4. Equipments used:

Electrical balance: A Mettler Toledo electronic balance, model PL202S, was used to precisely measure the quantities of soil samples and chemicals required for the analysis.

Mechanical shaker: For the extraction process, a rotary shaker (Pelican Equipment, Model: Rotek LSV XL) was utilized to agitate the soil suspension for a specified period.

Sand bath: The sand bath was utilized to dissolve various chemicals in water while maintaining the appropriate temperature range.

Centrifuge tubes: 100 ml centrifuge tubes were used for the fractionation study.

pH meter: The pH of the soil suspension (soil: water ratio 1:2.5) at room temperature was measured using a Systronics μ pH system 361.

Nitrogen Distillation Apparatus: The available nitrogen content of the soils was analysed using a Kel-Plus Nitrogen Distillation Apparatus manufactured by Pelican.

Spectrophotometer: Phosphorus content was spectroscopically determined using a Systronics spectrophotometer (Model 167). Quartz cuvettes were employed for the spectroscopic measurement.

Flame Photometer: The potassium content of the soil was determined using a Systronics flame photometer (Model 128).

Atomic Absorption Spectrophotometer: The concentration of zinc present in both the leachate and the filtrate collected at the conclusion of the process was determined using an Atomic Absorption spectrophotometer (Model-PinAAcle 900 F)

3.2. Methods followed:

3.2.1. Physico-chemical properties of soils

During this experiment, the analysis of various soil parameters like texture, pH, EC, oxidisable organic carbon, N, P, K of soil samples were done following standard methods mentioned below:

Soil pH: Soil samples suspended in a mixture of soil and water (ratio 1:2.5) were analysed for pH using a Systronics glass electrode pH meter (Jackson, 1967).

Electrical Conductivity (EC): The electrical conductivity of soil-water suspensions (soil: water ratio 1:2.5) was measured using a digital conductivity meter (Jackson, 1967).

Oxidizable Organic Carbon (OC): The oxidizable organic carbon content of the soils was measured by the wet oxidation method developed by (Walkley and Black, 1934).

Mechanical Analysis of Soils: The hydrometer method, as described by Dewis and Freitas in 1984, was used to determine the clay content of the soils. This method also provided information on the distribution of sand, silt, and clay particle sizes, contributing to the characterization of soil textures (Bouyoucos, 1962). The soil texture was determined by using triangular texture diagram of the International Society of Soil Science (ISSS).

Maximum water holding capacity: The maximum water holding capacity of soils was measured gravimetrically by using Keen Raczkowski box method as described by Piper (1950)

Available Nitrogen (N): The amount of available nitrogen in the soil was measured using a Kelplus-Distilled semi-autoanalyzer, employing the alkaline potassium permanganate ($KMnO_4$) method developed by Subbiah and Asija in 1956.

Available Phosphorus (P): The available Phosphorus content in the soil was determined by extracting it with a mixture of 0.03 M NH4F and 0.025 M HCL following the method described by Bray and Kurtz (1945).

Available Potassium (K): Soil samples were extracted using a neutral normal ammonium acetate (1N NH_4OAC, pH 7.0) solution, and the concentration of available potassium was determined using a flame photometer, as per the method outlined by Black in 1965.

Available Aluminium (Al): Exchangeable Al was determined by extracting the soils with ammonium acetate extractant having pH 4.8 (Baruah & Barthakur, 1997) and Al concentration was measured by Atomic Absorption Spectrophotometer.

Available Iron (Fe): Ten gram of air-dried soil and 20 ml of 0.005 M DTPA solution adjusted at pH 7.3(Soil: extractant: 1:2) were taken in 125 ml wide mouth plastic bottle and shaken for 2 hours (Lindsay and Norvel,1978) in a reciprocating shaker. The suspension was filtered through Whatman No. 42 filter paper and the filtrate was analysed for Fe using Atomic Absorption Spectrophotometer (AAS) (Model: Perkin Elmer, Analyst200)

Available Calcium: 58 g of $CaCl_2$ was added to 800 ml of distilled water. Distilled water was poured upto the volume of 1litre. After that, the osmolarity was measured by osmometer. Standard solution with calcium concentration of 0,5,10,15,20 ppm was prepared from this.

Available Magnesium: 120gm of $MgSO_4$ was dissolved to 1 litre of distilled water. Standard solution of 0,1,2,3,4,6,8 ppm was prepared from this.

3.2.2. Analysis of plant samples for Phosphorus

Plant samples, collected at the harvesting stage were dried in air initially. The samples were further dried in an air oven at 80°C and then grinded. 0.5 g of the plant and grain sample was digested with 10 ml of triacid mixture (9:4:1:: HNO_3: H_2SO_4: $HClO_4$ by volume). Following digestion, yellow colour was produced in the digested solution using vanado molybdo-phosphoric acid reagent to analyse the Phosphorus (P) content in plant tissues. Total amount of Phosphorus (ppm) present in the straw was measured in the Spectrophotometer.

Uptake of Phosphorus was calculated by using this formula-Nutrient Uptake (mg/plant) = Concentration of nutrient in plant part (straw/grain) (ppm) × Straw/grain weight of plant (g)

3.2.3 Estimation of inorganic Phosphorus fractions

Different inorganic P fractions such a saloid-P, Al-P, Fe-P, Ca-P, Occluded P and reductant soluble P were analysed by following the method (Chang and Jackson, 1957).

Saloid bound phosphorous (saloid-P): 0.5 g (<2 mm) of soil and 25 ml of 1M NH_4Cl was added to a 100 ml centrifuge tube. Mixture was Shaken for 30 min to extract the soluble and loosely bound P. The solution was then centrifuged at 7000 rpm for 5 minutes and the supernatant was collected into a 25-ml volumetric flask and the volume was made up with deionized water and the saloid-P content was analysed using the ascorbic acid method with a spectrophotometer. The soil sample was washed twice with

12.5-ml portions of saturated NaCl and centrifuged. The washings of extract A was discarded and brought to volume.

Aluminium bound Phosphorus (Al-P): 25 ml of 0.5 M ammonium fluoride solution was added to the residue left in the centrifuge tube after saloid-P extraction. The suspension was shaken for one hour and then centrifuged. The supernatant was transferred into a 50 ml volumetric flask (referred to as extract B). The soil sample remaining in the tube was washed twice with 12.5 ml portions of saturated NaCl solution and centrifuged. The washings were combined with extract B, and the Al-P content was analysed using the ascorbic acid method with a spectrophotometer.

Iron bound Phosphorus (Fe-P): To the residue, 25 ml of 0.1 M sodium hydroxide solution was added and shaken for 17 hours, followed by centrifugation. The supernatant was transferred into a 50 ml volumetric flask (referred to as extract C). The soil sample remaining in the tube was washed twice with 12.5 ml portions of saturated NaCl solution and centrifuged. These washings were then combined with extract C, and the Fe-P content was analysed using the ascorbic acid method with a spectrophotometer.

Reductant soluble Phosphorus: To the residue in the tube, 20 ml of 0.3 M trisodium citrate solution and 2.5 ml of 1 M sodium bicarbonate solution were added. The suspension was heated in a water bath at 85°C. Then, 0.5 gram of sodium dithionite was added and the mixture was rapidly stirred, followed by continuous heating for 15 minutes. The suspension was centrifuged, and the supernatant was transferred into a 50 ml volumetric flask (referred to as extract D). The soil sample remaining in the tube was washed twice with 12.5 ml portions of saturated NaCl solution and centrifuged. These washings were combined with extract D, and the Red-sol-P content was analysed using the ascorbic acid method with a spectrophotometer.

Occluded-Phosphorus: Occluded-Phosphorus was obtained by shaking the soil with 25 ml 0.1 M NaOH for an hour. Then The suspension was centrifuged (7000 rpm for 5 min). The supernatant solution was decanted into 50 ml volumetric flask and brought to the volume (extract E). The remaining was washed with 12.5ml of saturated NaCl and the washings were discarded. The occluded P content was analysed using the ascorbic acid method with a spectrophotometer.

Calcium bound Phosphorus (Ca-P): To the soil residue, 25 ml of 0.25 M H_2SO_4 solution was added and shaken for 1 hour. The suspension was then centrifuged, and the supernatant was transferred into a 50 ml volumetric flask (referred to as extract F). The soil sample remaining in the tube was washed twice with 12.5 ml portions of saturated NaCl solution and centrifuged. These washings were combined with extract F, and the Ca-P content was analysed using the ascorbic acid method with a spectrophotometer.

3.2.4: Chemical kinetics study

Prior to start the P release kinetic study soil samples were incubated for proper mixing of FYM with soils. For this purpose, each soil sample was subjected to three doses of well decomposed FYM @ 0, 5 and 10 t ha^{-1}. The incubated soil samples were kept for a period of 15 days, maintaining room temperature. Water was added periodically to maintain 50% of maximum water holding capacity. On expiry of the incubation periods, the appropriate soil samples were used for chemical kinetics study.

The FYM mixed samples were subjected to a successive extraction process using 0.01 M $CaCl_2$ solution, so that 25 ml of $CaCl_2$ was added into 5g of soil sample and that solution was agitated for 1 h on an orbital shaker and then incubated at 25 ± 1^{o}c temperature. After 23 h, the samples were shaken for 1h and centrifuged for 10 min at 3000 rpm. The supernatants were decanted and filtered using Whatman filter paper No. 42, and P was analysed by colorimetry (Murphy and Riley 1962). The filtered samples were again added 25 ml of 0.01 M $CaCl_2$ solution and incubated for the following extractions after 1, 4, 10, 14, 16, 24, 35 and 41 days following the same extraction procedure.

The kinetics of P release data which were obtained by from equilibrium P concentration at different time of incubation were fitted to the following kinetic equations:

Parabolic diffusion: $q = a + bt^{1/2}$

Power function equation: $\ln q = \ln a + b \ln t$

Elovich equation: $q = a + b \ln t$

First order equation: $\ln (q_0 - q_t) = a - bt$

Where q represents the released amount of P, q_t is the cumulative P released up to time t, t denotes the time of release, q_0 is the maximum P released, and a and b are constants.

These mathematical models were tested by least square regression analysis to determine which equation best describes non-exchangeable P release from soils. Coefficients of determination (R^2) were obtained by least square regression of measured versus predicted values. Standard errors (SE) of the estimate were calculated as follows:

$$\mathbf{SE} = \left[\frac{\sum(\mathbf{q} - \mathbf{q}*)^2}{(\mathbf{n} - \mathbf{2})}\right] \mathbf{1/2}$$

3.2.5. Pot -culture study:

A pot-culture experiment was conducted using a semi-dwarf, non-lodging, medium duration, high yielding rice variety (Uttar Ganga, released from Uttar Banga Krishi Viswavidyalaya) to investigate the uptake of Phosphorus by the rice plants. Bulk amounts of surface soils (0-15 cm depth) were collected from two locations: Pundibari, Cooch Behar and Samsing Forest, Kalimpong, both with different characteristics. Each pot was filled with 5 kg of soil. Three levels of farm yard manure (FYM) at 0, 5 and 10 t ha^{-1} were also incorporated into the pots before the start of the experiment. The soils were properly mixed with FYM. Standard doses of N:P: K fertilizers at 120:60:60 kg per hectare, supplied as urea, single super phosphate, and muriate of potash, were applied to the soil in the pots prior to transplanting. After transplanting, the pots were submerged with water and maintained in a submerged condition throughout the experiment. Each treatment consisted of two plants per pot, and the experiment was replicated three times. Soil and plant samples were collected at the harvesting stage for further analysis. The soils at harvest were also analysed for P fractionation.

3.2.6. Statistical Analysis

All data of soil P fractionation study were subject to the normality and homogeneity tests before analysis of variance (ANOVA) using SPSS statistical package (SPSS version 16.0, IBM Institute, Armonk, NC, USA). ANOVA in completely randomized design (CRD) was performed to detect significant differences at 95% ($p \leq 0.05$) level of probability in soil P fractions upon FYM addition. In pot culture experiment also the significance of the difference between means was estimated at 95% ($p \leq 05$) level of probability using ANOVA in CRD.

Plate No. 1: Addition of Tri acid mixtures in plant samples

Plate No. 2: Phosphorus analysis of plant samples

Plate No. 3: Phosphorus analysis of soil samples

Plate No. 4: Phosphorus analysis of soil samples by me in the laboratory

Plate No. 5: Phosphorus analysis of soil samples using spectrophotometer

Plate No. 6: Phosphorus fractionation study of soil samples

Plate No. 7: Nursery bed preparation

Plate No. 8: Panicle initiation stage of Rice

Plate No. 9: Pot culture study of Rice

RESULT AND DISCUSSION

CHAPTER 4 RESULT AND DISCUSSION

The results obtained from the various experiments conducted during the present investigation are given and discussed in this chapter under different heads as follows:

4.1. Findings from physico-chemical characteristics of the soils:

The important physico-chemical properties of the studied soils are presented in table 1. Soils collected from two different places of west Bengal comprises different soil orders as soil collected from Cooch Behar district belongs to Entisol order and soils collected from Kalimpong district is of Inceptisol. The table shows that the pH of soils of both these places were acidic in nature which is mainly caused by base leaching due to high sporadic rainfall and possibly high organic matter content. The acidity recorded on these soils might also be a result of the acidic nature of the parent rock coupled intensive leaching of bases (Akhtaruzzaman *et al.* 2014)

Electrical conductivity (EC) values were more in Cooch Behar soil in comparison to Kalimpong soil. This phenomenon may be influenced by temperature as there is different temperature regime between hill and terai region soils. Different textures and water content also can play a pivotal role in this phenomenon (Brevik *et al.*, 2004).

There was large difference in organic carbon content in soils of Cooch Behar and Kalimpong. An almost fivefold high organic carbon can be seen in Kalimpong soil (2.5%) than Pundibari soil (0.53%). The Kalimpong soils were collected from the forest area which received continuous litter addition due to leaf fall and thus have high organic matter content. The regular addition of organic matter through tree leaves is thought to be the cause of the rise in organic carbon in the forest land use system, from where the soil was collected. The texture of Pundibari soil was sandy loam with 12.62% clay and sandy clay loam in Kalimpong with 23.75% clay. Maximum water holding capacity of these soils are observed as 23% in Pundibari and 34% in Kalimpong. The available N and K content were higher in Kalimpong but the available P content was higher in Pundibari soil. Available Fe and Al contents were high in Kalimpong soil.

Table 1. Physico-chemical properties of soil

Properties	Pundibari	Kalimpong
Soil taxonomy	Typic Fluvaquent	Fluventic Eutrochrepts
Sand (%)	53.71%	50.56%
Silt (%)	33.67%	25.69%
Clay (%)	12.62%	23.75%
Textural class	Sandy loam	Sandy clay loam
pH (1:2.5)	5.9	4.26
Electrical conductivity (dSm^{-1})	0.21	0.13
Organic carbon (%)	0.53%	2.55%
Maximum water holding capacity	23 %	34%
Available N (kg $ha^{-1)}$	149.51	212.65
Available P (kg $ha^{-1)}$	14.36	8.37
Available K (kg $ha^{-1)}$	104.34	126.36
Available Ca^{2+} (me/100g)	1.3	0.4
Available Mg^{2+} (me/100g)	0.7	0.2
Available Fe (ppm)	31.8	51.7
Available Al (ppm)	3.89	6.23

4.2. Findings from the Kinetics of Phosphorus Release

Phosphorus release from unamended and FYM -amended soils at different times of extraction by 0.01M $CaCl_2$ is presented in table and the cumulative release pattern (time dependent) of P shown in the figure. The result indicates that the P release increased progressively with time. Phosphorus release was less (0.89 - 4.43 mg kg^{-1}) in both amended and unamended soil at $CaCl_2$ extraction after 24 h of incubation. Phosphorus extracted after 96 and 240 h of incubation were also low (2.81 -16.38 mg kg^{-1}). Phosphorus remains in soil in different forms, namely saloid -P, occulded-P, Fe-P, Al-P, Ca-P and residual P. Among these P fractions saloid and occluded P (Chang and Jackson, 1957) are the active fraction of P which are labile to crops. The saloid-P is loosly bound P in soil that is available for plant uptake and contribute to labile P in soil. The soils have less amount of saloid - P as shown in the fractionation study which may have resulted in the less release of P at initial extraction. The soils are acidic and contain high amount of Fe and Al which bounded a significant portion of total P in recalcitrant form which are less desorbable from in soil and doesn't have relationship with the plant uptake (Soremi *et al.*, 2017). At the later extraction period, the release of P increased to the release of P from Fe/Al oxides. Dissolution of less available inactive Fe-P, Al-P and Ca-P forms may have resulted in the increase of P release in the extraction at later period (384 hrs). The extraction made after 984 hrs (41 days) the amount of P extracted was 35.10 and 30.43 mg kg^{-1} in Pundibari and Kalimpong soil, respectively. The cumulative release curve shown in Figure 1 shows that there was a rapid increase in P released at 3rd and 4th extraction (240 and 336 hr) and after that the release came to a stationary phase.

Such a rapid release of P at certain time of extraction may be ascribed to the rapid dissolution of poorly crystalline or amorphous phosphatic compounds present in the soils, which were metastable. The later decrease in P release may be due to recrystallization (Hosseinpur and Pashamokhtari, 2008). As this experiment is carried on only for 41 days, thus a longer observation might result in a more stable pattern of Phosphorus release. The quick initial P release in soils can also be explained by the dissolution of unstable, poorly crystallized or amorphous phosphate forms. These temporary structures eventually change into more stable crystalline types, such as octacalcium phosphate and calcium hydroxyapatite (Griffin *et al.* 1974). The expected stationary phase might indicate the completion of decomposition procedure. The individual soil samples of Pundibari and Kalimpong soil shows an increasing trend in Phosphorus release pattern too.

Addition of FYM markedly increased the P release in both the soils at all extraction periods. The increased doses of FYM further increased P release at each extraction. In Pundibari soil P release increased from 0.89 mg kg^{-1} in unamended soil to 1.80 and 4.43 mg kg^{-1} at 5 and 10 t ha^{-1} FYM amended soil at extraction done at 24 hr. The amount of P released from the FYM treated soil after 41 days (984 hr) was higher than the normal soil. The FYM itself contain 0.5% P which may contributed to the increased P release by gradual decomposition. The FYM application might have increased the microbial activity in the soils. The active participation of soil microbial community in the decomposition of organic matter might be another reason to increase P release from amended soil. According to Sarapatka, (2003) the increased phosphatase enzyme activity also helps in the transformation of P from organic form to inorganic form, as these enzymes are responsible for soil organic P mineralization and the release of inorganic P (Garg *et al.*, 2006).

The release of phosphatic ions from the clay particle occur due to the exchange of other different anions (Cl^-, NO_3^-, SO_4^{2-}) with clay particles in the vicinity of solid-solution area (Ookubo *et al.*,1992). Organic matter is an important phosphate fixer in the soil (Borie *et al.*,1983). Thus, if we look into the cumulative P release graph, it is clear that the release of P is relatively low in the case of Kalimpong soils due to more organic matter content than the Pundibari soils. Martens *et al.* (1992) further reported that application of any organic material results in significant increase in phosphatase activity. Explaining another phenomenon, as the treatment increases the organic matter available to the soil also increases due to several reasons mentioned above. Singh *et al.* (2022) explained that with increasing dose of phosphate sources, their release also increases.

Table 2. Amount of P release in each extraction time

		Time of extraction (hr.)							
Soil	**FYM (Kg ha^{-1})**	**24**	**96**	**240**	**336**	**384**	**576**	**840**	**984**
Pundibari	0	0.89	3.05	9.11	16.90	22.74	26.98	31.5	35.10
	5	1.80	4.01	12.63	20.83	26.18	30.34	34.54	39.55
	10	4.43	8.85	16.20	24.17	28.35	32.35	37.20	40.33
Kalimpong	0	1.45	2.81	7.67	12.22	18.41	22.48	27.14	30.43
	5	2.05	5.47	13.18	17.69	21.28	25.42	29.19	31.36
	10	2.29	6.22	16.38	20.88	24.95	29.05	34.25	36.39

4.2.1. Application of mathematical models to Phosphorus release kinetics

Mathematical models play a crucial role in understanding P release dynamics in soil. These models are valuable for two main reasons: predicting how soil can provide P to crops when P levels are low, and determining appropriate amounts of Phosphorus-based fertilizers for various soil types. Different mathematical kinetic models are used by many scientists to evaluate and understand release pattern more accurately. Models like power function, first order, Elovich and parabolic diffusion are used in this objective (Ho, 2006, Sparks, 1989, Lagergren, 1898, Low, 1960)

In this study, In the parabolic diffusion curve, the maximum P release occurred in the case of 5t ha-1 treatment (Pundibari) which is 1.5339 mg kg^{-1}hr$^{-1/2}$ and in the control plot (0 t ha^{-1}) in the case of Kalimpong which is 1.3603 mg kg^{-1}hr$^{-1/2}$. Such use of the parabolic diffusion model to evaluate the P release data is used by Islas-Espinoza *et al.* (2013). Similarly, we used power function model, in which the maximum P release is in the case of control plot (0 t ha-1) of Pundibari (1.0457 mg^{-1}kg^{-1}hr) and in the case of 5t ha^{-1} of Kalimpong soil sample (0.8815 mg^{-1}kg^{-1}hr). Every value except the Pundibari control plot (0 t ha^{-1}) is less than 1. Yang *et al.* (2018) also used power function to evaluate these patterns. The Elovich 'b' represents an index of rate of P release from different soils. In the case of Elovich model Pundibari (5 t ha-1) and Kalimpong (10t ha^{-1}) takes the lead this time. The data varies from 10.471 mg^{-1}kg^{-1}hr in case of Pundibari (5 t ha^{-1}) soil to 8.088 mg^{-1}kg^{-1}hr in the case of Kalimpong (5 t ha^{-1}) soil. Regarding the first-order equation, it clearly follows an almost straight-line trend. It represents the cumulative data. Values of “b” are almost nearby, ranging from 0.0034 (mgkg$^{-1)-1}$ in the case of Kalimpong (10 t ha^{-1}) to 0.0028 (mgkg$^{-1)-1}$ for both Kalimpong (5 t ha^{-1}) and Pundibari (5t ha^{-1}) soils. Hosseinpur *et al.* (2008) also worked with first order kinetic model to derive the Phosphorus release pattern

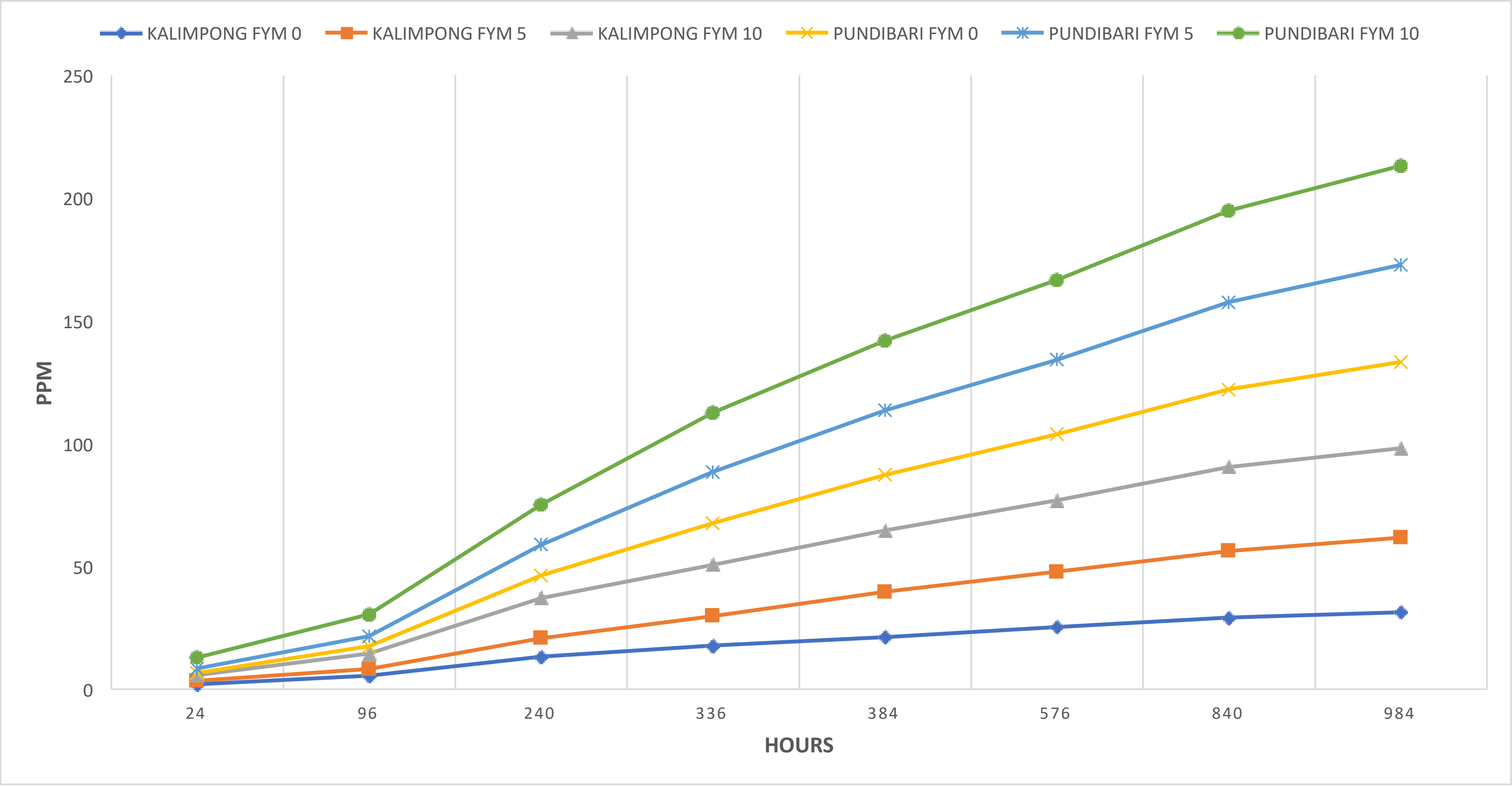

Fig. 1. Effect or FYM on cumulative P release from soils

Table 3. Parameters of different models used to describe the release of Phosphorus by 0.01 M $CaCl_2$

Soil	FYM (t ha^{-1})	Parabolic diffusion		Power function		Elovich		First order	
		b	a	b	a	b	a	b	a
		mg $kg^{-1}hr^{-1/2}$	$mgkg^{-1}$	mg $kg^{-1}min^{-1}$	$mgkg^{-1}$	$mg^{-1}kg^{-1}hr$	$mgkg^{-1}$	$(mgkg^{-1})^{-1}$	$mgkg^{-1}$
Pundibari	0	1.4012	-8.4162	1.0457	0.03193	9.727	-36.392	0.0029	3.7493
	5	1.5339	-7.8674	0.8971	0.09459	10.741	-39.014	0.0028	3.8187
	10	1.4293	-3.2537	0.6257	0.5793	10.143	-33.03	0.0030	3.7536
Kalimpong	0	1.3603	-4.6194	0.7764	0.2042	8.35	-28.735	0.0032	3.5825
	5	1.187	-7.287	0.8815	0.07315	8.0899	-30.142	0.0028	3.6199
	10	1.1734	-4.1581	0.7705	0.1807	9.7194	-33.333	0.0034	3.7495

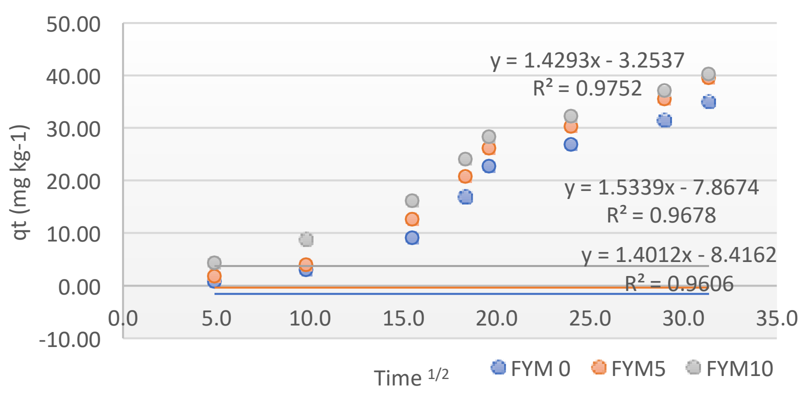

Fig 2. Parabolic diffusion curve for P release pattern in Pundibari soils

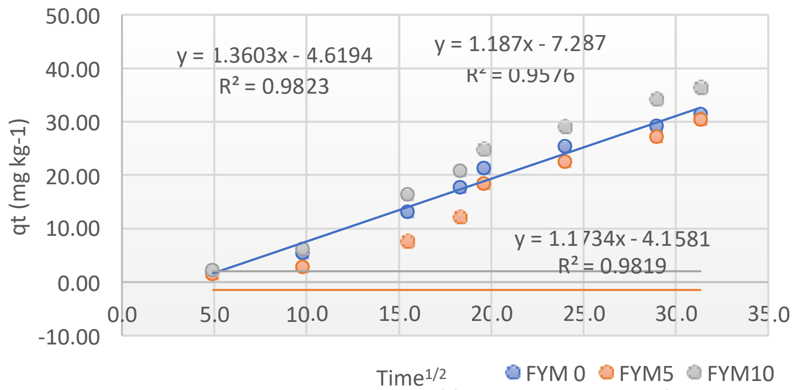

Fig 3. Parabolic diffusion curve for P release pattern in Kalimpong soils

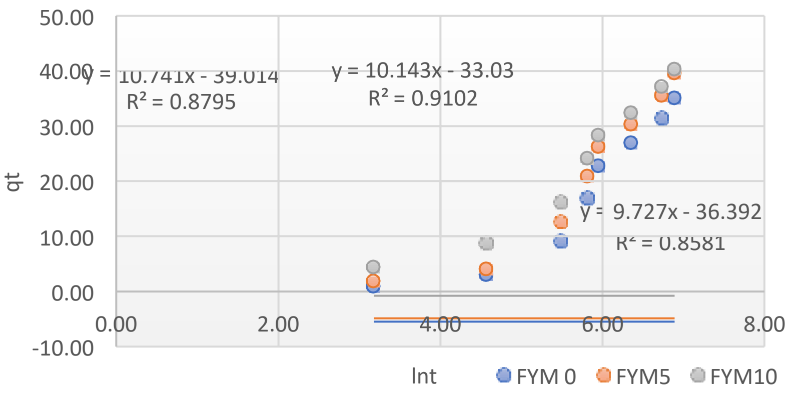

Fig 4. Elovich diffusion curve for P release pattern in Pundibari soils

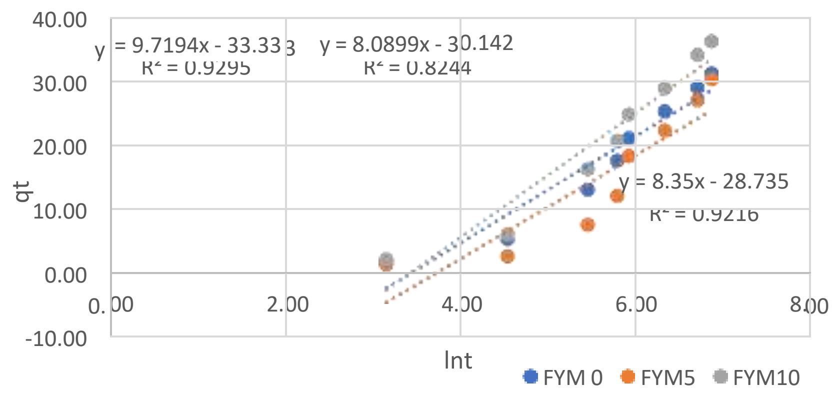

Fig 5. Elovich diffusion curve for P release pattern in Kalimpong soils

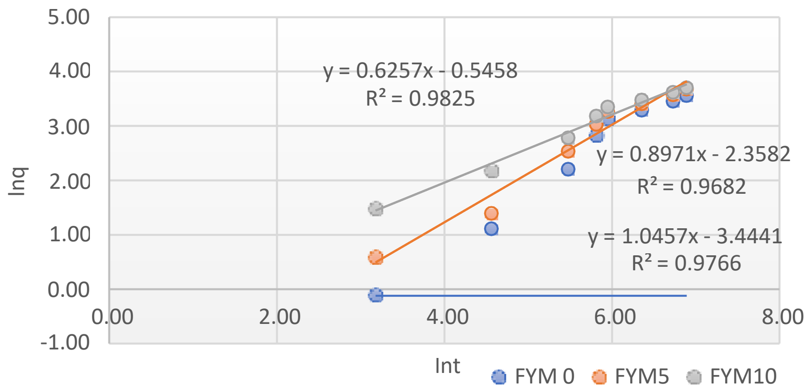

Fig 6. Power function curve for P release pattern in Pundibari soils

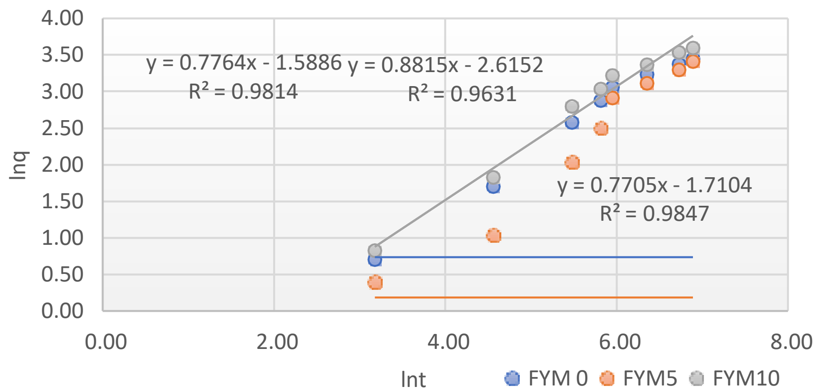

Fig 7. Power function curve for P release pattern in Kalimpong soils

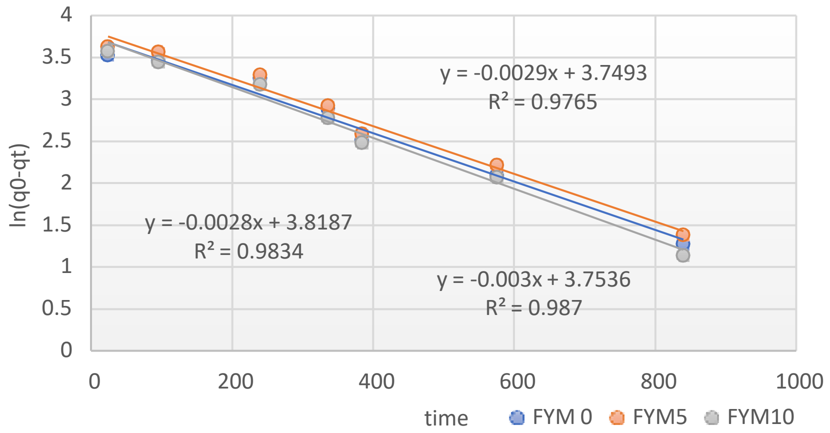

Fig 8. First order curve for P release pattern in Pundibari soils

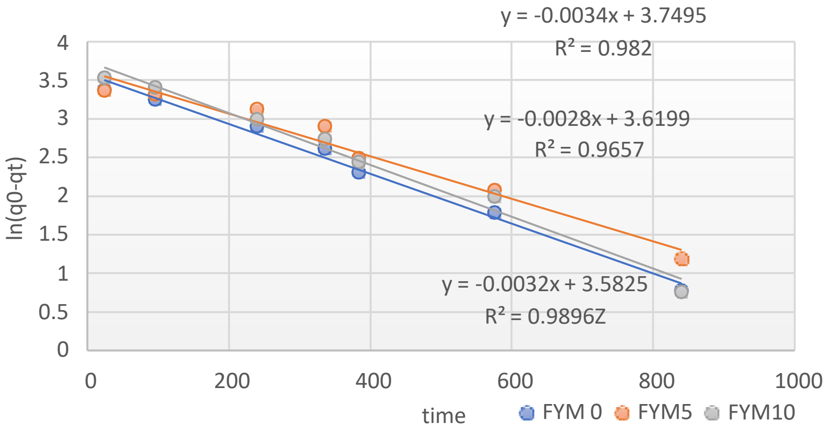

Fig 9. First order curve for P release pattern in Kalimpong soils

These models were examined for their fitting to explain the P release from soil by estimating Coefficient of Determination (R^2) and Standard Error of Estimate (SE). The best fir model could predict the P release from soil. The data summarized in table 7 shows that the power function and first-order models are the most suitable for describing P release patterns in soil. Shariatmadari *et al.* (2006) also found that first order kinetics describes the release pattern more accurately. Successful description of P release by the power equation was reported by Nafiu (2009).

Table 4. Coefficient of determination (R^2) and standard error of estimate (SE) of different kinetic models for the soils

Soil	**FYM ($t\ ha^{-1}$)**	**Parabolic Diffusion**		**Power Function**		**Elovich**		**First order**	
		R^2	**SE**	**R^2**	**SE**	**R^2**	**SE**	**R^2**	**SE**
PUNDIBARI	FYM0	0.9606	1.9414	0.9766	0.2037	0.8580	0.5018	0.9764	47.276
	FYM5	0.9678	1.7567	0.9682	0.2374	0.8795	0.4622	0.9834	39.70
	FYM10	0.9751	1.5414	0.9825	0.1760	0.9101	0.399	0.9870	35.131
KALIMPONG	FYM0	0.9817	1.3173	0.9847	0.1646	0.9216	0.3728	0.9895	31.488
	FYM5	0.9576	2.0141	0.9631	0.2556	0.8244	0.5580	0.9656	57.116
	FYM10	0.9823	1.3027	0.9814	0.1816	0.9295	0.3536	0.9820	41.335

4.3. Findings from different fraction of phospshorus in soils

Different P forms in Pundibari and Kalimpong initial soils were analysed by employing the P fractionation scheme of Chang and Jackson (1957) and the data is presented in table 5 . The results indicated that the Fe-P dominated in the Pundibari soil whereas in Kalimpong soil is dominated by Al-P. This could be attributed to the higher Fe (31.8 ppm) and Al (6.23 ppm) contents in Pundibari and Kalimpong soil, respectively. The saloid-P which is the most availabe fraction of soil P was lowest among the fractions in both soils. However, saloid-P was relatively higher in Pundibari soil (8.50 mg kg^{-1}) than Kalimpong soil (7.57 mg kg^{-1}). This was in accordance with higher available P status in Pundibari soil (14.36 kg ha^{-1}) than Kalimpong soil (8.37 kg ha^{-1}). The Al-P was followed by Fe-P in both the soils. The higher amount of Al-P and Fe-P in both soils may be due to the acidic nature of both soils. The Frcation of P in soil is pH dependent. Earlier the dominance of Al_P and Fe-P in the acidic soils of norther part of West Begal was also reported earlier (Wang *et al.*, 2023; Paramanik *et al.*, 2012). The lower Ca-P content was low in both the soils. Such low Ca-P in these soils could be attributed to the lower Ca^{2+} content in both the soils (Table 1) (Kiflu *et al.*, 2017). In Pundibari soil the P fractions followed the order Fe-P>Al-P>Reductant soluble-P>Ca-P>ocluded-P>saloid-P and in Kaloimpong soil the fractions followed the order Al-P>Fe-P>reductant solube-P>occluded-P>Ca-P.

Table 5. Different fractions of Phosphorus in Pundibari and Kalimpong soils

Soil	**Saloid P (mg kg^{-1})**	**Al-P (mg kg^{-1})**	**Fe-P (mg kg^{-1})**	**Reductant soluble P (mg kg^{-1})**	**Occluded P (mg kg^{-1})**	**Ca-P (mg kg^{-1})**
Pundibari	8.50	53.86	98.84	52.61	26.44	32.96
Kalimpong	7.57	45.08	43.99	35.46	19.85	16.51

4.4. Findings from pot culture experiment with rice

4.4.1. Effect of FYM application on the yield of rice:

The effect of adding organic matter, namely FYM on the yield of rice straw and grain is presented in the table 2. The table shows that the straw yield was lowest in both Pundibari (6174 kg ha^{-1}) and Kalimpong (4749 kg ha^{-1}) soil in the control where no FYM were added. The application of FYM significantly (at $p \leq 0.05$) increased yield of both straw and grains in both soils. In Pundibari soil the highest straw yield (8059 t ha^{-1}) was obtained at 10 t ha^{-1} FYM application and in Kalimpong soil the highest straw yield was recorded as 6199 kg ha^{-1}. Application of FYM at 5 t ha^{-1} also significantly (at $p \leq 0.05$) increase straw yield in both soils. The straw yield was increased by 24.2% and 30.52% over the control with application FYM at 5 and 10 t ha^{-1}, respectively. Comparison of treatments by Duncan Multiple Range Test (DMRT at $P \leq 0.05$) showed the significant difference in the straw yield in both soils with application of increasing doses of FYM. Singh *et al.* (2019) also found the same result while working with rice. Similar findings were also reported by Rinasoa *et al.* (2023) showing that FYM application significantly increased straw yield of low land rice in P deficient soil. Such positive impact of FYM on rice yield was attributed to the P supplying capacity of FYM in P deficient soil. The application of FYM increased the P release from soil native and applied P sources as shown in the previous release kinetics study, which may also increase the P uptake by rice and increase the plant growth and straw yield.

Similar trend was followed in the case of grain yield also, where the lowest grain yield was 4749 kg ha^{-1} in Pundibari soil and 3399 kg ha^{-1} in Kalimpong soil in control (table 2). The grain yield increased significantly (at $p \leq 0.05$) with the increased rate of FYM application at 5 and 10 t ha^{-1}. The highest grain yield was recorded as 6199 kg ha^{-1} in Pundibari soil and 5599 kg ha^{-1} in Kalimpong soil at 10 t ha^{-1} FYM application. According to DMRT (at $P \leq 0.05$), there is a clear significant difference between these treatments, making the dose with highest treatment the best one. Similar work also done by Satyanarayana *et al.* (2002) where he found that increasing dose of organic manure increases yield. The rice in the pot was grown under flooded condition. Several laboratory studies demonstrated that the higher P availability from organic matter increased spikelet fertility and yield of rice (Rakotoson and Tsujimoto, 2020; Asai *et al.*, 2021).

The yield of rice was relatively lower in Kalimpong soil as compared to Pundibari soil in same treatment combinations. This could be due to the higher native NPK content of the Pundibari soil which was collected from the cropped field having regular input of fertilizers. This practice could have increased the fertility level of the cultivated Pundibari soil than the Kalimpong soil which was mainly collected from a forest area. The pH of the Kalimpong soils was also low than Pundibari soil which also might lead to the lower rice yield (Lambert *et al.*,2000).

Table 6: Effect of FYM application on the yield of rice

Soil	**FYM ($t\ ha^{-1}$)**	**Straw Yield ($kg\ ha^{-1}$)**	**Grain Yield ($kg\ ha^{-1}$)**
Pundibari	0	6174c	4749c
	5	7669b	5899b
	10	8059a	6199a
	SEM (±)	5.09	4.811
	LSD ($P \leq 0.05$)	15.69	14.82
Kalimpong	0	4419c	3399c
	5	5795b	4457b
	10	7279a	5599a
	SEM (±)	7.92	5.33
	LSD ($P \leq 0.05$)	24.40	16.43

*Different letters at same column are significantly different by Duncan Multiple Range Test (DMRT) at p ≤05.

4.4.2. Effect of FYM application on the Phosphorus uptake by rice

The Phosphorus uptake by rice straw and grain per pot in pot culture experiment is presented in table 3. The table shows that FYM application significantly (at $P \leq 0.05$) increased P uptake by straw and grain of rice in both soils. In Pundibari soil the P uptake by grain increased from 28 mg pot^{-1} to 47 and 81 mg pot^{-1} with the application of 5 and 10 t ha^{-1} FYM, respectively. Whereas in Kalimpong soil the P uptake by grain increased from 18 mg pot^{-1} to 23 and 38 mg po^{-1} with the same rate of FYM application. The highest uptake was recorded in the highest rate of FYM application in both soils.

The uptake of P by rice grains was relatively higher than straw due to the higher mobility of P in plants. In Pundibari soil the P uptake by straws was increased from 84 g pot^{-1} in control to 113 and 150 g pot^{-1} with 5 and 10 t ha^{-1} FYM application, respectively. In Kalimpong soil these increments were from 53 mg pot^{-1} to 66 and 91 mg pot^{-1} with 5 and 10 t ha^{-1} FYM application. Analysis of mean difference by DMRT (at $p \leq 0.05$) showed that the effect of the treatments was significantly different at 95% probability level.

Such increase of P uptake by straw and grains of rice by FYM application is attributed to the inherent P content in FYM which releases P by mineralization in anaerobic condition (Rakotoson and Tsujimoto, 2020; Asai *et al.*, 2021). The rice was grown in pots in submerged condition. The change of pH and Eh in submergence is reported to increase P availability in soil and resulted in higher P uptake by plant parts (Ando *et al.*, 2022).

The uptake of P by rice straw and grain was lower than that of Pundibari soil might be due to the lower available P content in Kalimpong soil (table 1). Further, the reduced uptake of P in the hilly Kalimpong soils might also be due to the higher acidic nature and insoluble Fe/Al-phosphate formation (Hemwall,1957). The higher amount of organic matter present in the Kalimpong soil also binds the P making the phospho-metal-humate complex, thus reducing its availability to the plants (Sinha *et al.*,1971).

Table 7. Effect of FYM application on the uptake of Phosphorus by rice

Soil	**FYM (t ha^{-1})**	**uptake of P by grain (mg pot^{-1})**	**uptake of P by straw (mg pot^{-1})**
Pundibari	0	28c	84c
	5	47b	113b
	10	81a	150a
	SEM (±)	0.0009	0.002
	LSD ($P \leq 0.05$)	0.0027	0.0061
Kalimpong	0	18c	53c
	5	23b	66b
	10	38a	81a
	SEM (±)	0.001	0.0643
	LSD ($P \leq 0.05$)	0.0032	0.1981

* Different letters at same column are significantly different by Duncan Multiple Range Test (DMRT) at $p \leq 0.05$

4.4.3. Effect of FYM application on the dry matter production of rice

Dry matter production, i.e., the combination of straw and grain yield was affected by the FYM application in pot culture study (Table 4). Significant (at $p \leq 0.05$) increase in dry matter production was noticed with the application of FYM over the control. Considering the straw dry matter of Pundibari, the values ranged from 16.31 g in control pot and to 24.10 g in the highest dose of FYM (10 t ha^{-1}). In grain dry matter in Pundibari soils the control pot's plant has the dry matter of 12.54g and the highest value (18.66g) was observed by the sample having the highest FYM application. Analysis with DMRT (at $P \leq 0.05$) reveals that, in both cases, the treatments were significant of their own.

In Kalimpong soils, the lowest value of straw dry matter (16.53g) was measured in control pot. With increasing doses of FYM, the dry matter content also increased, resulting the highest dry matter weight (19.90g) in FYM at 10 t ha^{-1}. The grain dry matter content of Kalimpong soils ranged from 12.71g to 15.31g in control and 10 t ha^{-1} FYM application, respectively. In Kalimpong soil also the DMRT (at $P \leq 0.05$) analyisis showed the significant difference between treatments.

A prominent gap was noticed between the soils of Pundibari and Kalimpong in yield and P uptake (both straw and grain), but there was not so much difference of dry matter production. Nitrogen is the nutrient that helps the plant to gain its vegetative growth (Leghari *et al.*,2016). Whereas, Phosphorus is an important nutrient which increases yield of plant (Agegnehu *et al.*,2006). As the soil of Kalimpong was collected from a forest area, the organic matter content of the soil was very high. Organic matter can form a complex with P thus reducing its availability i.e. its uptake in plants, but applying organic matter (OM) to soil enhances its content of essential micro- and macro-elements needed for optimal crop growth. One of these elements is nitrogen which is a key nutrient (Ukalska-Jaruga *et al.*,2020). The enhanced nitrogen content in the soil, helped the plants fully to achieve its vegetative growth, but due to reduced Phosphorus supply to its straw and grains, its nutrient uptake and yield is less than the plants in Pundibari soil.

Table 8. Effect of FYM application on the dry matter of rice

Soil	FYM (t ha^{-1})	Straw (g pot^{-1})	Grain (g pot^{-1})
Pundibari	0	16.31c	12.54c
	5	20.27b	15.59b
	10	24.1a	18.66a
	SEM (±)	0.1951	0.1715
	LSD ($P\leq0.05$)	0.601	0.528
Kalimpong	0	16.53c	12.71c
	5	17.38b	13.36b
	10	19.90a	15.31a
	SEM (±)	0.134	0.064
	LSD ($P\leq0.05$)	0.412	0.198

* Similar letters in the same column represents non-significant data($p\leq0.05$)

4.5. Effect of application of FYM in Phosphorus fraction in pot soil

Saloid P

Saloid P fraction denotes the loosely bound P fractions of the soil and is labile for plant uptake. Considering the initial sample of Pundibari soil it was 8.50 mg kg^{-1}. While it was increased to 9.88 mg kg^{-1} at hsrvest of rice in soil of control pot where no FYM was added but recommended dose of P (60 kg P_2O_5 ha^{-1}) was added. The saloid-P which likely to be released from this fertlizers might has been uptake n by the crop. Therefore there was not much increase of saloid-P even after application of fertilizer. But the application of FYM in higher doses insignificantly (DMRT at $p\leq0.05$) decreased salod-P fraction in the soil may be deu to the uptake of P by rice. The soil was deficient in available P content. Therefore, the application of FYM even in higher doses could not increase the labile fraction of P.

The saloid-P fraction in Kalimpong soil also increased at harvest of rice than the initial stage. The saloid-P harvest of rice in control plot was 8.85 mg kg^{-1}. Application of FYM in different doses increased the saloid P fraction in soil but it was found insignificant at $P \leq 0.05$ by DMRT analysis. Such increase of saloid-P by application of organic manure was also reported by Soremi *et al.* (2017). The insignificant change of saloid-P in Kalimpong soil may be due to the inherent higher organic carbon (2.55%) present in it. It can be assumed that, as the soil was collected from forest, the litter enriches the soil with organic matter (Osman *et al.*, 2013) Thus, the bonding energy of that complex is such strong that, there was no much effect of applying treatments on that soil at all.

Aluminium P (Al-P)

Al-P fractions literally denotes that fraction of P that forms a bond with Aluminium ions in soil. Considering the intial value of Pundibari soils, the value of Al-P was 53.861 mg kg^{-1}. but in pot soil the Al-P increased with the application of P fertilizer. In the control pot where no FYM was added the Al-P was lowest (44.60 mg kg^{-1}) and the highest value was obtained in in FYM at 10 t ha^{-1} (52.41 mg kg^{-1}) ppm). Analysing with DMRT at $P \leq 0.05$ reveals that, these treatment combinations were significant of their own, leaving the treatment with highest dose of organic source the best one possible. According to best treatment combination, it follows the FYM10>FYM5>FYM0 trend.

In Kalimpong soil, the Al-P fraction was also increased in pot soil after the rice harvest than in the initial soil. In Kalimpong soils, the initial soil value is 45.08 mg kg^{-1} and it increased to 51.17 mg kg^{-1}. The application of FYM at higher doses significantly (DMRT at $P \leq 0.05$) increased the Al-P fraction and the highest (59.42 mg kg^{-1}) was noted in FYM at 10 t ha^{-1}.

Such increasing value of Al-P with increasing dose of FYM can be explained as the decomposition of FYM produces organic acids that can complex with aluminium ions in the soil, these can affect the solubility and availability of Phosphorus. As FYM application increases, these organic acids might promote the formation of soluble Al-P complexes, thus increasing the Al-P fraction in the soil.

Iron P (Fe-P)

The Fe bound P fraction (F-P) value of Pundibari's initial soil sample was 98.84 mg kg^{-1}. In the pot culrure experiment the Fe-P at the harvest of the soil was 70.33 mg kg-1 in Pundibari soil. Such decrese of Fe-P in rice soil may be due to the submergence which reduces Fe-oxides and hydoxides and releases Fe bound P in soil. Application of FYM in incressing doses significantly (DMRT at $P \leq 0.05$) increased Fe-P in the soil. The highest value of Fe-P (85.38 mg kg^{-1})was obtained in FYM dose of 10 t ha^{-1}. A similar type of value was found by Mukhopadhyay et.al (2007) too.

In the Kalimpong soils, the Fe-P value was decreased from initial soil in the pot culture experiment. Likewise, the FYM application significantly increased FE-P value on Kalimpong soil also and the highest value (48.21 mg kg^{-1}) was obtained in FYM dose of 10 t ha^{-1}.

Such increase of Fe-P fractions of both the soils in submerged rice cultivation may be due to the release of P from insoluble Fe-P fraction and also a substantial amount of P was added through the FYM. Organic acids and other compounds released from decomposing FYM can affect the solubility and availability of Fe and P. This phenomenon can also be described with the buffering capacity of the soil. If FYM slightly acidifies the soil (Kulhanek *et al.*,2015), it can help to keep iron in a more soluble form and can influence the availability of Phosphorus. This can increase the Fe-P fraction as iron becomes more available and can react with Phosphorus in the soil. The lower value of Fe-P of hill soil (Kalimpong) as compared to plain soil (Pundibari) can be for the reason of applying past fertilizer treatments. As plain soils were enriched with additional fertilizers or organic amendments, it could increase Fe and P availability and lead to higher Fe-P fractions compared to hill soils, which might not have received similar treatments.

Calcium P

There was not much changes in Ca-P content in initail soil and at the soils at harvest of rice in pot culture. Like the other fractions the Ca-P was also low in the control pot (33.03 mg kg^{-1}) in Pundibari soil. The application of FYM in increasing doses significantly (DMRT at $p \leq 0.05$) increased Ca-P content in Pundibari soil. The highest amount of Ca-P (43.83 mg kg^{-1}) was found in FYM dose of 10 t ha^{-1}.

The Kalimpong soil similar results were obtained. However, the Ca-P content was little bit lower than Pundibari soil in each FYM application rate. This could be due to the lower Ca^{2+} content in this soil (Table 1). The Pundibari soil had relatively higher pH and higher Ca^{2+} content. Relatively lower value of Ca-P in the Kalimpong soils could also be attributed to inherent soil characteristics of hill soils. Hill soils are often more acidic due to increased leaching of base cations. Lower pH can affect the solubility and availability of calcium. It is more available in the neutral pH (McCauley *et al.*,2009). Another reason may be that, hill soils typically have a deeper water table, which can affect nutrient distribution and availability in the soil profile thus a reduced quantity of Ca^{2+} present in the soil system. The soil was collected from a sloppy land, that's why the nutrient influx which was already present in the lowland soils of Pundibari was absent in the case of Kalimpong soils (Gafur *et al.*,2003)

Reductant soluble P

The reductant soluble P fraction is a form of insouble P which is unavailable for plants (Bauwin and Tyner, 1957). The reductant souble P of Pundibari soil increased in pot soil after harvest of rice from 52.61 mg kg^{-1} to 53.18 mg kg^{-1}. This might be solubilzation of FE/Al oxides in submerged soil. The apllication of FYM further signifiacntly (DMRT at $P \leq 0.05$) increased to 66.99 and 74.13 mg kg^{-1} with 5 and 10 t ha^{-1}, respectively.

In Kalimpong soil similar trend was noticed. The submergence increased reductant soluble P from 35.46 mg kg^{-1} in initial soil to 35.69 mg kg^{-1} in rice soil without addition of FYM. FYM application further significantly (DMRT at $P \leq 0.05$) to 52.96 and 69.11 mg kg^{-1} with 5 and 10 t ha^{-1}, respectively.

Such increase of reductant soluble-P in both soils was attributed to the effect or organic acids produced during the decomposition of FYM which might compete with phosphate for adsorption sites on soil particles, potentially increasing the reductant soluble P fraction. FYM application can also lead to the formation of organic P compounds, some of which may contribute to the reductant soluble P pool. In younger hill soils, more P may be bound in primary minerals or in forms less accessible to reductants. As soils develop, P tends to redistribute into different fractions, including potentially more reductant soluble forms. This can be the explanation of the lower reductant P fraction value of Kalimpong hill soils in comparison to plain soils of Pundibari.

Occluded P

Initial soil sample values of occluded P in in the Pundibari soils was 26.44 mg kg^{-1}. Considering the pots where treatments were applied, the highest value was in the case of FYM at 10 t ha^{-1}. (30.27 mg kg^{-1}) and the lowest value was observed in the case of the control pot present in the experiment (21.37 mg kg^{-1}). A clear increase of occluded P status with increasing FYM content was observed in pot. Duncan Multiple Range Test (DMRT at $P \leq 0.05$) reveals that the occluded P status of Pundibari soils is significant of their own and the treatment with the highest dose is the best treatment possible here. Mukhopadhyay *et al.* (2007) also found similar kind of results.

In the initial soil sample of Kalimpong, the value of occluded P is 19.85 mg kg^{-1}. In the treatment soils, the highest value was in the FYM at 10 t ha^{-1} (43.74 mg kg^{-1}) and the lowest value was in the case of the control soil pot (25.6 mg kg^{-1}). Here, the increment of Ca-P content with the increasing amount of FYM can also be seen. Duncan Multiple Range Test (DMRT at $P \leq 0.05$) found that, the treatments are significant of their own and the treatment with the highest dose is the best one.

With increasing dose of FYM, the occluded P also increases for both Kalimpong and Pundibari soils. This could be due to the soil structure improvement with FYM application leading to more and larger aggregates. Phosphorus can be occluded within these aggregates, as the organic matter and microbial activity contribute to the formation and stabilization of these structures. Another explanation can be, by addition of FYM microbial activity stimulates in the soil. Microbes break down the organic matter, leading to the formation of organic Phosphorus compounds and increasing the potential for Phosphorus to become occluded within microbial biomass or in association with microbial products.

Table 9: Effect of FYM on soil P fractions in rice soil in pot culture study

Soil	FYM (t ha^{-1})	Saloid P (mg kg^{-1})	Al-P (mg kg^{-1})	Fe-P (mg kg^{-1})	Reductant soluble P (mg kg^{-1})	Occluded P (mg kg^{-1})	Ca-P (mg kg^{-1})
Pundibari	0	9.89a	44.60c	70.33c	53.18c	21.37c	33.03c
	5	8.90b	48.49b	75.55b	66.99b	26.99b	37.17b
	10	8.79b	52.41a	85.38a	74.13a	30.27a	43.83a
	SEM (±)	0.190	0.83	0.945	0.88	0.603	1.01
	LSD (P≤0.05)	0.586	2.57	2.912	2.722	1.860	3.08
Kalimpong	0	8.85a	51.17b	31.24c	35.69c	25.60c	15.79c
	5	8.99a	54.65b	41.297b	52.96b	32.12b	22.75b
	10	9.25a	59.42a	48.21a	69.11a	43.74a	25.96a
	SEM (±)	0.205	1.21	0.892	0.78	0.637	0.53
	LSD (P≤0.05)	0.63	3.75	2.756	2.40	1.96	1.63

SUMMARY AND CONCLUSION

CHAPTER 5 SUMMARY AND CONCLUSION

Phosphorus fixation in acidic soils is a major concern for limiting plant growth and diminished yield. Phosphorus is one of the least mobile nutrients in soil compared to other major plant nutrients like nitrogen and potassium. In acidic soils, native P remains in different insoluble forms associated with Fe/Al oxides and hydroxides. Only a portion of P called as saloid P is comparatively more mobile in soil and labile for plant uptake. Such complexation with the dominant cations like Fe and Al may also render the applied P though fertilizers and organic sources unavailable for crops. The acidic soils of northern part of West Bengal are known have less P content and may be responsible as one major reason for limiting crop yield. Estimation of available P could not serve as a measure of P supplying capacity of soils except measuring dominance of different P fractions and release pattern in long term in soils. Organic matter application could lower the P fixation in soils and increase the P release from unavailable pools.

The experimental soils were collected from uncultivated land of Pundibari, Cooch Behar (26.3938º N, 89.383º E, altitude 47m) of the terai region and from the forest hill area of Samsing, Kalimpong (26.9952º N, 88.8064º E, altitude 576m). The soil samples were prepared before employing standard lab procedures to examine important soil characteristics. The physico-chemical properties of Pundibari soil exhibited its acidic and non-saline characteristics with pH of 5.9 and EC 0.21 dSm^{-1}, respectively. The Kalimpong soil was more acidic in nature with pH of 4.26. The organic carbon content in Pundibari soil was 0.53% and Kalimpong soil was 2.55%. The texture of the soils was sandy loam in Pundibari and sandy clay loam in Kalimpong. The Pundibari soil had low N and K content but relatively high P content than Kalimpong soil.

Before conducting time-dependent release kinetics study the soils were treated with FYM at 0, 5 and 10 t ha-1. And incubated for 15 days at room temperature at 50% of maximum water holding capacity. At the end of each incubation period, the soil samples underwent a sequential extraction process with 25 ml of 0.01 M $CaCl_2$ solution at different periods like 1, 4, 10, 14, 16, 24, 35, and 41 days, each time following the same extraction procedure.

Results of the kinetic experiments showed that there was a rapid increase in P released at 3rd and 4th extraction (240 and 336 hr) in both soils and after that, the release came to a stationary phase. Application FYM in increasing doses increased release of P from soil in all time span. Higher P releasing capacity was note in high P containing Pundibari soil. The cumulative P extracted at the end of extraction perid was 146.27 mg kg^{-1} in Pundibari and 122.61 mg kg^{-1} in Kalimpong soil. Organic matter application of 5 and 10 t ha^{-1} increased cumulative P release by 16.14% and 31.2% in Pundibari soil, respectively and in Kalimpong soil such increase was 18.78% and 38.98%. Fitting of different model to explain release kinetics showed that the best fit models were power function equation (R^2=0.984,0.982; SE=0.164,0.176) and parabolic diffusion equation (R^2=0.982,0.981; SE=1.30,1.31).

In the pot experiment growing rice with graded doses of FYM (0, 5 and 10 t ha^{-1}) maximum yield was obtained highest FYM dose in both soils. The highest yield parameters obtained was as follow: straw yield$_{\text{Pundibari}}$-8059 kg ha^{-1}, grain yield$_{\text{Pundibari}}$-6199 kg ha^{-1}; straw yield$_{\text{Kalimpong}}$-7279 kg ha^{-1}, grain yield$_{\text{Kalimpong}}$-5599 kg ha^{-1}) in FYM treated soil at 10 t ha^{-1}. Highest uptake of P was obtained in the case of the highest FYM applied for both of the soils (straw uptake$_{\text{Pundibari}}$-81 mg pot^{-1}, grain uptake$_{\text{Pundibari}}$-150 mg pot^{-1}; straw uptake$_{\text{Kalimpong}}$-38 mg pot^{-1}, grain uptake$_{\text{Kalimpong}}$-81 mg pot^{-1}). Highest rice dry matter was also obtained in FYM at 10 t ha^{-1} in both of the soils (straw DM$_{\text{Pundibari}}$-24.1g, grain DM$_{\text{Pundibari}}$-18.66g; straw DM$_{\text{Kalimpong}}$-19.90g, grain DM$_{\text{Kalimpong}}$-15.31g). The overall increasing trends followed the pattern of FYM10>FYM5>FYM0.

In the study of Phosphorus fractionation, six different types of P fractions were analysed viz. Saloid P, Al-P, Fe-P, reductant soluble P, occluded P and Ca-P by sequential extraction procedure. Fractionation study was also conducted in the pot soils after the harvest stage. The data of initial soil's P fractions showed that P fractions varied as Fe-P > Reductant soluble P>Al-P>Ca-P>occluded P> Saloid P in Pundibari soils and Al-P > Reductant soluble P>Fe-P>occluded P>Ca-P> Saloid P in Kalimpong soil. Application of FYM in increasing doses significantly increased P in different pools.

It also can be concluded that in the soils of Pundibari soil containing higher P can release P in long run for crop uptake than Kalimpong soil. Application of FYM at 10 t ha^{-1} can further increase the P release from soils.

FUTURE SCOPE OF RESEARCH

CHAPTER 6 FUTURE SCOPE OF RESEARCH

1. **Crystallographic study:** We could run a crystallographic study to better understand the phosphorus dynamics and it's association with different minerals viz. how it combines and reacts with different elements and minerals etc.
2. **Longer duration of research:** As this study was conducted in pot, if we run this study in field condition and for a longer period of time, then the release pattern will be more prominently understood.
3. **More comparison between soils:** As this study was carried between two soils only, more involvement of soil samples from diferent soil orders will be beneficial as this will give more detailed idea.
4. **Microbial Interactions:** The effect of microbial population on the availability of different nutrients, how it helps in plant growth, different microbial population management strategies can also be explored.

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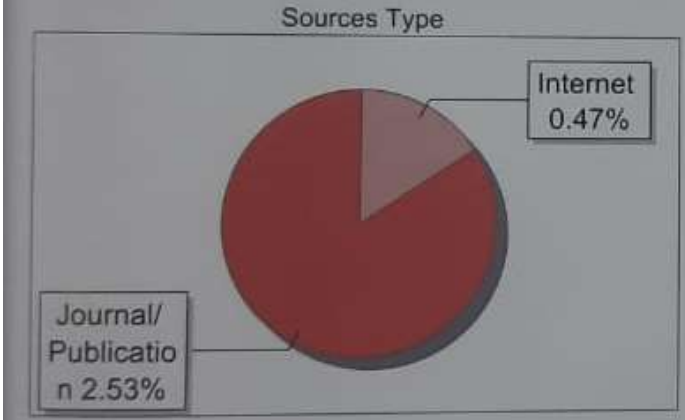

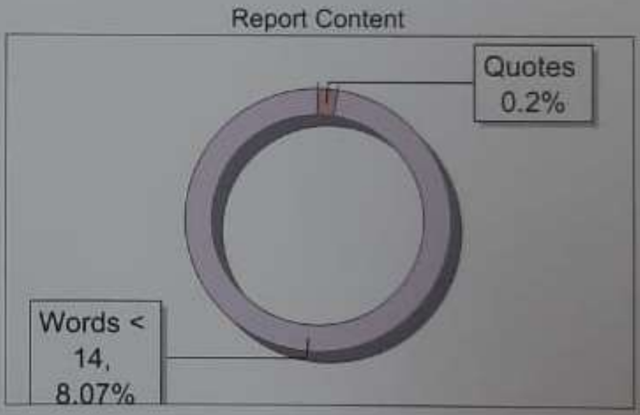

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