

सिलिकॉन संपन्न कृषि अपशिष्टों और फॉस्फेट घोलक सूक्ष्मजीवों का उपयोग करके गेहूं (*ट्रिटिकम एस्टिवम*) और मूंग (*विग्रा रेडियाटा*) के लिए मृदा फास्फोरस उपलब्धता को बढ़ाना

**ENHANCING SOIL PHOSPHORUS AVAILABILITY TO
WHEAT (*TRITICUM AESTIVUM*) AND MUNGBEAN (*VIGNA
RADIATA*) USING SILICON-RICH AGRICULTURAL WASTES
AND PHOSPHATE SOLUBILIZING MICROORGANISM**

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ICAR-INDIAN AGRICULTURAL RESEARCH INSTITUTE
NEW DELHI – 110 012**

2022

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USING SILICON-RICH AGRICULTURAL WASTES AND
PHOSPHATE SOLUBILIZING MICROORGANISM**

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A thesis
submitted to the Faculty of Post-Graduate School,
ICAR-Indian Agricultural Research Institute, New Delhi
in partial fulfilment of the requirements
for the degree of

**DOCTOR OF PHILOSOPHY IN
SOIL SCIENCE AND AGRICULTURAL CHEMISTRY**

2022

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CERTIFICATE

This is to certify that the thesis entitled “**Enhancing soil phosphorus availability to wheat (*Triticum aestivum*) and mungbean (*Vigna radiata*) using silicon-rich agricultural wastes and phosphate solubilizing microorganism**” submitted to the Faculty of Post Graduate School, ICAR-Indian Agricultural Research Institute, New Delhi, in partial fulfilment of the requirement of the degree of **Doctor of Philosophy in Soil Science and Agricultural Chemistry**, embodies the results of a *bonafide* research work carried out by **Mr. Khurshid Alam, Roll No. 11607** under my guidance and supervision, and that no part of this thesis has been submitted for any other degree or diploma.

It is further certified that any assistance and help availed during the course of investigation as well as the source of information have been duly acknowledged by him.

Place: New Delhi

Date: 20/01/2023

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ACKNOWLEDGEMENT

Words are a poor substitute for expressing one's emotions and feelings; nonetheless, there is no better option to describe one's sentiments on an occasion when one sits in acknowledging the debt of others. Firstly, I would like to bow my head before the Almighty, the Supreme Power, for making me capable enough to complete this gargantuan task within the stipulated time frame.

Words in the lexicon would be few and exiguous to express my deep sense of gratitude for Dr. Dipak Ranjan Biswas, Principal Scientist, Division of Soil Science and Agricultural Chemistry, and chairperson of my advisory committee, for his inspiring guidance, peerless but constructive criticism, unfailing patience, friendly approach, constant support, and continuous encouragement throughout the tenure of my research work and preparation of the thesis. He has always been a fountain of inspiration to me.

It is a great privilege for me to express my esteem and profound sense of gratitude to Dr. Ranjan Bhattacharyya, Principal Scientist, Division of Soil Science and Agricultural Chemistry, and Co-chairman of my Advisory Committee, for his wise counsel and constructive and valuable suggestions. I feel immense pleasure in conveying my heartfelt thanks to Dr. Debarup Das, Scientist, Division of Soil Science and Agricultural Chemistry, and member of my Advisory Committee, for his encouragement and invaluable suggestions endowed during the course of my research work. He was always there for all my needs and did his best to help whenever I sought it. I am highly indebted to Dr. Archana Suman, Principal Scientist, Division of Microbiology, and member of my Advisory Committee, for providing me with the liquid pure culture of the microbe and for her constructive suggestions and guidance. I would also like to thank Dr. T. K. Das, Professor and Principal Scientist, Division of Agronomy; and Dr. R. K. Paul, Senior Scientist, Division of Agricultural Statistics, for all the help and support they provided during the course of my research work.

I am highly indebted to Dr. Nayan Ahmed, Head, Division of Soil Science and Agricultural Chemistry, as well as to Dr. R. N. Pandey and Dr. B. S. Dwivedi, Ex-Heads of the Division of Soil Science and Agricultural Chemistry, for their constructive suggestions and generous advice. My sincere thanks to Dr. S. P. Datta, Professor, Division of Soil Science and Agricultural Chemistry, for providing me with the necessary facilities, encouragement, and guidance throughout this study.

I would like to sincerely thank Dr. Prasenjit Ray, Scientist, Division of Soil Science and Agricultural Chemistry, who has always helped me out with my personal and professional work at any stage whenever I had some problems and gave generous advice.

I take this opportunity to convey my heartfelt thanks to Dr. Abir Dey, Scientist; Dr. D. Golui, Scientist; Dr. Ruma Das, Scientist; Dr. Sunanda Biswas, Scientist; and Dr. V. K. Sharma, Principal Scientist, Division of Soil Science and Agricultural Chemistry, IARI, New Delhi, who helped me and gave me moral support during the entire course of time.

I would like to sincerely thank Dr. G. Chawla, Principal Scientist, Division of Nematology, and Dr. R. Kumar, Principal Scientist, Division of Agricultural Chemicals, for their technical guidance and assistance related to scanning electron microscopy (SEM) and FTIR analyses, respectively. I would also like to extend my thanks to the staff members of the Central Photo Laboratory for taking photographs of my pot culture experiments whenever they were requested to do so. My heartiest thanks to Mr. Sourav Adhya and Mr. Biswajit Giri of IISER, Kolkata, for the help they provided in XRF analysis.

I am extremely grateful to the staff members of my laboratory, Aftab ji, Arun ji, and Mahesh ji, for the heartfelt help offered to me during the course of my research work. I convey my heartfelt thanks to all the other distinguished scientists, administrative, technical, and semi-skilled staff members for their help and support whenever required.

It gives me immense pleasure to mention the names of my friends Krishnayan, Anjan, Subhadeep, Abhishek, Zaherul, Maju, Ranabir, Viswanath, and Arkaprava, whose constant help and collective efforts have been reflected in the completion of this venture. The unceasing affection and support of seniors like Abhijit (Sarkar) da, Kingshuk da, Neeraj da, Anshuman da, Sourav (Choudhury) da, Suman (Sen) da, Arka da, and Khushboo ma'am would be in my memory for all time. I extend my heartfelt thanks to my beloved juniors Ravi, Kiranmoy, Samrat, Jeet, Sourav, Prem, Rupesh, Soura Suvra, and Siyaram.

No wealth of words can suffice the love, care, and timely support during critical junctures that I received from my senior cum mentor and my labmate Avijit Ghosh (Avijit da). This gargantuan task would not have been possible without the constant support, tireless efforts, conscious motivation, and selfless help offered by him.

My vocabulary utterly fails in expressing my love to Maa, Baba, and Bunu, who have been the pillars of my strength, for having faith in me and encouraging me in all my endeavours. It was their constant encouragement, affection, blessing, and prayer that enabled me to reach the footsteps of my long-cherished aspiration.

Omission, if any, in this brief acknowledgement does not imply ingratitude.

Finally, the financial assistance provided by the university and ICAR (Indian Council of Agricultural Research) in the form of the "IARI Senior Fellowship" during the tenure is gratefully acknowledged.

Date: 20/01/2023

Place: ICAR-IARI, New Delhi

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Phosphorus (P) is an essential plant macronutrient and is popularly known as the ‘key of life’. Development of plant roots, formation of flower and seed, cellular integrity (phospholipids), energy turnover (adenosine triphosphate, ATP), genetic information such as constituent of deoxynucleic acid (DNA) and ribonucleic acid (RNA), breakdown of sugars, nitrogen (N)-fixation in legumes *etc.* are some of the major attributes of P in plant growth (Haygarth *et al.*, 2013). Phosphorus deficiency is a major constraint in agricultural soils worldwide and it is estimated that more than 40% of the cultivable lands of the world are deficient in plant-available P (Balemi and Negisho, 2012). Although most of the soils have appreciable amounts of total P content, a high proportion of this is stored in plant-unavailable forms. Therefore, in intensive agriculture, a huge quantity of phosphatic fertilizers is used to meet the crop requirement. However, due to the highly reactive nature of P, only a small fraction (15-20%) of the applied P-fertilizer is utilized by the crops, and the remaining 80-85% gets fixed and becomes a part of the recalcitrant soil P pool either due to sorption, precipitation or microbial immobilization within a short time period (Roberts and Johnston, 2015; Alam *et al.*, 2022b). In soils having low pH, soluble P can be precipitated by forming insoluble hydroxy-phosphate compounds with cations like aluminium (Al), iron (Fe) and manganese (Mn), whereas surfaces of insoluble oxides of Fe, Al and Mn strongly adsorb P making it inaccessible to the plants (Brady and Weil, 2002). Excessive use of P-fertilizers coupled with very low P use efficiency has led to the accumulation of P in fixed pool of soil and subsequent release of the P to surface water, causing eutrophication of aquatic environments (Van der Salm *et al.*, 2017). Such fixation and build-up of P leads to wastage of costly P-fertilizers causing huge monetary loss. On the other hand, rock phosphate (RP) is used as a raw material in the production of all phosphatic fertilizers, which is a finite, non-renewable natural resource and it is estimated that, at the current rate of extraction, global commercial phosphate reserves will no longer be available for use after 50-100 years (Sattari *et al.*, 2012). Phosphorus cycling in near future will also be affected by changes in temperature and soil moisture regime (IPCC, 2013). Therefore, a comprehensive understanding for generating new ideas in sustainable P management has become indispensable.

Model simulations indicated that the residual or native soil P pool could contribute to a 50% reduction in worldwide P-fertilizer consumption by 2050 (Sattari *et al.*, 2012). Even greater reductions in P-fertilizer inputs are possible if appropriate technologies are used to mobilize recalcitrant types of soil P that are currently ignored in P utilization models (Menezes-Blackburn *et al.*, 2018). Recent scientific efforts should be focused on optimal agronomic utilization of this critical P reserve to serve as a key source of plant-available P in agricultural production systems. However, detailed quantitative information on how much of the native soil P can potentially be mobilized through various interventions, is not available so far.”

In this context, it has been suggested that the total amount of accumulated P in agricultural soils could adequately cater for the P requirement of the crops for about 100 years if it can be made available to them by suitable means (Khan *et al.*, 2007). Application of phosphate solubilizing microorganisms (PSMs) for enhancing P availability to plants by utilization of fixed P pools in soil is a well-known method, which is eco-friendly and cost-effective too (Owen *et al.*, 2015). The PSMs have the capability to solubilize the insoluble inorganic forms of P in soil by several mechanisms such as chelation, acidification, organic acid production and exchange reactions (Singh and Reddy, 2011).

Silicon (Si) is the second most abundant element on the earth crust, still it is not fully accepted as an essential mineral element for plant, though its beneficial effects on plant growth and development are well documented in literature (Kostic *et al.*, 2017). The availability of Si in soil is generally low because of its low solubility from soil sources. In case of marine ecosystems, Si has been shown as a possibility to increase the P availability by mobilizing P from strong binding sites of Fe-containing minerals in marine sediments (Konhauser *et al.*, 2007; Planavsky *et al.*, 2010). Silicon has also been studied as a possibility to increase the P availability in soils, particularly those having P deficiency stress (Koski-Vahala *et al.*, 2001; Kostic *et al.*, 2017; Schaller *et al.*, 2019; Alam *et al.*, 2022b). Both silicate (SiO_4^{4-}) and phosphate anions (H_2PO_4^- and HPO_4^{2-}) are adsorbed by ligand exchange mechanism on the specific-surface sites of different soil components, mainly Fe and Al oxides. Silicate strongly competes with phosphate for specific soil sorption sites and previously adsorbed phosphate can be displaced by silicate anion, resulting in an increase in availability of P in soil solution for plant uptake (Smyth and Sanchez, 1980; Lee and Kim, 2007).

Kostic *et al.* (2017) showed that application of Si increased root exudation of organic acids that mobilized inorganic P (P_i) in the rhizosphere and up-regulated P_i transporters in P-deficient plant roots. Although the interaction between applied Si and P has been discussed for many years but it still is a matter of controversy. In addition, various sources of Si have been tried to enhance the P availability in soil. Potential sources of Si currently used for agricultural systems range from chemical products to natural minerals to by-products of steel and iron-industries (slags). Soluble potassium (K) and/or sodium (Na) silicates are too expensive for soil application and may not be available for most of the farmers. On the other hand, slag-based silicate fertilizers are less soluble and repeated use of these may arise potential environmental risks due to the heavy metals contained in them (Liang *et al.*, 2015). Hence, it appears imperative to find out alternative sources of Si for application in farmlands for utilization of native P reserves in soils; and such sources should simultaneously be cost-effective, environment-friendly and sustainable.

Natural sources of Si found in agricultural wastes such as by-products of different agro-industries can suitably serve our purpose in this regard. Sugarcane bagasse ash (SBA), rice husk ash (RHA) and corn cob ash (CCA) are examples of such Si-rich wastes. Bagasse is the fibrous left-over after the crushing of sugarcane for juice extraction in sugar mills and since long, it is used as a fuel in boilers for cogeneration process of sugar mill. Rice husk is the hard covering of the rice grain and is separated as a by-product during milling of rice. It is mostly used as fuel in the boilers for processing rice, producing energy through direct combustion and/or by gasification. On the other hand, it is estimated that by 2050, the demand for corn/maize in developing countries would double and it would have become the crop with the greatest production globally as well as in developing countries (CIMMYT and IITA, 2011). Corn cobs are agricultural wastes obtained from corn and is generally used as fuel in rural households. Corn cob ash (CCA) waste is also produced in the boilers of the animal feed industry, especially in western countries (Suwanmaneechot *et al.*, 2015). The CCA contains small amounts of metallic elements (Adesanya and Raheem, 2009) and obtained as fine powder after combustion, so that it does not require further grinding (Velmurugan *et al.*, 2015). Such solid agro-wastes are plentiful, especially in nations like India, which generates 44,200 tonnes of SBA per day (Gopinath *et al.*, 2018), and ~20 million tonnes (Mt) of RHA per annum (Vigneshwari *et al.*, 2018).

Basically, these solid residues from agricultural wastes are abundant, particularly in agricultural countries like India and their disposal has become a critical concern now-a-days due to lack of disposal lands to dispose such huge quantities as well as associated environmental restrictions like foul odour, attraction of pests that might affect human health and so on (Bahurudeen *et al.*, 2015; Norsuraya *et al.*, 2016). Utilization of such solid wastes as sources of Si to utilize native P reserves of soil will not only tackle the problem associated with their disposal, but also will convert these wastes into wealth in a sustainable manner.

Recently, research on the interaction of Si and plant growth-promoting rhizobacteria (PGPR) in combination has been suggested as a novel field in plant nutrition (Etesami, 2018). The feasibility of Si to mobilize P from strong binding sites of Fe-minerals has been shown for marine sediments but is less well studied in soils. Although the ability of PSM (at a broader scale) as well as Si (at a limited scale) to utilize the native fixed pool of P in soil has been investigated, there is essentially meagre information on their combined application. Also, the Si sources used in the previous studies were mainly natural minerals, Si-rich by-products of steel and iron-industries (slags) or soluble salts of silicate. Detailed studies on the application of these solid agro-wastes as a Si source and their potential to solubilize the soil native P are scarce. Utilization of such solid agro-wastes as sources of Si will not only address the waste disposal issue, but also sustainably convert these wastes into wealth. The present study, formulated to investigate the combined as well as individual effects of Si-rich agricultural wastes and PSM on P dynamics in soils and subsequent P availability to plants, might be a frontier area of research in the domain of soil fertility management as well as environmental management.

Keeping in view the aforesaid aspects, the present research work was carried out with the following specific objectives:

1. To monitor the release pattern of phosphorus in Alfisol and Inceptisol as affected by silicon-rich agricultural wastes and phosphate solubilizing microorganism
2. To study the effect of silicon-rich agricultural wastes on adsorption-desorption behaviour of phosphorus in soils

3. To assess the effect of applied silicon-rich agricultural wastes and phosphate solubilizing microorganism on phosphorus availability to wheat (*Triticum aestivum*) and mungbean (*Vigna radiata*) crops
4. To find out the changes in different fractions of soil phosphorus as affected by silicon-rich agricultural wastes and phosphate solubilizing microorganism

The literature relevant to the present investigation has been reviewed under the following heads:

1. Role of phosphorus in plant nutrition

Phosphorus (P) makes up between 0.1 and 0.5% of the dry weight of plants (Havlin *et al.*, 2016). Phosphorus is one of the most essential plant nutrients that has a profound effect on the overall growth of plants (Wang *et al.*, 2009) by influencing key metabolic processes such as cell division and development, energy transport, signal transduction, macromolecular biosynthesis, photosynthesis, and respiration (Shenoy and Kalagudi, 2005). As an essential component of the DNA and RNA structures, P transmits genetic information to the progeny. As a component of ADP (adenosine diphosphate), ATP (adenosine triphosphate), DPN (diphosphor-pyridine nucleotide), and TPN (tri-phosphor-pyridine nucleotide), it plays a key role in the storage and transformation of energy. It is also essential for respiration and photosynthesis. As the energy requirement is high for growing shoot and root tips, due to high metabolism and rapid cell division, thus P is required there in very large quantities. Phosphorus reduces disease incidence and increases the quality of specific crops; it also promotes root and fruit growth and blossom commencement (Rattan and Goswami, 2009). Important metabolic pathways in plants, such as the calvin cycle, glycolysis, photorespiration, pentose phosphate pathway, amino acid, and nucleotide metabolism, nitrogen (N) and sulphur (S) assimilation, *etc.*, as well as the pathways that lead to the synthesis of lignin and polyphenol-like compounds, are highly dependent on P nutrition because P is present in these cycles in the form of phosphorylated intermediates (Buchanan *et al.*, 2002; Siedow and Day, 2000). The energy required for nodulation and N fixation in the nodules of the leguminous plant is given by P in the form of ATP, making biological N fixation dependent on P (Hussain, 2017). Phosphorus-deficient plants typically have small, brown leaves, a poor growth rate, a brittle stem, and low yields (Mahantesh and Patil, 2011; Khan *et al.*, 2013). They also have dark green, reddish, or purple foliage because, in P deficit plants, an abundance of anthocyanin is formed in the plant body, which lends these hues to plant foliage (Teng *et al.*, 2005; Amtmann *et al.*, 2007). As a result, it is generally established that

crops should be given adequate P nutrition from the earliest stages of their development in order to maximize crop yield.

2. Phosphorus dynamics in soil

Unlike N, the atmosphere does not provide soluble P to plants. Hence, the source of P in soil is largely the primary and secondary minerals and/or organic compounds. The total P content of the 0-15 cm of soil depth ranges from 200-2000 kg ha⁻¹ with an average value of 1000 kg ha⁻¹. But, in comparison to other nutrients, the concentration of P in soil solution is much lower and ranges from 0.001 to 1 mg L⁻¹ (Brady and Weil, 2002). Broadly, the P compounds in the soil can be categorized into three classes: (i) inorganic compounds, (ii) organic compounds of the soil humus, and (iii) organic and inorganic P compounds associated with the cells of living matter. Mostly, the predominant form of P in soil is inorganic P, contributing 20 to 80% of the total P in surface soil layers (Chand and Tomar, 2003). Mineral compounds of P usually contain aluminium (Al), iron (Fe), and calcium (Ca) and vary from soil to soil depending on soil pH. For example, P forms a complex with cations like Al, and Fe in acidic soils, while in alkaline soils, it reacts very strongly with Ca. Of the total soil P pool, about 50% of P is in organic forms (Richardson, 2001), which varies between 4 and 90% in most soils (Yadav and Verma, 2012). The organic P in plants includes mainly inositol phosphate (10-50% in soil) which represents a series of phosphate esters ranging from monophosphates up to hexaphosphates. Phytic acid (inositol hexakisphosphate) is the main compound that plants use to store P in seeds to support early seedling growth following germination. Phytin, a Ca-Mg salt of phytic acid, is the most abundant of the known organophosphorus compounds in soils. Other organic P in soils occur as sugar phosphates, nucleotides (0.2-2.5%), phosphoprotein (trace), phosphonates and phospholipids (1-5%) (Yadav and Verma, 2012). Of the various forms of P, plants take up only negatively charged primary and secondary orthophosphate ions (H₂PO₄⁻ and HPO₄²⁻) as a nutrient.

Inorganic P in the soil refers to the P associated with various metals like Fe, Al, Ca, and Mg; depending upon the pH of the soil. Soil pH is the single determining factor that plays a pivotal role in determining the solubility of different P minerals in the soil and with an increase in soil pH, the solubility of Fe and Al-phosphates increases, whereas, that of Ca-phosphates decreases, except for pH values more than 8 (Hinsinger, 2001).

The dynamics of transformations of P and its subsequent fixation and release phenomena in soil are mainly governed by (i) adsorption-desorption and (ii) precipitation-dissolution reactions (Sanyal, 2018). At a low concentration of solution P, adsorption predominates; but when solution P concentration exceeds the solubility product of the specific P-bearing mineral, precipitation reactions take place (Havlin *et al.*, 2016). In acidic soil conditions, predominant adsorption sites for P are Fe/Al oxides and hydroxides like gibbsite, goethite, and hematite (Parfitt, 1989). Soil clay minerals and Fe or Al oxides and hydroxides having very high specific surface area provide a large number of adsorption sites for P in soil.

In neutral to calcareous soils, the dominant P retention mechanism is precipitation reaction (Lindsay *et al.*, 1989), although some amount of P can also be adsorbed on the surface of calcium carbonate (Larsen, 1967) and clay minerals (Devau *et al.*, 2010). Initially, the phosphate is precipitated with Ca as di-calcium phosphate (DCP), but with time, this DCP is gradually transformed into more insoluble forms like octacalcium phosphate and hydroxyapatite, which are not available for plant absorption (Arai and Sparks, 2007). With a decrease in soil pH, there is a concomitant increase in the dissolution of hydroxyl apatites. It denotes the importance of the “rhizosphere acidification” process employed by several plants to get access to the P in calcareous soils (Wang and Nancollas, 2008). The phosphate which is adsorbed on different adsorbent sites can be released again through a desorption reaction. There is a complex equilibrium between all these forms of P, ranging from very stable, less available pools to plant-available P pools (Shen *et al.*, 2011).

Inorganic P in soils is supposed to be associated with four pools namely, (i) soil solution P, (ii) surface-adsorbed P, (iii) strongly bonded or absorbed P, and (iv) very strongly bonded or inaccessible or mineral P, and this demarcation is based on the ease of extractability and accessibility *vis-à-vis* its availability to the plant (Syers *et al.*, 2008). The first pool of P which is present in soil solution is immediately accessible to the plant. The second pool refers to the surface adsorbed P on various soil components and it is readily extractable. This P is supposed to be in dynamic equilibrium with the P in the first pool. Phosphorus present in the third pool indicates the P which is more strongly bonded to soil components or is present as adsorbed P within the matrices of different soil components. Phosphorus present in this pool

gradually becomes plant available with time. The pool of P that is very strongly bonded to soil components, or precipitated as sparingly soluble compounds, or present as a part of soil minerals constitutes the fourth pool of P in soil. This pool is very slowly available for plant uptake and often takes years to become available to plants.

3. Phosphorus status of Indian soils

The first fertility map of soil P in India was published in 1979 and was further updated in 1993 (Hasan, 1996). In the updated map, it was found that about 49.3% of the districts and Union Territories were low, 48.8% were medium and 1.9% were high in available P status. Compared to the earlier test summaries prepared by Ghosh and Hasan (1979), samples in low fertility class increased by 3%, while the medium and high categories exhibited a decrease of 2.7 and 0.3%, respectively. Hasan (1996) concluded that generally, the deep black, red loamy, grey-brown, and desert soils of semi-arid regions showed medium P-fertility status. Similarly, alluvial strips of the northern region, foothill soils, and the coastal alluvium which were not sandy in nature also largely represented medium available P status. The vast alluvial tracts of eastern, central, and southern parts of the country, medium black, red (gravely) loams of semi-humid regions, laterite and lateritic, mixed red and black soils, and sandy coastal alluvium were generally low in available P status. Sanyal *et al.* (2015) compiled data on available P content of surface (0-15 cm) soil generated by soil testing laboratories from time-to-time and it is evident from the data that soils of more than 90% of the districts of India represented low to medium P fertility categories indicating the necessity for P fertilization to obtain optimum crop yields. The total P content of Indian soils mostly ranged from 120 to 2166 mg kg⁻¹, however, some extremes of 44 mg kg⁻¹ to more than 3500 mg kg⁻¹ were also reported. In Indian soils, inorganic P generally contributes 54-84% of total P, whereas the share of organic P varies from 16 to 46% in different states (Sanyal *et al.*, 2015). Patel and Vishwanath (1946) reported that the P-fixation capacity of Indian soils varied from 1.54 to 87.05% with an average value of 33.8%. Nad *et al.* (1975) reported that the P-fixing capacity of major soil groups of India varied from 14.0 to 72.4% with an average value of 40.7%. It can be concluded that the amount of plant available P is very low relative to the total soil P. Moreover, the majority of the soil P is fixed, and only a small fraction of P is available for uptake by plants.

4. Peak phosphorus scenario and scarcity of rock phosphate: the need for utilization of native soil phosphorus

Rock phosphate (RP) is the most important raw ingredient in the worldwide production of commercial P-fertilizers. Nonetheless, these naturally occurring RP reserves are limited and non-renewable, with a global estimate of 60 billion tonnes (Van Kauwenbergh, 2010). According to a report published by the United States Geological Survey, the reserve is projected to be approximately 67 billion tonnes, and if the present projections and pace of P production continues, the resources will only fulfill the needs of P production for the next 350 years (Chien, 1998). However, the majority of estimates place the reserve's anticipated lifetime between 70 and 175 years (Cordell *et al.*, 2009). Recent reports also estimated that at the current rate of extraction, global commercial phosphate reserves will no longer be available for use after 50-100 years (Sattari *et al.*, 2012). The global demand for phosphate has increased at a Compound Annual Growth Rate (CAGR) of 73.5% over the past 15 years, despite the fact that P supplies remain restricted. In the context of rising worldwide demand for P-based fertilizers, the concept of 'peak phosphorus,' which is anticipated to occur in 2033, has emerged as an important and somewhat frightening development (Cordell *et al.*, 2009). The core concept underlying the widespread application of peak theory is that there will be a point in time when the growing demand for the key resource will exceed the economically viable supply, and from that point on, the negative impacts of human actions will become more apparent.

In India, the total P resource is only 260 Mt, out of which only 142 Mt are recoverable as P reserves (FAI, 2012). Also, the amount of high-grade RP (>30% P₂O₅) is only 15.27 Mt (Kumari and Phogat, 2008), which makes India the largest importer of RP in the world, with an annual import of 7.5 Mt (Sujata, 2014). Therefore, it is evident that the 'peak phosphorus' could have severe ramifications for food security and sustainable crop production on the Indian subcontinent, if an alternative to commercial P-fertilizers is not considered immediately. We can say unequivocally that P fertilization alone is not a feasible method for enhancing crop P nutrition. The efficiency with which farms use P must be improved. Increasing P-use efficiency in agricultural systems requires addressing the need to reduce P-loss and increase the bioavailability of soil solution P. If we are more conscientious about how we utilize P, we may be able to delay the predicted year of depletion of this resource and the peak of P production.

Model simulations indicated that the residual or native soil P pool could contribute to a 50% reduction in worldwide P-fertilizer consumption by 2050 (Sattari *et al.*, 2012). Even greater reductions in P-fertilizer inputs are possible if appropriate technologies are used to mobilize recalcitrant types of soil P that are currently ignored in P utilization models (Menezes-Blackburn *et al.*, 2018). Recent scientific efforts should be focused on optimal agronomic utilization of this critical P reserve to serve as a key source of plant-available P in agricultural production systems. However, detailed quantitative information on how much of the native soil P can potentially be mobilized through various interventions is not available so far.

5. Impact of exogenous silicon application on enhancing soil phosphorus availability to plants

Reports on the effects of applied silicate on P nutrition of plants are encouraging, but explanations for this effect vary. Silicon not only increases P availability but also imparts biotic and abiotic stress resistance to various crops (Artyszak, 2018). The first information on the beneficial effect of Si on the P nutrition of plants came from a long-term field experiment conducted at the Rothamsted Experimental Station (UK). Application of 448 kg ha⁻¹ sodium silicate annually has been reported to increase the available P in the soil as well as P uptake of barley (*Hordeum vulgare*) to a considerable extent, this effect being most marked when no superphosphate was added (Fischer, 1929). Suehisa *et al.* (1963) observed the effect of Si on P availability in *Sudan* grass grown on Hawaiian soils. They found that total P uptake for two successive cuttings of *Sudan* grass showed definite increases over controls when Si was applied, either with or without applied P. Without any P fertilization, Si fertilization increased the P content of rice grain as well as straw during the wet and dry seasons of 1964 and 1965 at IRRI, Philippines (IRRI, 1965; 1966). This increased P content in rice plants was ascribed to the better availability of soil P and/or increased mobility of P from roots to stems mediated by applied silica. When phosphatic fertilizers were applied along with Si, the P-use efficiency seemed to increase. Fertilizer P absorption by rice crops increased from 26 to 34% when P in the form of single superphosphate (SSP) at 26 kg ha⁻¹ was applied along with a silicate fertilizer (IRRI, 1988). Indian Agriculture Research Institute (IARI), New Delhi also reported that superphosphate application along with Si-fertilizer enhanced rice P absorption by 8% in its annual report (1987). Subramanian and Gopalswamy (1990)

conducted a pot experiment in acid soils using several sources of silicate materials (sodium metasilicate, furnace slag, and rice husk) at the level of 500 ppm SiO_2 , along with two sources of P (SSP and RP) at the level of 25 ppm P_2O_5 . Results showed that the application of silicate and phosphate materials not only increased the available P and Si content in the soil but also the uptake of P and Si by rice plants. Rice husk ranked first in increasing the availability of P and Si in the soil as well as the uptake of these nutrients by rice plants. Ma and Takahashi (1990) conducted a pot experiment in a P-deficient soil using silicic acid instead of silicate salt as a silica source, to avoid the complication of changes in soil pH. They recorded an increased shoot dry weight as well as an improved P utilization in rice plants. In an experiment conducted by Savant and Sawant (1996), black-grey ash of rice hull was applied to rice (variety- Jaya) seedbeds at 0.5-2.0 kg m^{-2} and an increased P content of the rice seedlings was observed. Owino-Gerrho and Gascho (2005) investigated the impact of applied silicate (in the form of CaSiO_3) on soil P nutrition and growth of maize grown in a low pH soil from the coastal plain of Georgia by conducting pot experiments. The increase in plant-available P when Si was applied, was ascribed to the increase in the soil pH from the accompanying calcium (Ca^{2+}). Also, Si concentration in the soil solution helped to improve the growth conditions of the maize plants resulting in greater P uptake and utilization. Thind *et al.* (2012) carried out a field experiment applying different levels of silica-rich wastes like rice husk ash (RHA), bagasse ash (BA) and fly ash (FA). The application of all three types of ashes generally significantly increased the available P and resulted in a positive P balance in the rice-wheat cropping system. Kostic *et al.* (2017) examined the role of Si on P uptake along with the expression of inorganic P transporters in wheat grown in low P acid soil in comparison with P fertilization and liming. They found that the application of Si in the form of sodium silicate (Na_2SiO_3) increased shoot P concentration in wheat plants to an adequate level in the range of P-fertilized plants. Silicon application also ameliorated the low soil pH and high Al^{3+} concentration of soil solution, comparable to the effect of liming. They further concluded that applied Si increased root exudation of organic acids that mobilized inorganic P (P_i) in the rhizosphere and up-regulated the expression of P_i transporter genes (*TaPHT1.1* and *TaPHT1.2*) in P-deficient plant roots. Rezakhani *et al.* (2019) showed that the application of either Si or PSM strains (*Bacillus simplex* UT1 and *Pseudomonas* sp. FA1) independently enhanced the P use efficiency as well as shoot accumulation of P, Si and K in wheat

plants fertilized with either soluble or insoluble sources (RP) of P. However, the combined application of the PSM with Si yielded the greatest enhancement in these aforesaid parameters, in turn, demonstrating the synergistic relationship between applied PSM and Si. Schaller *et al.* (2019) investigated the effect of Si on soil P mobilization for 143 Arctic soils (representing contrasting soil characteristics), which have not been affected by agriculture or other anthropogenic management practices. Laboratory experiments confirmed that Si addition significantly increased P mobilization, by mobilizing Fe(II) bound P phases from mineral surfaces. Silicon addition also increased soil respiration in P-deficient soils. Barman *et al.* (2020) also observed that the application of different levels of silica through sodium silicate and basic slag showed a significant positive impact on the available P content in a low pH acidic soil of Assam, India. Such an increase in available P content in soil with Si application was attributed to the replacement of phosphate by silicate from binding sites in soil, as well as the increment in soil pH due to the application of the Si sources.

6. Solubilization of recalcitrant soil phosphorus by phosphate solubilizing microorganisms

In 1903, the first evidence of the presence of naturally occurring phosphate solubilizing microorganism (PSM) from the root rhizosphere was reported (Khan *et al.*, 2007). Several groups of microorganisms, like bacteria, fungi, actinomycetes, *etc.*, known as phosphate solubilizing microorganisms (PSMs) are capable of dissolving fixed P reserves in soil (Sundara Rao and Sinha, 1963). Many researchers have explored the phosphate solubilizing bacteria (PSB) isolated either from soils (Chen *et al.*, 2006; Widawati and Rahmansyah, 2009; Gupta *et al.*, 2013) or from rhizosphere (Poonguzhali *et al.*, 2008; Khan *et al.*, 2013). Whitelaw (1999) suggested that the strains of *Pseudomonas*, *Enterobacter*, *Bacillus*, *Penicillium*, and *Aspergillus* are most efficient in P solubilization. *Aspergillus awamori* has been found to have better P solubilization capacity than *Pseudomonas striata* or *Bacillus polymyxa*, as reported by Singh *et al.* (1984). When experimenting with various PSMs, Vidyasekeram *et al.* (1973) discovered that all of the examined microbes were successful in solubilizing tricalcium phosphate (TCP), albeit the result varied depending on the kind of soil, and *Aspergillus awamori* was said to solubilize more P than any other PSMs. Wani and Patil (1979) evaluated the effectiveness of different PSMs in solubilizing phosphate in

a liquid media and found that the isolates consistently solubilized TCP to a significantly greater extent than RP. These organisms soluble the most P during the 14-day incubation period in a liquid medium. For all of the isolates, the ideal temperature was between 30 and 35 °C, however, *Bacillus megaterium* had distinct temperature maxima. Gaind and Gaur (1990) examined the effectiveness of the PSMs in solubilizing different sources of phosphates namely, TCP [$\text{Ca}_3(\text{PO}_4)_2$], aluminium phosphate (Al-P, Al_3PO_4), iron phosphate (Fe-P, Fe_3PO_4) and RP at three different temperatures (35, 40 and 45 °C) using an experiment comprising eight PSMs. The solubilization of TCP, Al-P, Fe-P and RP by two bacterial cultures viz., *Bacillus circulans* and *B. subtilis*, was excellent at all three temperatures. The PSMs living in many soil habitats may convert the insoluble forms of P, such as TCP, Al-P, Fe-P, etc. into soluble P (Gupta *et al.*, 2007; Song *et al.*, 2008; Khan *et al.*, 2013; Sharma *et al.*, 2013). In this context, it has been discovered that soil microorganisms are generally more successful in releasing P to plants from both inorganic and organic sources by solubilizing and mineralizing, respectively, complex P molecules (Bishop *et al.*, 1994; Toro, 2007; Wani *et al.*, 2007). Several workers have documented their findings in order to better understand how the microbial populations cause the solubilization of insoluble P (Khan *et al.*, 2002, Etesami *et al.*, 2021). Of the various strategies adopted by microbes, the involvement of low molecular weight organic acids like citric, α -ketobutyric, lactic, succinic, oxalic, maleic, fumaric, tartaric acids, etc. secreted by microorganisms has been a well-recognized and widely accepted theory as a principal means of P solubilization, and various studies have identified and quantified organic acids and defined their role in the solubilization process (Marra *et al.*, 2012, Etesami *et al.*, 2021). These organic acids produced by many P-solubilizers, for example, bacterial cultures or fungi, in the natural environment or under *in-vitro* conditions form a chelate with different polyvalent cations like Al, Fe and Ca releasing the P associated with these cations in soil (Pradhan and Shukla, 2005). The organic anions can replace the sorbed phosphate on Fe- and Al-oxide surfaces via ligand exchange (Whitelaw, 1999). Also, the organic anions compete with the phosphate anions for the same adsorption sites in soil and thereby, increasing P availability in soil solution (Nahas, 1996; Roy *et al.*, 2015). Consequently, the acidification of microbial cells and their surrounding leads to the release of phosphate ions from the P-mineral by H^+ substitution for Ca^{2+} (Trivedi and Sa, 2008). Apart from the organic acid theory, some of the inorganic acids (Reyes *et al.*, 2001; Richardson, 2001) such as HCl, nitric acid,

and sulphuric acid produced by chemoautotrophs and the H^+ pump, for example, in *Penicillium rugulosum*, have also been reported to solubilize the insoluble P (Reyes *et al.*, 2001). The inorganic acids so released convert TCP to di- and mono-basic phosphates with the net result of enhanced availability of the element to plants. Organic P compounds undergo mineralization, and the resulting P is taken up as a nutrient by plants. In this regard, numerous soil microbes or rhizosphere microflora possess the ability to transform organic P into soluble forms of P (Rodriguez *et al.*, 2006). This mineralization process is mediated by enzymes especially phosphatases and phytases, released by the soil microbes. The enzyme phosphatases (acid and alkaline phosphatases) released exterior to the cell (exo-enzymes) are non-specific in nature and use organic P as a substrate to convert it into an inorganic form. Of the two phosphatases, acid phosphatases, a widely distributed enzyme and commonly found in fungi, for example, *Colletotrichum graminicola*, is considered as the principal mechanism for mineralization of soil organic P where it catalyzes the release of inorganic P from organic P compounds such as inositol hexaphosphate (Tarafdar, 2006). As PSMs render phosphates into solution in amounts exceeding their own requirement for growth and metabolism, the surplus can be utilized by plants.

7. Impact of exogenous silicon application on adsorption-desorption behaviour of phosphorus in soil

Obihara and Russell (1972) studied the adsorption of silicate and phosphate from pure and mixed solutions in four soils having high P-fixation capacity. The maximum adsorption of silicate by three of the soils from the pure solution occurred at pH 9.2, and the maximum adsorption curve for phosphate by two of the soils from its pure solution had a break in its slope at pH 6.4 and 11.6. The presence of phosphate in the mixed solution always depressed the adsorption of silicate. However, the presence of silicate in the mixed solution did not affect the amount of phosphate adsorbed until the pH is over 6.5-7.0. Smyth and Sanchez (1980) while performing laboratory as well as greenhouse experiments using a Typic Haplustox soil from the Cerrado region of Brazil found decreased P-fixation and improved cation retention properties. Silica-rich amendments ($CaCO_3$, $CaSiO_3$) were added at rates to replace 1 or 2 times of exchangeable Al, and P was applied at rates to provide equilibrium solution concentrations of 0, 0.05, 0.1 and 0.2 ppm P. All the treatments decreased the P sorption by soil, however previous P applications were more effective in decreasing P

sorption than the amendments. Applied P at 540 ppm decreased P sorption by 65% without amendments. Combined application of amendments along with 540 ppm P decreased P sorption by 85-91%. Results of several laboratory experiments involving Rhenania phosphate (thermally treated RP and Si mixture) suggested that the Si present in it decreased the P retention capacity of the soil, thereby increasing the level of water-soluble P (intensity factor) in soil (Roy *et al.*, 1971; Kundu *et al.*, 1988; Subramanian and Gopalswamy, 1991). Ma and Takahashi (1990) conducted an adsorption-desorption experiment in a P-deficient soil using silicic acid instead of a silicate salt, as a silica source to avoid the complication of changes in soil pH. Results showed that silicic acid did not displace P nor decrease the ability of the soil to adsorb P. In contrast, Si desorption increased with increasing P concentration in the solution and Si adsorption was reduced when P was applied first. In a laboratory experiment, Owino-Gerrho and Gascho (2005) investigated the impact of applied sodium silicate on soil P sorption and availability using a low-pH soil from the coastal plain of Georgia. Results indicated that the applied silicate markedly reduced the soil's high P sorption and it was attributed to the increase in the soil pH from the accompanying Na cation. Lee and Kim (2007) conducted competitive adsorption tests with phosphate and silicate anions under varying conditions of pH, ion concentrations, and order of anion addition along with single adsorption properties of each ion at 20 °C. In the single ion adsorption study, it was observed that phosphate adsorption decreased with increasing pH, however, the reverse was true for silicate adsorption. They also found that increasing Si concentration and pH increased the efficiency of Si in reducing soil P adsorption. Silicate added to soil significantly reduced P adsorption above pH 7.0; whereas at pH 9.0, P was ineffective in reducing silicate adsorption in soil. Furthermore, the presence of Si strongly depressed P adsorption when Si was added before P compared to P and Si added as a mixture. Sandim *et al.* (2014) conducted an experiment to compare the effect of silicate application with that of liming on P desorption, in soils with previously adsorbed P. It was found that the slags (steelmaking slag, ladle furnace slag and wollastonite) increased the P content in the soil to a higher extent compared to dolomitic lime, suggesting a positive interaction between Si and P in the soil. Gupta *et al.* (2014) conducted laboratory studies to examine the short- as well as long-term effects of applied rice husk ash (RHA) and bagasse ash (BA) on adsorption-desorption characteristics of P in an alkaline soil of north India under a wheat-rice cropping system. The addition of RHA or BA (10 Mg

ha⁻¹) yielded a significant reduction in P adsorption compared to the control. The reduction in P adsorption was lower when RHA and BA were applied to either rice or wheat as compared with when applied to both crops. The BA was more effective in lowering P adsorption than RHA because of its higher P concentration. Fresh addition of RHA and BA at 1% (dry-weight basis) showed little effect on P adsorption as compared to their long-term application. Desorption of P was minimum in the control plots and maximum with BA followed by RHA, especially when applied to both the crops. Agostinho *et al.* (2017) had conducted a series of pot experiments using three P rates (0, 112 and 224 kg ha⁻¹) combined with five Si treatments (wollastonite and slag applied at 4.5 t ha⁻¹ and foliar Si solution applied at 20, 40 and 80 mg Si L⁻¹). The presence of P and Si in the soil created a synergistic effect on soil Al, manganese (Mn), and arsenic (As) ($P < 0.01$); but not on rice growth and P uptake. Wollastonite and slag application were most effective in raising rice Si content than foliar-applied Si ($P < 0.001$). Haynes and Zhou (2018) examined the impacts of pH on the adsorption of phosphate and silicate, either singly or in competition in two acid soils. Adsorption isotherms at pH 5.0, 5.5, 6.0 and 6.5 showed that Si adsorption increased, whereas P adsorption decreased greatly with increasing pH. When there was simultaneous addition of Si and P at equimolar concentrations, the presence of P decreased Si adsorption between pH 6.0 and 8.0, while the presence of Si decreased P adsorption between the pH region of 6.0 and 11. They further concluded that the approach of adding Si to lower P requirements in acid soils was not likely to be effective, while the addition of fertilizer P might well lower Si adsorption and endorse its increased mobility.

8. Effect of applied phosphorus, silicon and phosphate solubilizing microorganisms on different fractions of phosphorus in soil

According to Takahashi and Anwar (2007), the inorganic P, Al-P, Fe-P and Ca-P increased with P fertilization at 0-15 cm soil depth. In the treatments with P application, total inorganic P was greater than organic P and the reverse was true in the case of the treatments without P application. Setia *et al.* (2009) studied the change in inorganic P fractions in soil due to long-term fertilization and concluded that generally, Ca-P shared the maximum percentage towards total P in neutral to alkaline soil, while loosely bound P shared the minimum, while, Fe-P and Al-P remained in between these two. After 11 years of research, it was revealed that plots getting

continuous P fertilization had a considerable rise in the fraction of loosely bound P, whereas, in plots receiving no-P fertilization, this fraction decreased gradually up to 11 years and increased thereafter. Zamuner *et al.* (2012) found that the most significant increase was in the labile and moderately labile fractions of P due to the P fertilizer application. Inorganic P extracted with 0.5 M NaHCO₃ was found to be 51 per cent higher in fertilized plots as compared to the unfertilized control. Similarly, Fe-P concentration was significantly higher in P-fertilized soil with an average concentration of 47.1 mg P kg⁻¹, than in the unfertilized soil with an average concentration of 28.4 mg P kg⁻¹. Singh *et al.* (2013) conducted a field study to evaluate the impacts of P application through RHA and BA on the changes in different inorganic (P_i) fractions of P in a Typic Ustochrept under a rice-wheat cropping system. It was observed that the 3-year-long continuous application of RHA and BA caused significant increases in the various P_i fractions (Al bound P, Fe bound P and Ca bound P) including the Olsen P in both surface and sub-surface soil layers. In a laboratory incubation experiment by Dotaniya *et al.* (2014), three levels of Si-rich organic residues (0, 2.5 and 5 g kg⁻¹ soil) and two levels of P (0 and 10 mg P₂O₅ kg⁻¹ soil) were applied to a Typic Haplustept soil and incubated for a period of 12 months. The organic residue was prepared by mixing press mud (sulphitation press mud), bagasse, and chopped rice straw in a ratio of 1:1:1 (w/w). Results indicate that application of organic residue reduced the P fractions namely, Al bound P and Ca bound P in soil. However, available P (Olsen-P) in soil solution increased with increasing levels of organic residue as well as larger incubation time. It was concluded that organic residues should be incorporated into soils for in-situ mobilization of non-labile P into available forms, thereby maintaining soil solution P in long ways. Alam *et al.* (2022a) studied the impact of the application of phosphate solubilizing fungi (PSF) and lime on the soil inorganic P fractions in a Ultisol of north-eastern India. They found that all the inorganic P fractions (soluble and loosely bound P, Al bound P, Fe bound P, reductant soluble P, occluded P, Ca bound P), except the residual P, increased significantly with P fertilization. Either liming or PSF application significantly increased the soluble and loosely bound P fraction and decreased the Al bound and Fe bound P fractions in soil. Liming increased the soluble and loosely bound P fraction from 0.43 to 0.48% and decreased Al bound P fraction from 4.13 to 3.94%, and Fe bound fraction of P from 12.3 to 12.0% of total P. Moreover, the soluble and loosely bound P fraction increased significantly from 0.44

to 0.47%, while the Al bound P decreased from 4.08 to 3.99%; and the Fe bound P decreased from 12.3 to 12.0% of total P due to PSF inoculation.

9. Effect of applied silicon and phosphate solubilizing microorganisms on phosphorus uptake as well as yield of crops

9.1. Impact of exogenous silicon application

In a pot experiment, Ma and Takahashi (1990) observed that the shoot dry weight of rice plants grown on silicic acid-treated soil ($0.47 \text{ mg Si g}^{-1} \text{ soil}$) increased significantly under both non-flooded and flooded conditions. Owino-Gerrho and Gascho (2005) investigated the impact of applied silicate (in the form of CaSiO_3) on soil P nutrition and growth of maize grown in a low pH soil from the coastal plain of Georgia by conducting pot experiments. Both shoot and root dry weights of maize plants were increased by applications of silicate, phosphate, and by applications of silicate along with phosphate. Thind *et al.* (2012) carried out a field experiment for three and half years, in which they applied different levels of silica-rich wastes like rice husk ash (RHA), bagasse ash (BA), and fly ash (FA) to either wheat or rice or both wheat and rice in a rice-wheat cropping system. Direct application of RHA and BA to wheat resulted in a 25 and 24% increase in the mean grain yield of wheat; and a 10 and 11% increase in subsequent rice crop, respectively. However, direct application to rice resulted in an 8 and 11% yield increase in rice; and a 10 and 14% increase in subsequent wheat for RHA and BA, respectively. Alovisei *et al.* (2014) conducted two greenhouse experiments by applying different doses of Si and P to bean plants grown in two different soils, namely Orthic Quartzarenic Neosol (RQo) and Dystroferic Red Latosol (LVdf). Results indicated that the application of Si did not influence the dry matter production of the aerial part or the grain dry matter as well as P accumulation in the aerial part of the bean plants. On the other hand, applied P not only increased the aerial as well as grain dry matter yield of the plants, but also the P accumulation in the aerial part of the bean plants. Pati *et al.* (2016) carried out a field experiments for two consecutive seasons and diatomaceous earth as a Si source along with recommended doses of fertilizer NPK was applied to the rice crop. Results indicated that application of diatomaceous earth at 600 kg ha^{-1} along with standard NPK fertilization significantly increased grain and straw yield as well as yield-attributing parameters such as plant height, number of tillers, number of panicles, and 1000-grain weight of rice. It also caused a concomitant improvement in uptake of P

by the crop. Jinger *et al.* (2018) conducted a field experiment applying different levels of Si and P to the aerobic rice crop. The highest grain yield of aerobic rice was recorded with 120 kg Si and 90 kg P₂O₅ ha⁻¹ followed by 80 kg Si and 60 kg P₂O₅ ha⁻¹ and the lowest in control. The grain, straw yield, and water productivity increased by 10-40, 5-30 and 10.2-39 per cent, respectively in different treatments over control. Sandhya and Prakash (2019) conducted a pot experiment in acidic (pH 5.86), neutral (pH 7.10) and alkaline (pH 9.38) soils of Karnataka amended with three Si sources: calcium silicate (CaSiO₃), diatomaceous earth and rice husk biochar. In acidic soil, the grain and straw yield of rice increased significantly with the application of CaSiO₃ (8.21 and 8.45 g pot⁻¹, respectively) followed by diatomaceous earth (6.18 and 5.89 g pot⁻¹, respectively) at both the rates of applied Si (250 and 500 kg Si ha⁻¹), over no Si. A significantly higher straw dry weight of rice was recorded with the application of diatomaceous earth at 250 and 500 kg Si ha⁻¹ (8.48 and 9.36 g pot⁻¹, respectively) followed by CaSiO₃ (7.60 and 7.83 g pot⁻¹, respectively) in neutral soil, compared to control.

9.2. Impact of application of phosphate solubilizing microorganisms

Kloepper *et al.* (1989) found that inoculation with *Azotobacter* and *Bacillus* sp. could increase the wheat yield by up to 30 and 43 per cent, respectively, over no inoculation. Kim *et al.* (1997) studied the seed inoculation with PSM and found a significant increase in the P concentration in the biomass of wheat. By putting *Pseudomonas fortinii* into two alpine *Carex* species, Bartholdy *et al.* (2001) got the plants to grow faster and have more P content. Due to PSM inoculation, the amount of sugarcane yield increased by 12.6 per cent (Sundara *et al.*, 2002). The PSMs can enhance the availability of soluble P and improve plant growth by making it easier for plants to fix N (Ponmurugan and Gopi, 2006). It was found that *Pseudomonas* sp. increased the total number of nodules, the dry weight of nodules, grain yield, other parts of yield, nutrient availability, and uptake by soybean crops (Son *et al.*, 2006). Single and dual inoculation of PSM along with P-fertilizer increased wheat grain yield by 30-40 per cent compared to sole P fertilization. Dual inoculation without P-fertilizer increased wheat grain yield by 20 per cent compared to sole P fertilization (Afzal and Bano, 2008). Yazdani *et al.* (2009) said that co-inoculation of plant growth-promoting rhizobacteria (PGPR) and PSM reduced the amount of P applied by 50% without affecting corn yield in a significant way. Namli *et al.* (2017) found

that when soil was inoculated with PSM, plant N and P content, as well as above- and below-ground biomass (both fresh and dry weight) increased significantly compared to a control that was not inoculated. Pradhan *et al.* (2018) found that the pod yield of groundnut plants increased significantly when they were treated with PSM (*Bacillus amyloliquefaciens* strain CTC12 or *Burkholderia cepacia* strain KHD08) and 100% of the recommended dose of P (RDP), supplied through SSP. Also, when PSM (CTC12 or KHD08) inoculation was combined with either 75% or 100% of RDP, it yielded significantly higher P contents in kernel and shoot and also increased the kernel P uptake significantly. Alam *et al.* (2022a) observed a positive growth response of soybean toward the application of P, lime, and PSM. Application of the PSM, *Aspergillus niger* increased the P uptake and dry matter yield by 16.7 and 7.77 per cent, over no inoculation.

The research work entitled “**Enhancing soil phosphorus availability to wheat (*Triticum aestivum*) and mungbean (*Vigna radiata*) using silicon-rich agricultural wastes and phosphate solubilizing microorganism**” was carried out at the Division of Soil Science and Agricultural Chemistry, ICAR-Indian Agricultural Research Institute (IARI), New Delhi. Laboratory, as well as pot-culture experiments, were conducted for this purpose. In this chapter, the detailed procedure of collection of the materials used, as well as the methodologies followed in different experiments, have been discussed.

3.1. Materials

3.1.1. Experimental soil

Two bulk surface soil samples (0-15 cm) were collected for the present study, one each from Ranchi district of Jharkhand (Alfisol, pH= 6.32) and IARI research farm, New Delhi (Inceptisol, pH= 8.12) were collected. Details of the sites from where bulk samples were collected are discussed below.

The bulk surface soil sample (0-15 cm) of Ranchi, Jharkhand was obtained from an uncultivated plot (23°42' N latitude, 85°32' E longitude, and ~618 m above mean sea level). The soil is classified as Typic Haplustalf. The study region has a humid subtropical climate with an average annual temperature of 24.5 °C. The mean summer and winter temperatures are 28 and 19 °C, respectively. Annual rainfall is approximately 1057 mm, with the peak rainfall being in July-August and the trough occurring in November.

Another bulk surface soil sample (0-15 cm) was taken from an uncultivated plot of the research farm (28°37' - 28°39' N latitude, 77°9' - 77°11' E longitude, and ~220 m above mean sea level), ICAR-IARI, New Delhi, India. The soil of the experimental field is classified as Typic Haplustept, which is a type of alluvial association of the Indo-Gangetic plains. The study area has a semiarid, tropical climate with hot, dry summers (May-June) and bitterly cold winters (December-January), with summer minimum and maximum temperatures of 26.4 and 44.1 °C and winter minimum and maximum temperatures of 5.6 and 23.7 °C, respectively, and an annual average maximum and minimum temperature of 40.5 and 6.5 °C, respectively.

The average annual rainfall is ~760 mm, out of which 80% is received during July-September.

3.1.2. Silicon-rich agricultural wastes

The sugarcane bagasse ash (SBA) used in this study was obtained from a sugar processing unit located in the central part of India (Chhattisgarh), as a by-product of the boilers of the sugar mill's cogeneration process. The rice husk ash (RHA), produced as a by-product after the incineration of rice husk as a fuel in boilers of rice processing units was obtained from a rice mill located in the eastern part of India (West Bengal). On the other hand, for the preparation of the small amount of corn cob ash (CCA) required for this study, corn cobs were collected from farmers' fields and dried in sun. Thereafter, the dried cobs were burnt completely in a metal container in the laboratory under proper aeration to simulate the common practice of its usage as a fuel in rural households. The corn cobs were burnt until complete conversion into ash and the temperature was monitored and limited to a maximum of 650 °C with a digital pyrometer. All three ashes were air-dried in shade after collection.

3.1.3. Pure culture of phosphate solubilizing microorganism (PSM)

Liquid pure culture of the phosphate solubilizing microorganism (PSM) *viz.*, *Lactococcus lactis* ($\sim 10^9$ cfu mL⁻¹), was obtained from the Division of Microbiology, ICAR-IARI, New Delhi, India. This bacterial species is considered “generally recognized as safe (GRAS)” and is reported to solubilize/mineralize phosphate in vitro with different inorganic and organic P sources (de Lacerda *et al.*, 2016; Marag and Suman, 2018).

3.2. Characterization of silicon-rich agricultural wastes

3.2.1. Chemical properties

For the pH measurement, the ash to deionized water ratio of 1:10 ratio was used in order to get a homogeneous suspension, and the pH was determined after 1 h of equilibration (Lee *et al.*, 2013) using a digital pH meter. The electrical conductivity (EC) was determined in the supernatant liquid of the same extracts used for pH determination with the help of a digital conductivity meter and the results were expressed in dS m⁻¹ at 25 °C. Compositions of major oxides (%) present in the ashes were determined using wavelength-dispersive X-ray fluorescence spectroscopy (WD-XRF). Total carbon (C), nitrogen (N), and sulphur (S) content (%) of the ashes were determined by the dry combustion method (Nelson and Sommers, 1983).

3.2.2. X-ray diffraction (XRD)

The crystallinity of SBA, RHA, and CCA was assessed through X-ray diffraction (XRD). The powdered ashes were scanned with a Philips X-ray diffractometer (XRD) (PW 1710 diffractometer control, PW 1729 X-ray generator) using Ni-filtered Cu-K α radiation (wavelength, 1.542 Å) over a range of 4-50° 2 θ at a scanning speed of 0.025 °2 θ s⁻¹.

3.2.3. Fourier transform infrared (FTIR) spectroscopy

The surface chemical bonding and the functional groups were determined by the spectra obtained from Fourier transform infrared (FTIR) spectrophotometer in the range of 4000-600 cm⁻¹ spectral region using an Attenuated Total Reflection (ATR) sampling technique. Typically, 24 scans were collected with a scanning resolution of 4 cm⁻¹.

3.2.4. Scanning electron microscopy (SEM)

The surface morphology of the ashes (SBA, RHA, and CCA) was analyzed through scanning using the Tescan Vega-3 LMU SEM operated at 10 kV HV. Samples were assessed after a thin layer coating of gold-palladium using the Denton Vacuum model DESK II sputter.

3.3. Processing of soil samples

The collected soil samples were first shade-dried and then ground well. Then it was passed through a 2 mm sieve and a part of the processed soil samples was used for characterization of different initial physicochemical properties of the soils, while another part was used for the incubation as well as pot-culture experiments.

3.4. Analysis of physical and chemical properties of soils

Different physical and chemical properties of the initial experimental soils as well as of the post-harvest soil samples were determined according to the following procedures:

3.4.1. Soil texture

Mechanical composition of the soils was determined by hydrometer method (Bouyoucos, 1962). The textural triangle proposed by USDA (Gee and Bauder, 1986) was used to determine the texture of the experimental soils.

3.4.2. Soil moisture at field capacity

A pressure plate apparatus was used to assess the amount of water held at field capacity (0.033 MPa) (Richards, 1949).

3.4.3. Soil pH and electrical conductivity (EC)

The pH of the soil samples was measured in 1:2.5 soil:water suspension using a digital pH meter having a combined electrode (glass and calomel electrodes). The electrical conductivity (EC) was determined in the supernatant liquid of the same extracts used for pH determination with the help of a conductivity meter and the results were expressed in dS m^{-1} at 25 °C.

3.4.4. Organic carbon (OC)

Organic carbon content in the soil was determined by the wet oxidation method as described by Walkley and Black (1934). Soil samples used for OC determination were ground to pass through a 0.2 mm sieve.

3.4.5. Cation exchange capacity

The cation exchange capacity (CEC) of the soil samples was determined by the ammonium acetate method of Jackson (1973).

3.4.6. Available nitrogen

Available nitrogen (N) in the soil samples was measured following the alkaline KMnO_4 method as given by Subbiah and Asija (1956).

3.4.7. Available phosphorus

In order to extract the available phosphorus (P) in soil, the soil samples were extracted with Bray's P-1 reagent in the case of Alfisol of Jharkhand (Bray and Kurtz, 1945), and Olsen's reagent for Inceptisol of New Delhi (Olsen *et al.*, 1954). Ascorbic acid reduced phosphomolybdate blue colour method of P determination was followed in both the soils (Watanabe and Olsen, 1965). The intensity of the blue colour was measured at 730 nm using a UV-VIS spectrophotometer.

3.4.8. Available potassium

Available potassium (K) content of the soil samples was extracted by 1N ammonium acetate solution of pH 7.0 as described by Hanway and Heidel (1952), followed by subsequent determination of K in the extracts with the help of a flame photometer.

3.5. Incubation study for assessment of the P and Si release in soil

An incubation study was conducted to assess the P and Si release kinetics from the soil samples treated with Si-rich agro-wastes (ashes) and PSM. Processed soil samples (40 g, oven dry weight equivalent) were taken in a series of 500 mL wide-mouth chemical-resistant polythene bottles and were adjusted to 80% of their field capacity moisture and pre-incubated for a week at room temperature to rejuvenate their approximate natural condition. Treatment combinations were made according to a factorial completely randomized design (CRD) with three factors namely, Si sources, PSM, and Si doses. The Si sources had three levels: SBA, RHA, and CCA; while PSM had two levels: without PSM (-PSM), and with PSM (+PSM); and Si doses had three levels: no Si (Si_0), 125 mg Si kg^{-1} soil (Si_{125}), and 250 mg Si kg^{-1} soil (Si_{250}). Each treatment combination was replicated thrice. Two identical sets of treated soil samples were taken: one for assessment of P release kinetics and the other for assessment of Si release kinetics from the treated soil samples. After applying treatments, field capacity moisture (0.033 MPa) was maintained inside the bottles, which were kept in an incubator maintained at 25 °C. Four to five fine perforations were made in the lid of each bottle to facilitate air exchange and to prevent the development of anaerobic conditions inside the bottle. Constant moisture content was maintained by adding deionized water after measuring the weight losses in every 2 days.

Details of treatments

The incubation experiment was carried out with the following treatments:

(a) Source of Silicon: Three

- (i) Sugarcane bagasse ash (SBA)
- (ii) Rice husk ash (RHA)
- (iii) Corn cob ash (CCA)

(b) Dose of Silicon: Three

- (i) 0 mg Si kg^{-1} soil (Si_0)
- (ii) 125 mg Si kg^{-1} soil (Si_{125})
- (iii) 250 mg Si kg^{-1} soil (Si_{250})

(c) Phosphate solubilizing microorganism (PSM): Two

- (i) No PSM (-PSM)
- (ii) PSM (+PSM)

- ❑ **No. of replications:** 3
- ❑ **No. of soils:** 2
- ❑ **Experimental design:** Factorial completely randomized design (CRD)

Soil analysis for phosphorus

Destructive samplings were done at 7, 15, 30, 45, 60, and 90 days after incubation (DAI) and analyzed for P. Soil samples were extracted with 0.01 M CaCl₂ solution for 1 h at a soil: solution ratio of 1:10, followed by centrifugation to get the clear extract. The P, such extracted, denotes the solution P (Kuo, 1996). The P content in the extract was determined by the ascorbic acid reduced phosphomolybdate blue colour method (Watanabe and Olsen, 1965). The following exponential model was selected to study the P release kinetics in soil:

$$P_t = P_a \exp(k_p t) \quad \dots (i)$$

where, P_t = total soil solution P after t days of incubation; P_a = initial solution P; and k_p = release rate constant of solution P.

The P_t at 90 DAI has been denoted as ' P_{90} ', throughout the thesis.

Soil analysis for silicon

Destructive samplings were done at 7, 15, 30, 45, 60, and 90 DAI and analyzed for Si. Soluble Si was extracted from soil samples with 0.01 M CaCl₂ (1:10 ratio and 16 h of continuous shaking) and Si in the extract was determined spectrophotometrically (Liang *et al.*, 2015).

A linear model was selected to study the Si release kinetics in soil:

$$Si_t = (k_s t) + Si_a \quad \dots (ii)$$

where, Si_t = total soluble Si after t days of incubation; Si_a = initial soluble Si; and k_s = release rate constant of soluble Si.

The Si_t at 90 DAI has been denoted as ' Si_{90} ', throughout the thesis.

3.6. Pot culture experiment

Wheat

Based on the P-release pattern under the incubation study, four best-performing treatments were selected for the pot culture experiment for assessing their abilities to supply P for plant uptake. The treatments were:

- (i) SBA @ 250 mg Si kg⁻¹ soil + PSM
- (ii) RHA @ 250 mg Si kg⁻¹ soil + PSM
- (iii) CCA @ 250 mg Si kg⁻¹ soil + PSM
- (iv) CCA @ 125 mg Si kg⁻¹ soil + PSM

The above four treatments were combined with 2 doses of P (No P, and 50% of recommended dose of P, *i.e.*, 20 mg P kg⁻¹ soil). Along with these treatments (4×2 = 8), one treatment consisting of 100% of the recommended dose of P (40 mg P kg⁻¹ soil), one treatment consisting of 75% of the recommended dose of P (30 mg P kg⁻¹ soil), and one control treatment were tested. The pot culture experiment was carried out in the net-house of the Division of Soil Science and Agricultural Chemistry, IARI, New Delhi in a wheat-mungbean cropping sequence. Crops were grown in two contrasting soils *viz.*, Alfisol from Ranchi, Jharkhand, and Inceptisol from IARI farm, New Delhi. The experiment was laid out in a completely randomized design (CRD) with three replications. Processed soil samples (4 kg) were filled in each plastic pot. A uniform basal dose of 2/3rd of recommended dose of N and a full dose of K *i.e.* 54 and 22 mg kg⁻¹ of N and K was added to the soil of each pot through urea and muriate of potash, respectively. The soil in each pot was then irrigated to field capacity with distilled water and incubated for one week at ambient temperature. The remaining 1/3rd recommended dose of N was added as a split dose after one month of sowing. The pot culture experiment was performed with the following treatments:

T1: Control

T2: 100% P

T3: 75% P

T4: SBA @ 250 mg Si kg⁻¹ soil + PSM

T5: RHA @ 250 mg Si kg⁻¹ soil + PSM

T6: CCA @ 125 mg Si kg⁻¹ soil + PSM

T7: CCA @ 250 mg Si kg⁻¹ soil + PSM

T8: SBA @ 250 mg Si kg⁻¹ soil + PSM + 50% P

T9: RHA @ 250 mg Si kg⁻¹ soil + PSM + 50% P

T10: CCA @ 125 mg Si kg⁻¹ soil + PSM + 50% P

T11: CCA @ 250 mg Si kg⁻¹ soil + PSM + 50% P

□ **No. of replications:** 3

□ **Experimental design:** Completely randomized design (CRD)

Wheat (*Triticum aestivum*) was grown as the test crop in the net-house. Seeds of wheat were inoculated with and without the pure culture of the PSM (*Lactococcus lactis*) as per the treatment combinations. For inoculation, seeds of wheat were treated with a liquid pure culture of *Lactococcus lactis* (containing $\sim 10^9$ cfu mL⁻¹) along with 1% carboxymethyl cellulose (CMC) agar, which acts as an adhesive and helps in the better coating of the seeds with inoculum. Then, the wet seeds were kept under laminar airflow for drying. Air-dried seeds were then sown immediately. Ten inoculated or uninoculated seeds of wheat corresponding to PSM (+) and PSM (-), respectively were sown in each pot by dibbling manually at the end of November 2020, which were thinned to five plants per pot after two weeks of germination. Pots were watered daily with the required amount of water on weight basis to maintain field capacity. The necessary agronomic package of practices was followed. Above-ground parts of the plants were harvested after attaining physiological maturity.

Mungbean

To study the residual effects of the applied Si-rich ago-wastes and PSM on soil P availability, mungbean (*Vigna radiata*) was grown as a test crop in the same pots after the harvest of wheat. After the harvest of wheat plants, the soil was taken out from the pot, dried, and mixed thoroughly. A uniform basal dose of N (13.3 mg kg⁻¹ soil) and K (13.3 mg kg⁻¹ soil) was applied in all the pots. The required quantity of N was provided in the form of urea solution, whereas K was provided in the form of a solution of potassium chloride (KCl), and thoroughly mixed with soil. Soils were then poured again into the same pots used for growing wheat. The soil in each pot was then irrigated to field capacity with distilled water and incubated for one week at ambient temperature. Ten mungbean seeds were sown in each pot by dibbling manually, and after two weeks of sowing, a uniform plant population (five plants per pot) was maintained. Pots were watered daily with the required amount of water on a weight basis to maintain field capacity. Above-ground parts of the plants were harvested after attaining physiological maturity.

3.7. Analyses of plant samples

The harvested above-ground plant samples (straw and grain) were then washed first under running tap water, followed by rinsing with dilute HCl (0.001 N), distilled water, and finally with deionized water. Washed samples were first air-dried. After

that, they were kept in a hot air oven at 65 ± 2 °C. When the samples attained constant weight, dry biomass yields of the plant samples were recorded, and further, they were ground in a mechanical grinder made of stainless steel. Ground samples were stored in paper packets for further analysis. Plant samples of wheat and mungbean were analyzed for the total P content in grain and straw. For this, 0.5 g of the plant sample was digested using 10 mL of the di-acid mixture (HNO_3 and HClO_4 in a 9:4 ratio) on a hot plate till the content becomes colourless and white fume came for 10 min. After digestion, a small amount of distilled water was added to the digested samples, and filtered through Whatman No. 42 filter paper. The final volume of the filtrate was made up to 100 mL. The P content in the aliquot was then measured spectrophotometrically by the vanadomolybdo-phosphoric yellow colour method at 420 nm (Jackson, 1973). Phosphorus uptake in grain (or straw or stover) was computed as:

$$\text{P uptake (mg pot}^{-1}\text{)} = \text{Grain (or straw or stover) yield (g pot}^{-1}\text{)} \times \text{P content (\% in grain (or straw or stover))} \times 10$$

$$\text{Total P uptake} = \text{P uptake in grain} + \text{P uptake in straw (or stover)}$$

3.8. Analyses of post-harvest soil samples

After the harvest of each crop, soil samples were collected from each pot. For physicochemical analysis, collected soil samples were air-dried, ground, and passed through a 2 mm sieve. The soil samples were extracted with Bray's P-1 reagent in the case of Alfisol of Jharkhand (Bray and Kurtz, 1945), and Olsen's reagent in the case of Inceptisol of Delhi (Olsen *et al.*, 1954) for the determination of available P. Ascorbic acid reduced phosphomolybdate blue colour method of P determination was followed in both the soils (Watanabe and Olsen, 1965). Readily plant-available Si was extracted from post-harvest soil samples with 0.01 M CaCl_2 (1:10 ratio and 16 h of continuous shaking) and Si in the extract was determined spectrophotometrically (Liang *et al.*, 2015) for both the soils.

3.9. Sequential fractionation of soil phosphorus

The sequential fractionation of soil P was done to find out the changes in different fractions of soil P as affected by Si-rich agricultural wastes and PSM. The post-harvest soils after the harvest of the mungbean crop were subjected to the fractionation scheme for inorganic P as proposed by Kuo (1996). This scheme is

basically a modification of the earlier method as proposed by Chang and Jackson (1957) fractionation scheme.

The following five fractions of soil inorganic P were extracted sequentially:

- a) **Soluble or loosely bound P** using 1 *M* ammonium chloride (NH_4Cl);
- b) **Al-bound P (Al-P)** using 0.5 *M* ammonium fluoride (NH_4F) at pH 8.2;
- c) **Fe-bound P (Fe-P)** using 0.1 *M* NaOH;
- d) **Reductant soluble P (ReS-P)** using 0.3 *M* sodium citrate ($\text{Na}_3\text{C}_3\text{H}_6\text{O}_7$),
1 *M* sodium bicarbonate (NaHCO_3), and 0.5 g sodium dithionate ($\text{Na}_2\text{S}_2\text{O}_6$);
- e) **Ca-bound P (Ca-P)** using 0.25 *M* sulphuric acid (H_2SO_4).

A flow-chart of the sequential fractionation scheme followed is given below:

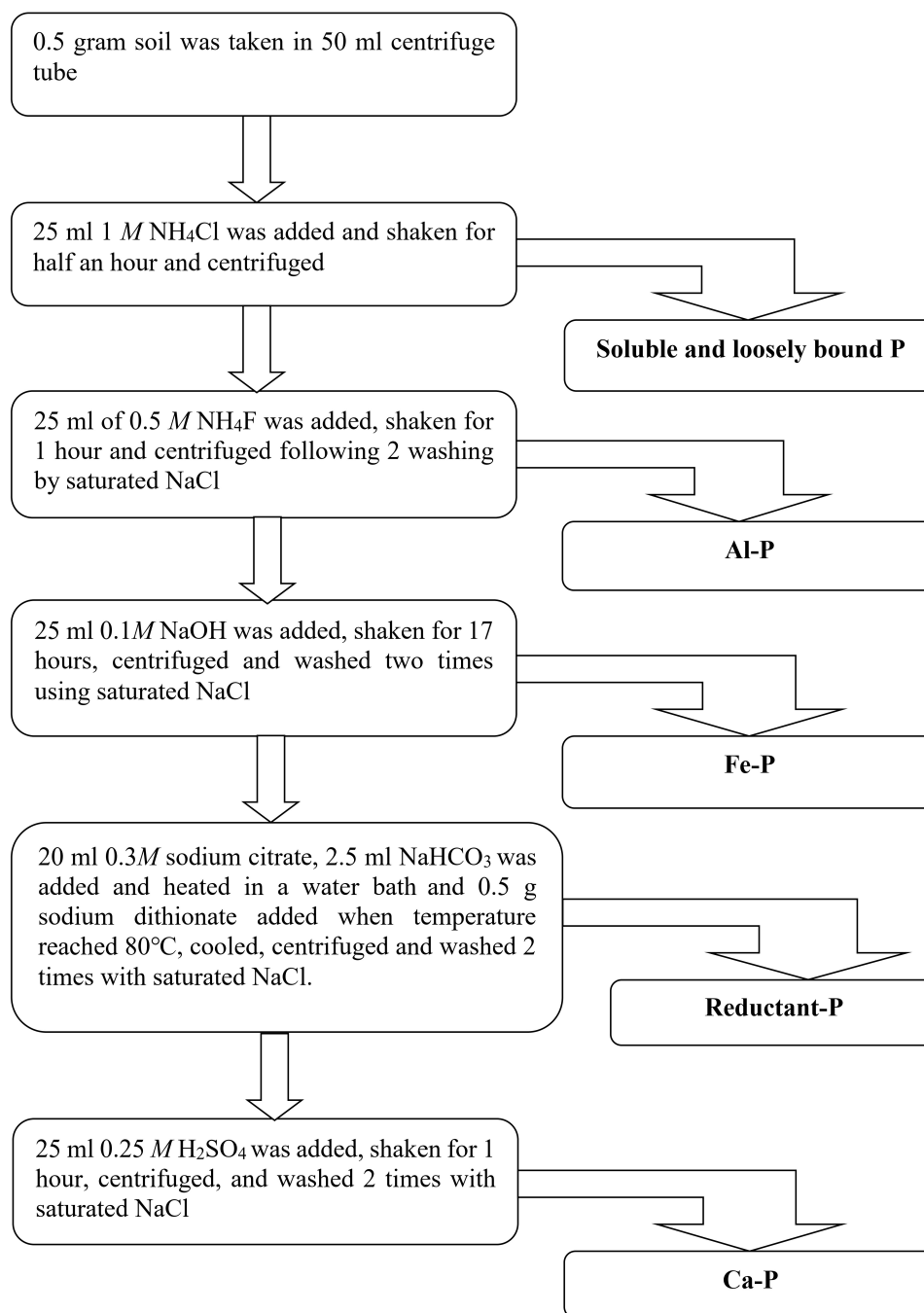


Figure 3.1. Flow-chart for sequential fractionation of inorganic P

In a nutshell, after each fractionation step, the soil-extractant suspension was centrifuged and the supernatant was decanted in a 50 mL volumetric flask (except the first fraction where 25 mL volumetric flask was used) followed by two washings with saturated NaCl solution and decantation. The supernatant after centrifugation was added to the previous filtrate and volume was made-up. An aliquot containing 2 to 40 $\mu\text{g P mL}^{-1}$ from each extract was transferred to a 25 mL volumetric flask. Five to 10 mL of distilled water and 5 drops of *p*-nitrophenol indicator were added to the volumetric flasks containing aliquots of Fe-P and Ca-P, and the pH was adjusted with 2 M HCl or 2 M NaOH until the indicator colour just changed to colourless. Twelve mL of 0.8 M H_3BO_3 was added to the volumetric flask containing 8 mL extract of Al-bound P. Phosphorus concentrations in the various extracts were determined following the ascorbic acid blue colour method (Watanabe and Olsen, 1965). Phosphorus standards that contained the same volume of extracting solution as in the extracts were prepared. The intensity of the blue colour developed was measured at 730 nm using a UV-VIS spectrophotometer.

Moreover, besides these five fractions, organic P, as well as the total P content of the soil samples were also determined separately.

Organic P

Additionally, total organic P in soil was determined separately by the ignition method. Soil samples were ignited at 550 °C for 1 h and extracted with 0.5 M sulphuric acid (H_2SO_4) (Kuo, 1996).

Total P

The total P content of the soil was determined by digesting 1 g of soil with 15 mL 60% HClO_4 in a sand bath at 180 °C (Olsen and Sommers, 1982). Total P content in the extract was then determined spectrophotometrically by the vanadomolybdo-phosphate yellow colour method at a wavelength of 420 nm wavelength using a UV-VIS spectrophotometer (Jackson, 1973).

3.10. Phosphorus adsorption-desorption

To study the effect of Si-rich agricultural wastes on the adsorption-desorption behaviour of P in soils (Alfisol and Inceptisol), a separate incubation experiment was set up. Soil samples were treated with the highest dose of Si (*i.e.* 250 mg Si kg^{-1} soil),

as it showed the highest cumulative Si release in the Si-release incubation experiment. The treatments consisted of the following:

T1: Control

T2: SBA @ 250 mg Si kg⁻¹ soil

T3: RHA @ 250 mg Si kg⁻¹ soil

T4: CCA @ 250 mg Si kg⁻¹ soil

□ No. of replications: 4

□ No. of soils: 2

□ Experimental design: Completely randomized design (CRD)

After applying treatments, field capacity moisture (0.033 MPa) was maintained inside the bottles, which were kept in an incubator maintained at 25 °C for 90 days. Constant moisture content was maintained by adding deionized water after measuring the weight losses in every 2 days. After the incubation period (*i.e.*, 90 days), soil samples were air-dried and processed. These processed soil samples were further subjected to equilibration with solutions containing graded concentrations of P and subsequent determination of the amount of P sorbed on the solid surface as well as solution P concentration.

For the adsorption study, a 3 g soil sample was taken in a 50 mL centrifuge tube containing 5, 10, 20, 40, 60, 80, and 100 mg P L⁻¹ in 0.01 M CaCl₂ solution and equilibrated for a period of six days. Two drops of toluene were added to each tube to check microbial activity. The tubes were shaken in a mechanical shaker for 30 min twice a day over six consecutive days (Singh and Jones, 1976). Phosphorus in equilibrium solution was determined by the phosphomolybdo-blue colour method using a UV-Visible spectrophotometer at 730 nm wavelength (Watanabe and Olsen, 1965). Data obtained were fitted to the Freundlich and Langmuir equations.

For studying P desorption, the soil from the adsorption run (after the supernatant liquid was decanted off) was re-suspended with vigorous shaking in an aliquot of 28 mL of 0.01 M CaCl₂ (P-free) and equilibrated for 24 h with a further shaking for a 30 min period after 12 h period. Samples were, thereafter, centrifuged and P was determined in the supernatant solution. Necessary corrections for the carried-over supernatant from the preceding sorption/desorption run were made for P desorption calculation (Fox and Kamprath, 1970).

3.10.1. Adsorption and desorption parameters

Adsorbed P

The difference between the amount of P in solution after shaking and the amount initially present was taken as the amount of P adsorbed by the soil from the equilibrating solution.

The following adsorption equations were used to describe P adsorption in the soil:

Freundlich equation

$$x = a c^{1/n} \quad \dots \text{(iii)}$$

where, 'x' is the amount of adsorbed P (mg kg⁻¹ soil); 'c' is the equilibrium concentration of P (mg L⁻¹); and 'a' and '1/n' are two equation parameters that are calculated using the linear transformation of the above equation as:

$$\log x = \log a + (1/n) \log c \quad \dots \text{(iv)}$$

Constant 'a' may be considered a hypothetical index of P sorbed from a solution having a unit equilibrium P concentration and gives a measure of the relative P sorption capacity of different soils (Biggar and Cheung, 1973). The value of the parameter '1/n' ranges between 0 and 1.

Langmuir equation

$$x = k.b.c / (1 + k.c) \quad \dots \text{(v)}$$

The parameters 'b' and 'k' were calculated using the linear transformation

$$c/x = c/b + 1/(k.b) \quad \dots \text{(vi)}$$

where, 'c' and 'x' denotes the same as that of the Freundlich equation; 'b' is the maximum P adsorption capacity (mg kg⁻¹ soil); and 'k' is a constant mirroring the relative rate of P adsorption and desorption at equilibrium and thus an affinity term related to bonding energy (L mg⁻¹).

Maximum phosphate buffering capacity (MPBC)

By combining the maximum P adsorption capacity and bonding energy constant, an index MPBC was calculated (Reddy *et al.*, 2005).

Desorbed-P

Desorbed P was calculated as the difference between equilibrium P concentration at each desorption step and the equilibrium P concentration previous to each desorption step, divided by 15 (dilution factor).

Hysteresis index (H)

The hysteresis index (H) was estimated as the difference in the middle of areas beneath the sorption (A_s) and desorption (A_d) lines (Deng *et al.*, 2010), using the following formula:

$$H = \frac{(A_s - A_d) \times 100\%}{A_s} \quad \dots \text{(vii)}$$

3.11. Statistical analyses

Data generated from incubation study and pot-culture experiments were subjected to statistical analysis. All data generated were analyzed using analysis of variance (ANOVA) for a completely randomized design (CRD). Fisher's Least Significant Difference (LSD) test was used as a post-hoc mean separation test ($P < 0.05$) (Gomez and Gomez, 1984). Regression analyses were also carried out to assess the contribution of various P fractions toward yield and P uptake by plant, as per the objectives of the present study. Principal Components Analysis (PCA) was performed with mean values of post-harvest soil and plant variables and components with Eigen value >1 was extracted for ordination. A hierarchical cluster analysis (dendrogram) was performed to identify the most influential variable for P mobilization. An attempt was made to quantify the relative contribution of different soil P fractions as well as Si availability in soil towards the total yield of wheat and mungbean in Alfisol and Inceptisol through stepwise multiple linear regression analysis.

To accomplish the objectives of the present investigation as outlined earlier, laboratory and pot-culture experiments were carried out. The salient findings of these experiments have been presented in this chapter.

4.1. Physical and chemical properties of the experimental soils

Some important physical and chemical properties of the experimental soils are presented in table 4.1. For the present investigation, bulk surface soils of Alfisol and Inceptisol orders were collected from Ranchi (Jharkhand) and IARI research farm (New Delhi), respectively. In the case of Alfisol of Ranchi, the soil texture was sandy clay loam with sand, silt and clay concentrations of 48.2, 25.2, and 26.6%, respectively. The soil was slightly acidic ($\text{pH} = 6.32$), non-saline ($\text{EC} = 0.12 \text{ dS m}^{-1}$) and carried the status of low fertility for oxidizable organic C (3.06 g kg^{-1}), available N (117.9 mg kg^{-1}) and available Si (35.1 mg kg^{-1}); while medium fertility status for available K (60.7 mg kg^{-1}). Although the soil was low in plant-available P (Bray-P, 6.78 mg kg^{-1}), the total P of this soil was quite high (332.7 mg kg^{-1}) and aimed to solubilize a part of it.

On the other hand, the Inceptisol of IARI contained 54.2% sand, 22.8% silt, and 23.0% clay, and can be categorized as sandy clay loam in texture. The soil was alkaline ($\text{pH} = 8.12$), non-calcareous (free CaCO_3 1.39%), non-saline ($\text{EC} 0.19 \text{ dS m}^{-1}$), low in oxidizable organic C (4.07 g kg^{-1}), of marginally medium-fertility in terms of Si availability (42.4 mg kg^{-1}); high with respect to available K (130.3 mg kg^{-1}), and low with respect to available N (89.7 mg kg^{-1}). The experimental soil was deficient (marginally medium status) in plant-available P (Olsen-P, 5.29 mg kg^{-1}); however, the total P content of this soil was substantially high (607.3 mg kg^{-1}), and sought to solubilize a portion of it.

4.2. Characterization of silicon-rich agricultural wastes

4.2.1. Chemical characterization

The chemical compositions and some chemical properties of the ashes are mentioned in table 4.2. In all the ashes, SiO_2 was the major oxide present, with variable amounts of other constituents.

Table 4.1. Physical and chemical properties of the experimental soils

Properties	Ranchi, Jharkhand (Alfisol)	IARI farm, New Delhi (Inceptisol)
<i>Mechanical compositions</i>		
Sand (%)	48.2	54.2
Silt (%)	25.2	22.8
Clay (%)	26.6	23.0
Textural class	Sandy clay loam	Sandy clay loam
<i>Other physicochemical properties</i>		
pH	6.32	8.12
EC (dS m ⁻¹)	0.12	0.19
Oxidizable organic C (%)	0.31	0.41
CEC [cmol(p ⁺) kg ⁻¹]	9.10	14.4
<i>Selected nutrient status</i>		
Available N (mg kg ⁻¹)	117.9	89.7
Available P (mg kg ⁻¹)	6.78	5.29
Available K (mg kg ⁻¹)	60.7	130.3
Available Si (mg kg ⁻¹)	35.1	42.4
<i>P fractions</i>		
Soluble and loosely bound P (mg kg ⁻¹)	3.03	5.52
Aluminium bound P (mg kg ⁻¹)	47.5	56.3
Iron bound P (mg kg ⁻¹)	68.3	40.1
Reductant soluble P (mg kg ⁻¹)	89.7	72.1
Calcium bound P (mg kg ⁻¹)	34.4	258.7
Total organic P (mg kg ⁻¹)	89.8	174.6

Table 4.2. Chemical compositions and selected physicochemical properties of the silicon-rich agro-wastes (ashes)

Properties	Sugarcane bagasse ash (SBA)	Rice husk ash (RHA)	Corn cob ash (CCA)
<i>Chemical compositions</i>			
SiO ₂ (%)	76.2	82.7	46.9
P ₂ O ₅ (%)	1.80	0.87	6.65
Al ₂ O ₃ (%)	1.81	0.91	4.51
CaO (%)	2.92	1.06	2.42
Fe ₂ O ₃ (%)	1.08	0.32	1.61
K ₂ O (%)	2.09	1.46	23.2
MgO (%)	3.57	0.66	3.63
Na ₂ O (%)	0.01	0.04	0.55
MnO (%)	0.39	0.26	0.29
Total C (%)	5.03	3.71	3.19
Total N (%)	0.30	0.20	0.22
Total S (%)	0.26	0.19	0.22
<i>Other physicochemical properties</i>			
pH (1:10:: ash:water)	10.1	9.66	10.8
EC (dS m ⁻¹)	0.95	0.86	2.23

4.2.2. Morphological Characterization

4.2.2.1. X-Ray Diffractometry (XRD)

In the XRD diffractogram (Figure 4.1), the widened, loping, and broad humps (approximately between 10° and 35°) indicated the presence of silica in the amorphous forms, whereas, the sharp peaks showed the presence of crystalline silica in the form of quartz or cristobalite. The relative crystallinity index (CI) of SBA, RHA and CCA was found to be 29.2, 32.8 and 15.2%, respectively.

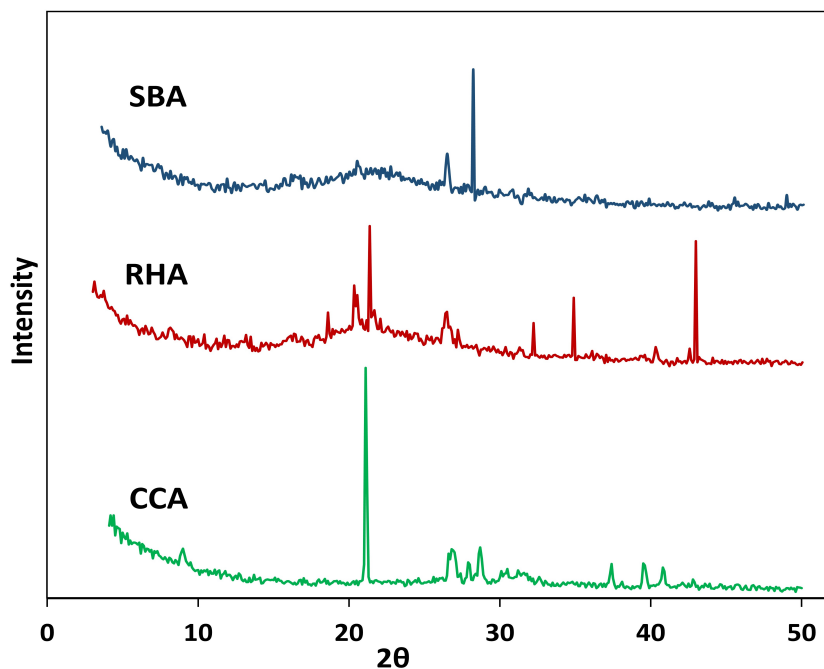


Figure 4.1. X-ray diffractogram (XRD) of sugarcane bagasse ash (SBA), rice husk ash (RHA), and corn cob ash (CCA)

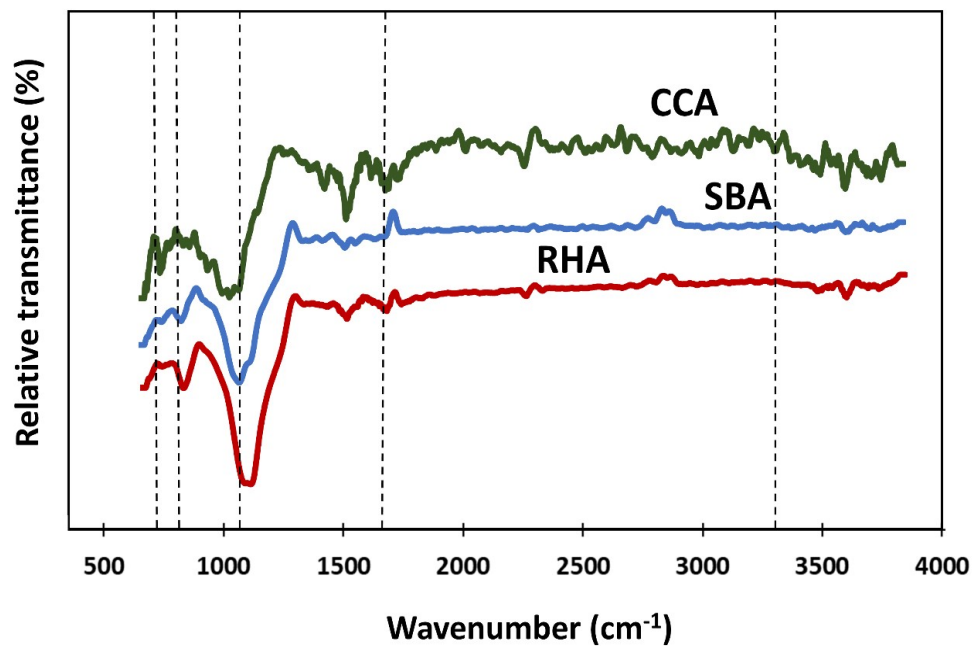


Figure 4.2. Fourier-transformed infrared (FTIR) spectra of sugarcane bagasse ash (SBA), rice husk ash (RHA), and corn cob ash (CCA)

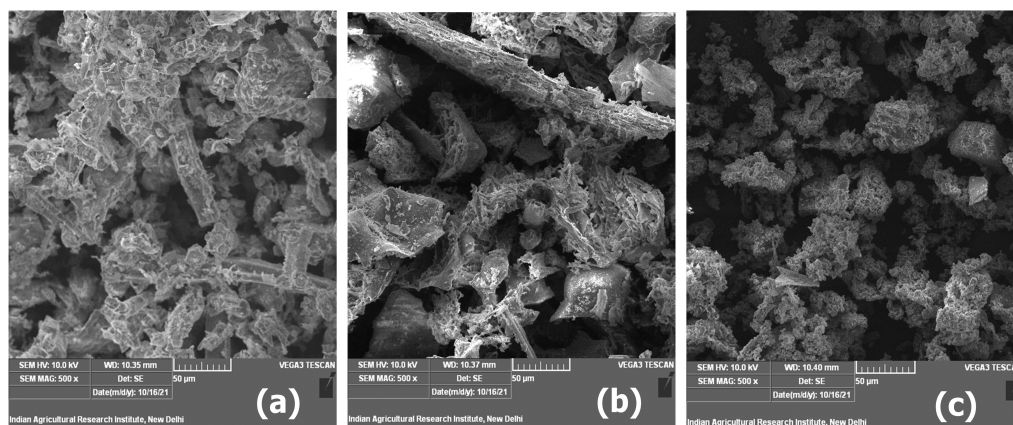


Figure 4.3. Scanning electron micrograph (SEM) of (a) sugarcane bagasse ash (SBA), (b) rice husk ash (RHA), and (c) corn cob ash (CCA) at 500X magnification

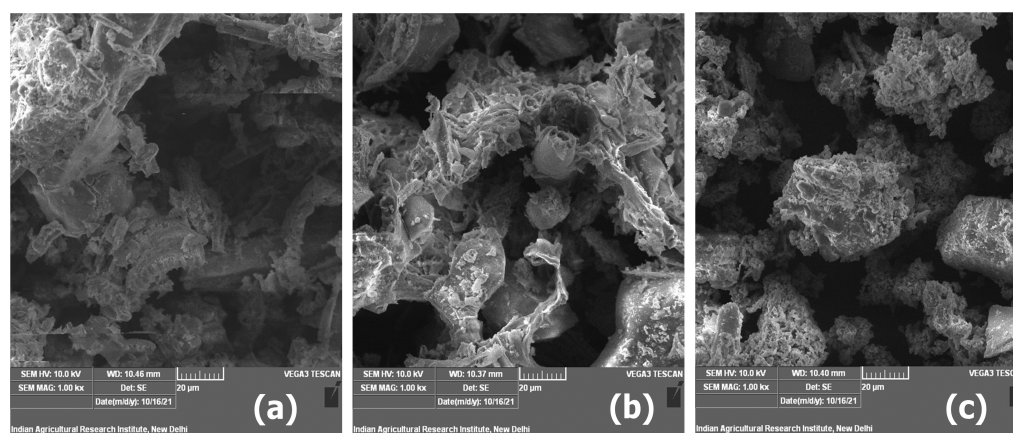


Figure 4.4. Scanning electron micrograph (SEM) of (a) sugarcane bagasse ash (SBA), (b) rice husk ash (RHA), and (c) corn cob ash (CCA) at 1000X magnification

4.2.2.3. Scanning electron microscopy (SEM)

The SEM micrographs of ash samples with 500X and 1000X magnification are shown in figures 4.3 and 4.4, respectively. The micrographs clearly show that the ash samples comprised granules of varying sizes and shapes. They were prismatic, spherical, and fibrous in shape. The prismatic particles are primarily composed of Si and O. The spherical particles are composed of Si and O, as well as a few other minor compounds. The fibrous one is entirely composed of C (Batra *et al.*, 2008). Also, some sponge-like masses can be seen, which are attributed to the presence of sub-microcrystalline masses.

4.3. Phosphorus mineralization kinetics in the Alfisol during incubation

An incubation study was conducted to assess the effect of Si-rich agro-wastes and PSM on the release of P from soils and the results are presented in figure 4.5. Soil solution P (0.01 M CaCl₂ extractable) increased significantly in 90 days due to PSM application as well as applied Si (Table 4.3). Among different Si sources, CCA maintained a significantly higher level of mean solution P (0.73 mg kg⁻¹), followed by SBA (0.69 mg kg⁻¹) and RHA (0.67 mg kg⁻¹). By and large, PSM application increased the mean solution P level by ~22.2 per cent, over no PSM treatment; whereas, Si₁₂₅ and Si₂₅₀ increased the same by ~60.4 and 77.1 per cent, respectively, over Si₀ (Figure 4.5). Interestingly, interaction of PSM×Si doses was also significant in increasing the P bioavailability in soil solution (Table 4.3). Values of k_p were similar for different Si sources. However, under PSM application, the mean k_p value was ~1.35 times greater than no PSM treatment; whereas, under Si₁₂₅ and Si₂₅₀ application, these values were ~1.11 and 5.55 times greater than Si₀, respectively.

4.4. Silicon mineralization kinetics in the Alfisol during incubation

Soluble Si increased significantly in the soil at 90 DAI with increasing doses of Si application as well as due to PSM inoculation (Table 4.3). Among the different Si sources, there was no significant difference between the mean Si solution Si level ($P < 0.05$). By and large, PSM application increased the mean solution Si level by ~10.63 per cent, over no PSM treatment; whereas, Si₁₂₅ and Si₂₅₀ increased the same by ~41.5 and 55.5 per cent, respectively, over Si₀ (Figure 4.6). Either PSM or varied Si sources could not change the mean values of k_s significantly (Table 4.3). On the other hand, under Si₁₂₅ and Si₂₅₀ application, the mean k_s values differed significantly and were ~14 and 18.1 times greater than Si₀, respectively.

4.5. Phosphorus mineralization kinetics in the Inceptisol during incubation

Soil solution P (0.01 M CaCl₂ extractable) increased significantly in 90 days due to application of PSM, doses of Si, as well as varied Si sources (Table 4.4). Among different Si sources, CCA maintained a significantly higher level of mean solution P (0.88 mg kg⁻¹), than SBA (0.83 mg kg⁻¹) and RHA (0.82 mg kg⁻¹). By and large, PSM application increased the mean solution P level by ~17.2 per cent, over no PSM treatment; whereas, Si₁₂₅ and Si₂₅₀ increased the same by ~44.3 and 57.1 per cent, respectively, over Si₀ (Figure 4.7).

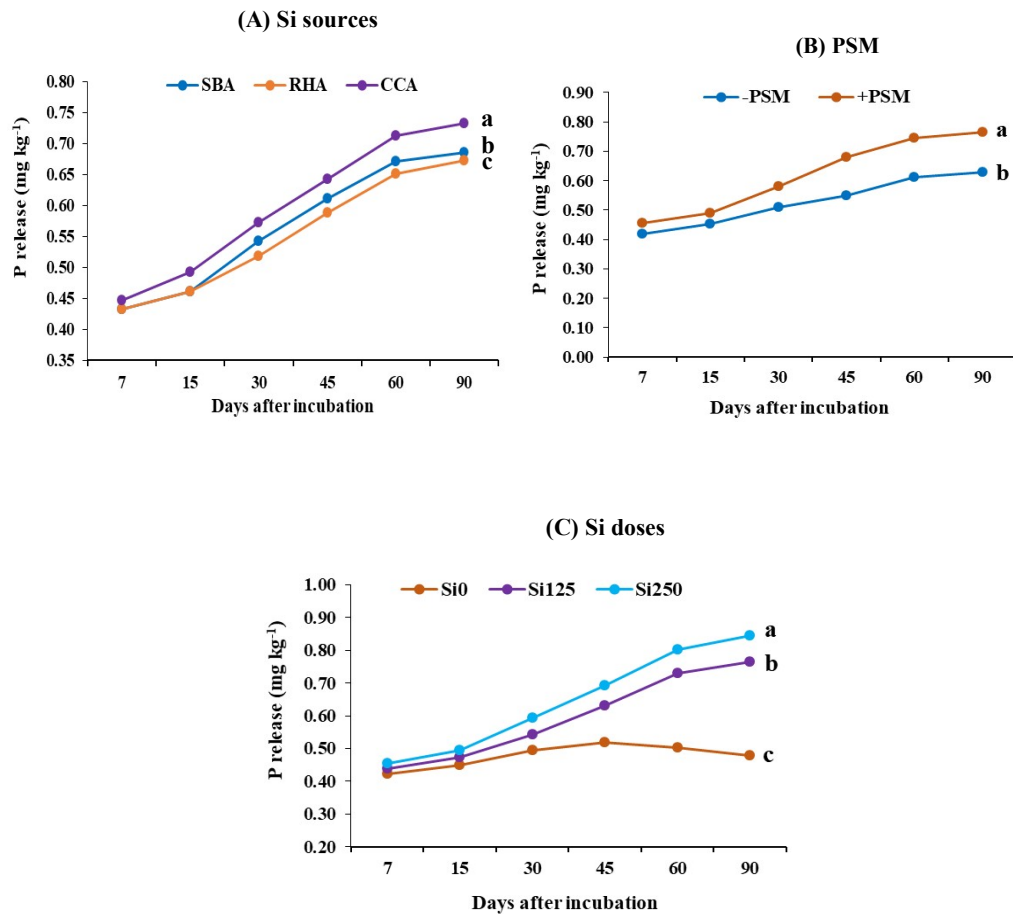


Figure 4.5. Impact of (A) Si sources, (B) phosphate solubilizing microorganism (PSM), and (C) Si doses on P release (mg kg⁻¹) pattern in Alfisol. Similar lower-case letters, in each graph, denote no significant difference between mean solution P release values at 90 days of incubation, as per Fisher's LSD test ($P < 0.05$).

SBA=Sugarcane bagasse ash; *RHA*=Rice husk ash; *CCA*=Corn cob ash

Table 4.3. Impact of silicon (Si) sources, phosphate solubilizing microorganism (PSM), and Si doses on solution phosphorus (P_{90}) (mg kg^{-1}) and silicon (Si_{90}) release kinetics in Alfisol

Treatment factors	P_{90} (mg kg^{-1})	$k_P (\times 10^{-3})$	Si_{90} (mg kg^{-1})	$k_S (\times 10^{-1})$
<i>Silicon (Si) sources</i>				
SBA	0.69b	5.51a	48.3a	1.51a
RHA	0.67c	5.25a	48.0a	1.51a
CCA	0.73a	5.66a	49.0a	1.51a
<i>Phosphate solubilizing microorganism (PSM)</i>				
-PSM	0.63b	4.65b	44.2b	1.48a
+PSM	0.77a	6.30a	48.9a	1.54a
<i>Silicon (Si) doses</i>				
Si_0	0.48c	1.42c	36.6c	0.14c
Si_{125}	0.77b	7.12b	51.8b	1.92b
Si_{250}	0.85a	7.88a	56.9a	2.47a
<i>Significant interaction(s)</i>				
<i>LSD ($P = 0.05$)</i>	<i>PSM $\times$ Si doses = 0.019</i>	<i>All interactions are NS*</i>	<i>PSM $\times$ Si doses = 0.61</i>	<i>All interactions are NS*</i>

SBA=Sugarcane bagasse ash; RHA=Rice husk ash; CCA=Corn cob ash; *NS = Non-significant, P_{90} = total solution P at 90 days of incubation, Si_{90} = total soluble Si at 90 days of incubation, k_P = release rate constant of solution P, k_S = release rate constant of soluble Si

**Values in each column with no common lower-case letters indicate significant difference according to Fisher's LSD test ($P < 0.05$).

Further, interaction of PSM $\times$ Si dose was also significant in increasing the P bioavailability in soil solution (Table 4.4). Among the different Si sources, the rate of P release (k_P) from CCA was ~ 5.92 and 12.6 per cent higher than SBA and RHA, respectively (Table 4.4). However, under PSM application, the mean k_P value was ~ 1.38 times greater than that of no PSM treatment; whereas, under Si_{125} and Si_{250} application, these values were ~ 4.10 and 4.64 times greater than that of Si_0 , respectively (Table 4.4).

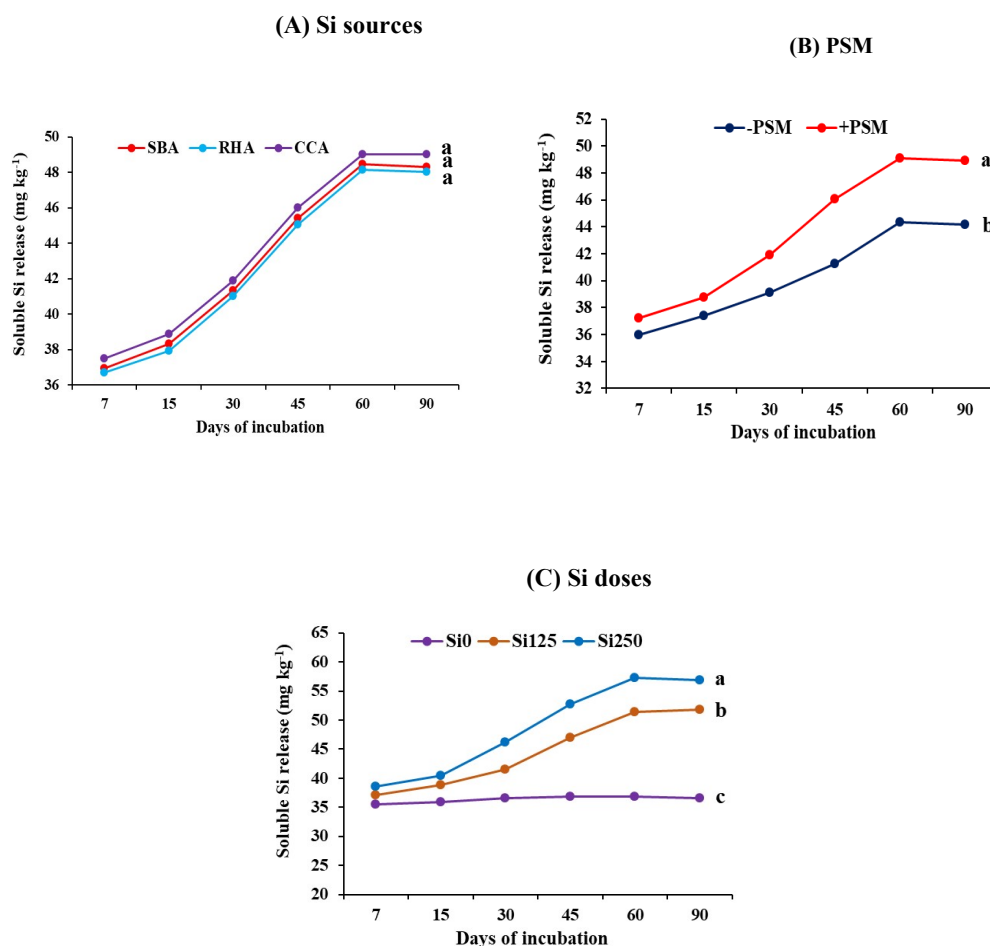


Figure 4.6. Impact of (A) Si sources, (B) phosphate solubilizing microorganism (PSM), and (C) Si doses on soluble Si release (mg kg⁻¹) pattern in Alfisol. Similar lower-case letters, in each graph, denote no significant difference between mean soluble Si release values at 90 days of incubation, as per Fisher's LSD test ($P < 0.05$).

SBA=Sugarcane bagasse ash; *RHA*=Rice husk ash; *CCA*=Corn cob ash

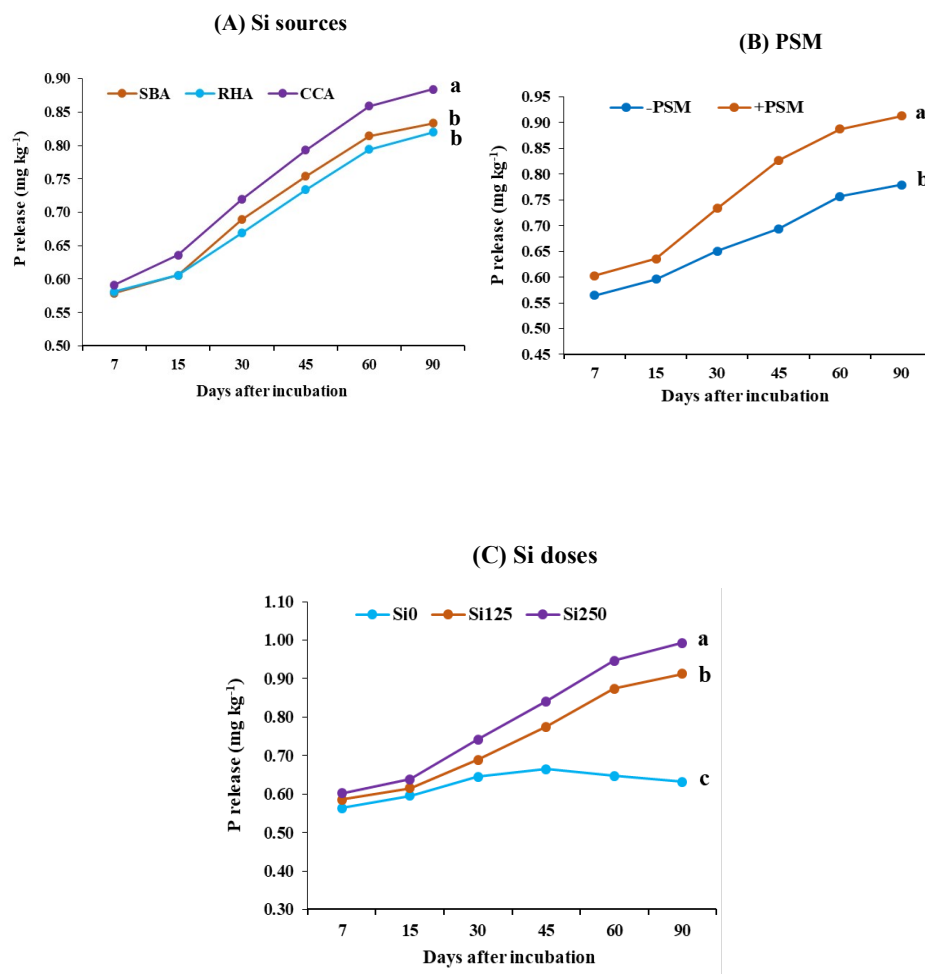


Figure 4.7. Impact of (A) Si sources, (B) phosphate solubilizing microorganism (PSM), and (C) Si doses on P release (mg kg⁻¹) pattern in Inceptisol. Similar lower-case letters, in each graph, denote no significant difference between mean solution P release values at 90 days of incubation, as per Fisher's LSD test ($P < 0.05$).

SBA=Sugarcane bagasse ash; *RHA*=Rice husk ash; *CCA*=Corn cob ash

Table 4.4. Impact of silicon (Si) sources, phosphate solubilizing microorganism (PSM) and Si doses on solution phosphorus (P_{90}) (mg kg^{-1}) and silicon (Si_{90}) release kinetics in Inceptisol

Treatment factors	P_{90} (mg kg^{-1})	$k_P (\times 10^{-3})$	Si_{90} (mg kg^{-1})	$k_S (\times 10^{-1})$
<i>Silicon (Si) sources</i>				
SBA	0.83b	7.60ab	55.9a	1.23a
RHA	0.82b	7.15b	55.7a	1.21a
CCA	0.88a	8.05a	56.5a	1.26a
<i>Phosphate solubilizing microorganism (PSM)</i>				
-PSM	0.78b	6.39b	52.6b	1.20a
+PSM	0.91a	8.81a	56.4a	1.26a
<i>Silicon (Si) doses</i>				
Si_0	0.63c	2.34c	43.1c	0.12c
Si_{125}	0.91b	9.60b	59.9b	1.48b
Si_{250}	0.99a	10.86a	65.0a	2.10a
<i>Significant interaction(s)</i>				
<i>LSD ($P = 0.05$)</i>	<i>PSM $\times$ Si doses = 0.022</i>	<i>All interactions are NS*</i>	<i>PSM $\times$ Si doses = 0.52</i>	<i>All interactions are NS*</i>

SBA = Sugarcane bagasse ash; RHA = Rice husk ash; CCA = Corn cob ash; *NS = Non-significant, P_{90} = total solution phosphorus at 90 days of incubation, Si_{90} = total soluble silicon at 90 days of incubation, k_P = release rate constant of solution P, k_S = release rate constant of soluble Si

**Values in each column with no common lower-case letters indicate significant difference at $P < 0.05$, according to Fisher's LSD test.

4.6. Silicon mineralization kinetics in the Inceptisol during incubation

Soluble Si increased significantly in the soil at 90 DAI with increasing dose of Si application as well as due to PSM inoculation (Table 4.4). Among the different Si sources, there was no significant difference between the mean Si solution Si level ($P < 0.05$). By and large, PSM application increased the mean solution Si level by ~7.22 per cent, over no PSM treatment; whereas, Si_{125} and Si_{250} increased the same by ~39.0 and 50.8 per cent, respectively, over Si_0 (Figure 4.8). There was no significant

difference in the release rate of Si (k_s) among the different Si sources (ashes). However, PSM application increased the k_s value by ~5 per cent, over no inoculation. On the other hand, under Si_{125} and Si_{250} applications, the mean k_s values were ~12.3 and 17.5 times that of Si_0 , respectively (Table 4.4).

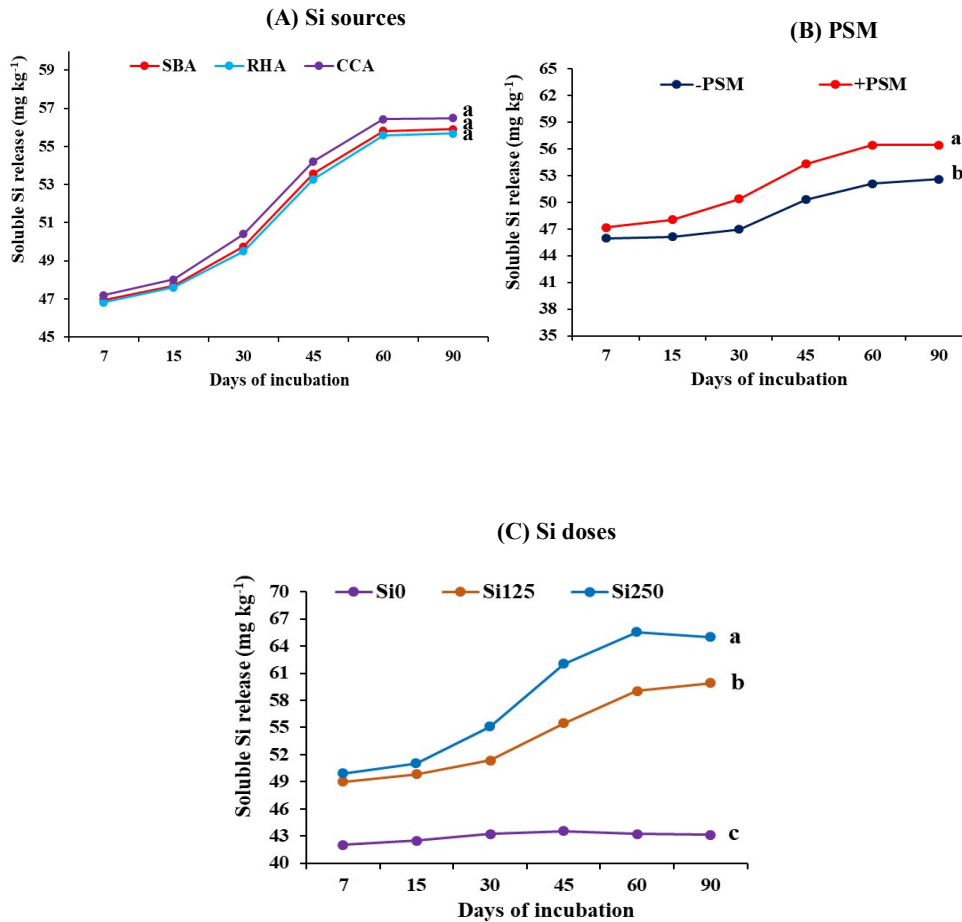


Figure 4.8. Impact of (A) Si sources, (B) phosphate solubilizing microorganism (PSM), and (C) Si doses on soluble Si release (mg kg⁻¹) pattern in Inceptisol. Similar lower-case letters, in each graph, denote no significant difference between mean soluble Si release values at 90 days of incubation, as per Fisher's LSD test ($P < 0.05$).

SBA=Sugarcane bagasse ash; *RHA*=Rice husk ash; *CCA*=Corn cob ash

4.7. Adsorption-desorption behaviour of P in soils as impacted by Si-rich agro-wastes after 90 days of incubation

4.7.1. Phosphorus adsorption

The amount of P adsorbed (x) at different concentrations of added P solutions in the case of Alfisol and Inceptisol are presented in figures 4.9(A) and 4.9(B), respectively. The adsorption data (c vs x) were best fitted in second-order polynomial equations in both soils. The graphs suggest that the amount of P adsorption decreased significantly due to the application of Si-rich agro-wastes, with respect to untreated control. Among different treatments, the application of CCA to supply 250 mg Si kg⁻¹ soil, caused the maximum decrement in the amount of P adsorbed, in both soils. Different P adsorption parameters were calculated and the data were fitted to the linear forms of the Freundlich and Langmuir equations for better understanding.

4.7.2. Langmuir adsorption isotherm

Different Langmuir adsorption parameters as impacted by Si-rich ashes in Alfisol and Inceptisol are presented in tables 4.5 and 4.6, respectively. The mean values of prediction coefficients (r²) ranged from 0.95 to 0.97 for Alfisol, whereas it ranged from 0.97 to 0.99 for Inceptisol, suggesting an excellent fit of the adsorption data to Langmuir isotherm in both soils. By and large, the values of the adsorption maxima 'b' in Alfisol were 2-3 times that of the values of 'b' in Inceptisol. In the case of Alfisol, the adsorption maxima 'b' varied from 454.5 mg kg⁻¹ in CCA (at the rate of 250 mg Si kg⁻¹ soil) treatment to 666.7 mg kg⁻¹ in control (Table 4.5).

Table 4.5. Different Langmuir adsorption parameters as impacted by Si-rich agro-wastes in Alfisol

Treatment	r ²	b (mg kg ⁻¹)	k (L mg ⁻¹)	MPBC (mL g ⁻¹)
Control	0.96	666.7a	0.18a	120.0a
SBA @ 250 mg kg ⁻¹ Si	0.97	526.3b	0.16b	84.7b
RHA @ 250 mg kg ⁻¹ Si	0.96	555.6b	0.16b	89.4b
CCA @ 250 mg kg ⁻¹ Si	0.95	454.5c	0.15c	69.1c

***Values in each column with no common lower-case letters indicate a significant difference at P<0.05, according to Fisher's LSD test.*

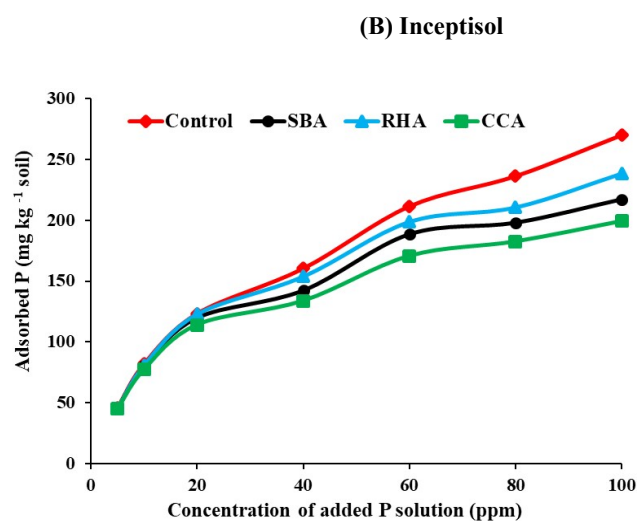
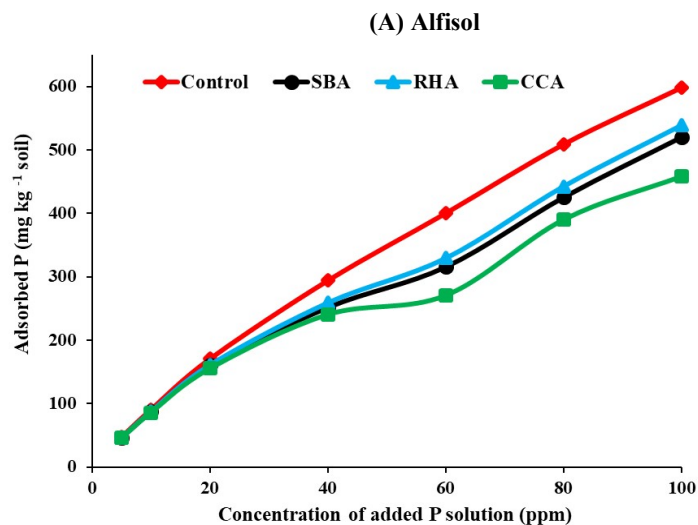


Figure 4.9. Adsorbed P (mg kg⁻¹ soil) at different concentrations of added P solution as impacted by Si-rich agro-wastes in (A) Alfisol and (B) Inceptisol

**Treatment details:*

Control= untreated control, SBA= application of sugarcane bagasse ash containing 250 mg Si kg⁻¹ soil, RHA= application of rice husk ash containing 250 mg Si kg⁻¹ soil, CCA= application of corn cob ash containing 250 mg Si kg⁻¹ soil

In the case of Inceptisol, ‘b’ varied from 196.1 mg kg⁻¹ in the case of CCA (at the rate of 250 mg Si kg⁻¹ soil) treatment to 227.3 mg kg⁻¹ in control (Table 4.6). Therefore, it is evident from the data that the application of Si-rich agro-wastes significantly reduced the adsorption maxima in both soils. The affinity coefficient *i.e.* the bonding energy coefficient ‘k’ also reduced significantly due to the application of Si-rich agro-wastes. However, among the ashes, mostly there were no significant differences between the ‘k’ values. The ‘k’ values ranged from 0.15 to 0.18 in the case of Alfisol, and from 0.13 to 0.15 in the case of Inceptisol. In the case of Alfisol, maximum phosphate buffering capacity (MPBC) values assorted between 120.0 mL g⁻¹ in control to 69.1 mL g⁻¹ in the treatment containing CCA in terms of 250 mg Si kg⁻¹ soil (Table 4.5). In the case of Inceptisol, the MPBC values assorted between 34.1 mL g⁻¹ in control to 25.5 mL g⁻¹ in the CCA treatment (Table 4.6). Here also, it was clear that the application of Si-rich agro-wastes resulted in a significantly reduced value of MPBC than the untreated control, in both soils.

Table 4.6. Different Langmuir adsorption parameters as impacted by Si-rich agro-wastes in Inceptisol

Treatment	r ²	b (mg kg ⁻¹)	k (L mg ⁻¹)	MPBC (mL g ⁻¹)
Control	0.97	227.3a	0.15a	34.1a
SBA @ 250 mg kg ⁻¹ Si	0.99	204.1b	0.13b	26.5b
RHA @ 250 mg kg ⁻¹ Si	0.97	208.3b	0.13b	27.1b
CCA @ 250 mg kg ⁻¹ Si	0.98	196.1b	0.13b	25.5b

***Values in each column with no common lower-case letters indicate a significant difference at P<0.05, according to Fisher’s LSD test.*

4.7.3. Freundlich adsorption isotherm

Phosphorus adsorption data were also fitted to the linearized Freundlich equation (log c vs log x). Different Freundlich adsorption parameters as impacted by Si-rich ashes in Alfisol and Inceptisol are presented in tables 4.7 and 4.8, respectively. The mean r² values ranged from 0.93 to 0.97 for Alfisol, whereas it ranged from 0.92 to 0.96 for Inceptisol, suggesting an excellent fit of the adsorption data to Freundlich isotherm in both soils. In the case of Alfisol, adsorption parameter ‘a’ varied from 95.9 in untreated control to 71.9 in the treatment containing CCA in terms of 250 mg Si kg⁻¹ soil (Table 4.7).

Table 4.7. Different Freundlich adsorption parameters as impacted by Si-rich agro-wastes in Alfisol

Treatment	r^2	a	1/n
Control	0.93	95.9a	0.49a
SBA @ 250 mg kg ⁻¹ Si	0.97	77.9b	0.46b
RHA @ 250 mg kg ⁻¹ Si	0.96	79.1b	0.47ab
CCA @ 250 mg kg ⁻¹ Si	0.95	71.9c	0.44b

***Values in each column with no common lower-case letters indicate a significant difference at $P < 0.05$, according to Fisher's LSD test.*

In the case of Inceptisol, the 'a' value assorted between 64.8 in control to 55.3 in the CCA treatment (Table 4.8). It was obvious that the application of Si-rich agro-wastes resulted in a significantly reduced value of the adsorption parameter 'a', in both soils. The values of another adsorption parameter '1/n' also decreased significantly due to Si application in both the soils. The '1/n' values ranged from 0.44 to 0.49 in the case of Alfisol, and from 0.28 to 0.33 in the case of Inceptisol.

Table 4.8. Different Freundlich adsorption parameters as impacted by Si-rich agro-wastes in Inceptisol

Treatment	r^2	a	1/n
Control	0.96	64.8a	0.33a
SBA @ 250 mg kg ⁻¹ Si	0.94	59.9b	0.29c
RHA @ 250 mg kg ⁻¹ Si	0.93	60.7ab	0.31b
CCA @ 250 mg kg ⁻¹ Si	0.92	55.3c	0.28c

***Values in each column with no common lower-case letters indicate a significant difference at $P < 0.05$, according to Fisher's LSD test.*

4.7.4. Phosphorus desorption

The amount of P desorbed at different concentrations of added P solutions in the case of Alfisol and Inceptisol are presented in figures 4.10(A) and 4.10(B), respectively. The desorption data were best fitted in second-order polynomial equations in both soils. The graphs suggest that the amount of P desorption increased significantly due to the application of Si-rich agro-wastes, with respect to untreated control. Among

different treatments, CCA at the rate of 250 mg Si kg⁻¹ soil, caused the maximum increment in the amount of P adsorbed, in both soils. The amount of desorbed P, expressed as a percentage of the adsorbed P, at different concentrations of added P, in Alfisol and Inceptisol are presented in tables 4.9 and 4.10, respectively.

Table 4.9. Desorbed P (%) as a percentage of the adsorbed P, at different concentrations of added P, as impacted by Si-rich agro-wastes in Alfisol

Treatment	Concentrations of added P						
	5 ppm	10 ppm	20 ppm	40 ppm	60 ppm	80 ppm	100 ppm
Control	8.15c	8.73c	7.41c	5.11c	4.75d	4.10d	4.18d
SBA @ 250 mg kg ⁻¹ Si	10.64b	11.54b	10.30b	7.71b	8.02b	6.47b	7.48b
RHA @ 250 mg kg ⁻¹ Si	10.39b	11.26b	10.02b	7.33b	7.16c	5.91c	6.84c
CCA @ 250 mg kg ⁻¹ Si	11.51a	12.55a	11.32a	8.65a	10.12a	7.69a	9.20a

***Values in each column with no common lower-case letters indicate a significant difference at $P<0.05$, according to Fisher's LSD test.*

Table 4.10. Desorbed P (%) as a percentage of the adsorbed P, at different concentrations of added P, as impacted by Si-rich agro-wastes in Inceptisol

Treatment	Concentrations of added P						
	5 ppm	10 ppm	20 ppm	40 ppm	60 ppm	80 ppm	100 ppm
Control	11.77b	13.02b	14.06c	13.97d	12.31d	11.53d	10.94d
SBA @ 250 mg kg ⁻¹ Si	13.17a	15.08a	16.39ab	17.76b	15.44b	15.77b	18.40b
RHA @ 250 mg kg ⁻¹ Si	12.13b	13.92b	15.36b	15.59c	13.89c	14.06c	15.90c
CCA @ 250 mg kg ⁻¹ Si	13.45a	15.87a	17.44a	19.41a	17.48a	17.53a	20.49a

***Values in each column with no common lower-case letters indicate a significant difference at $P<0.05$, according to Fisher's LSD test.*

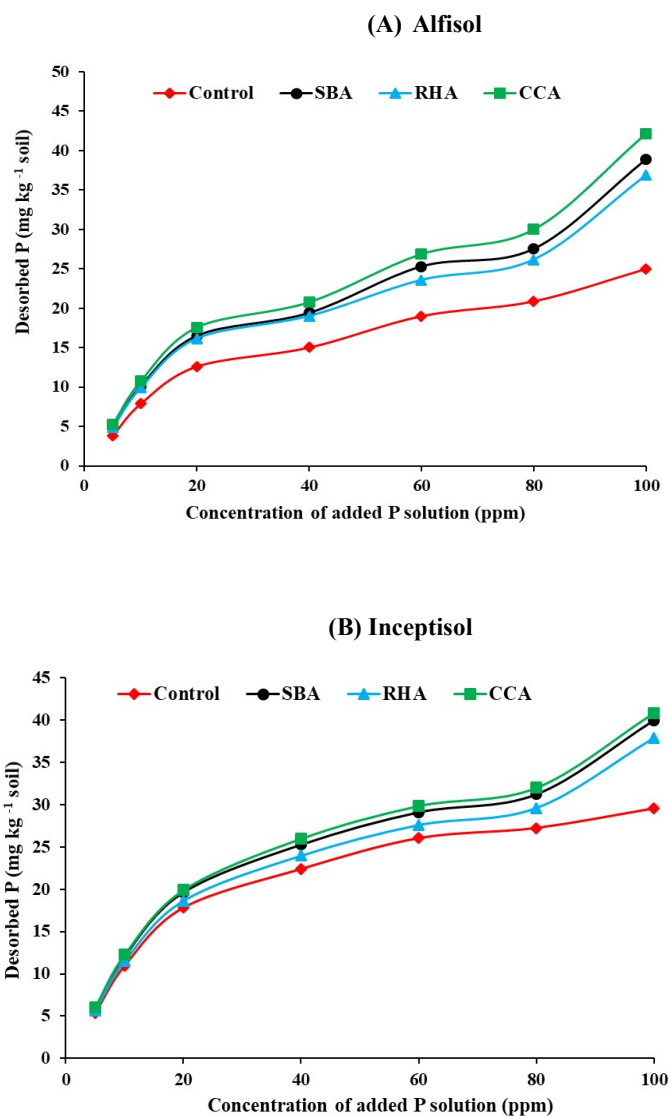


Figure 4.10. Desorbed P (mg kg^{-1} soil) at different concentrations of added P solution as impacted by Si-rich agro-wastes in (A) Alfisol and (B) Inceptisol.

**Treatment details:*

Control= untreated control, SBA= application of sugarcane bagasse ash containing $250 \text{ mg Si kg}^{-1}$ soil, RHA= application of rice husk ash containing $250 \text{ mg Si kg}^{-1}$ soil, CCA= application of corn cob ash containing $250 \text{ mg Si kg}^{-1}$ soil.

In Alfisol, the amount of P desorbed ranged from 4.10% to 12.55% of the adsorbed P. On the other hand, in Inceptisol, the amount of desorbed P ranged from 10.94% to 20.49% of the P adsorbed, at different concentrations of added P solutions. Therefore,

it was evident that the desorption of P, adsorbed to soil solid phase, was much higher in Inceptisol than that of Alfisol.

The hysteresis index (H) values (%) of different treatments in Alfisol and Inceptisol is presented in figures 4.11(A) and 4.11(B), respectively. In Alfisol, hysteresis index varied from 87.5% in control to 81.9% in the treatment containing CCA at 250 mg Si kg⁻¹ soil. On the other hand, in Inceptisol, hysteresis index varied from 95.2% in control to 90.7% in the treatment containing CCA at 250 mg Si kg⁻¹ soil.

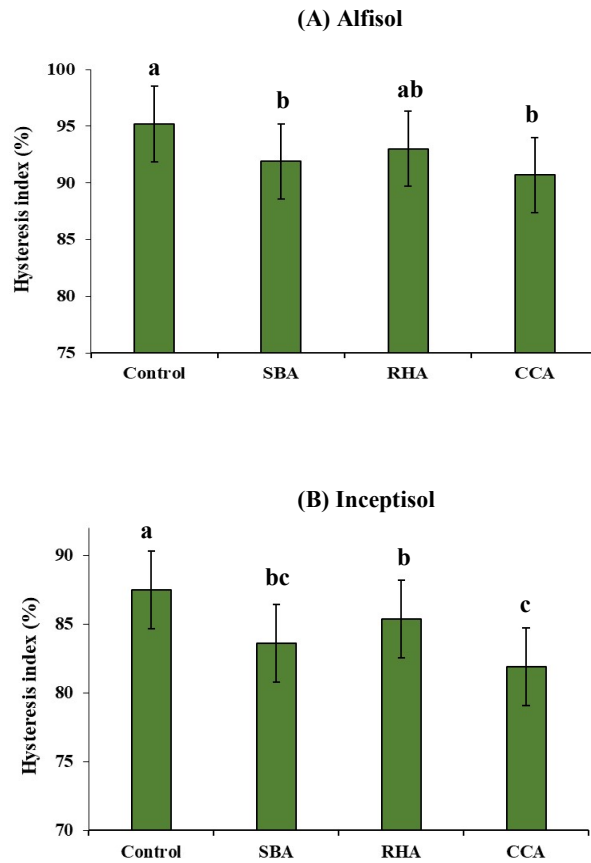


Figure 4.11. Hysteresis index (%) as impacted by Si-rich agro-wastes in (A) Alfisol and (B) Inceptisol. Similar lower-case letters, in each graph, denote no significant difference between mean values, as per Fisher's LSD test ($P < 0.05$).

**Treatment details:*

Control = untreated control, SBA = application of sugarcane bagasse ash containing 250 mg Si kg⁻¹ soil, RHA = application of rice husk ash containing 250 mg Si kg⁻¹ soil, CCA = application of corn cob ash containing 250 mg Si kg⁻¹ soil.

4.8. Available P status in the post-harvest soil samples of Alfisol

4.8.1. Available P status after the harvest of wheat

Data on the available P (Bray-1 extractable P) status of soil samples after the harvest of wheat are presented in figure 4.12(A) and table 4.11.

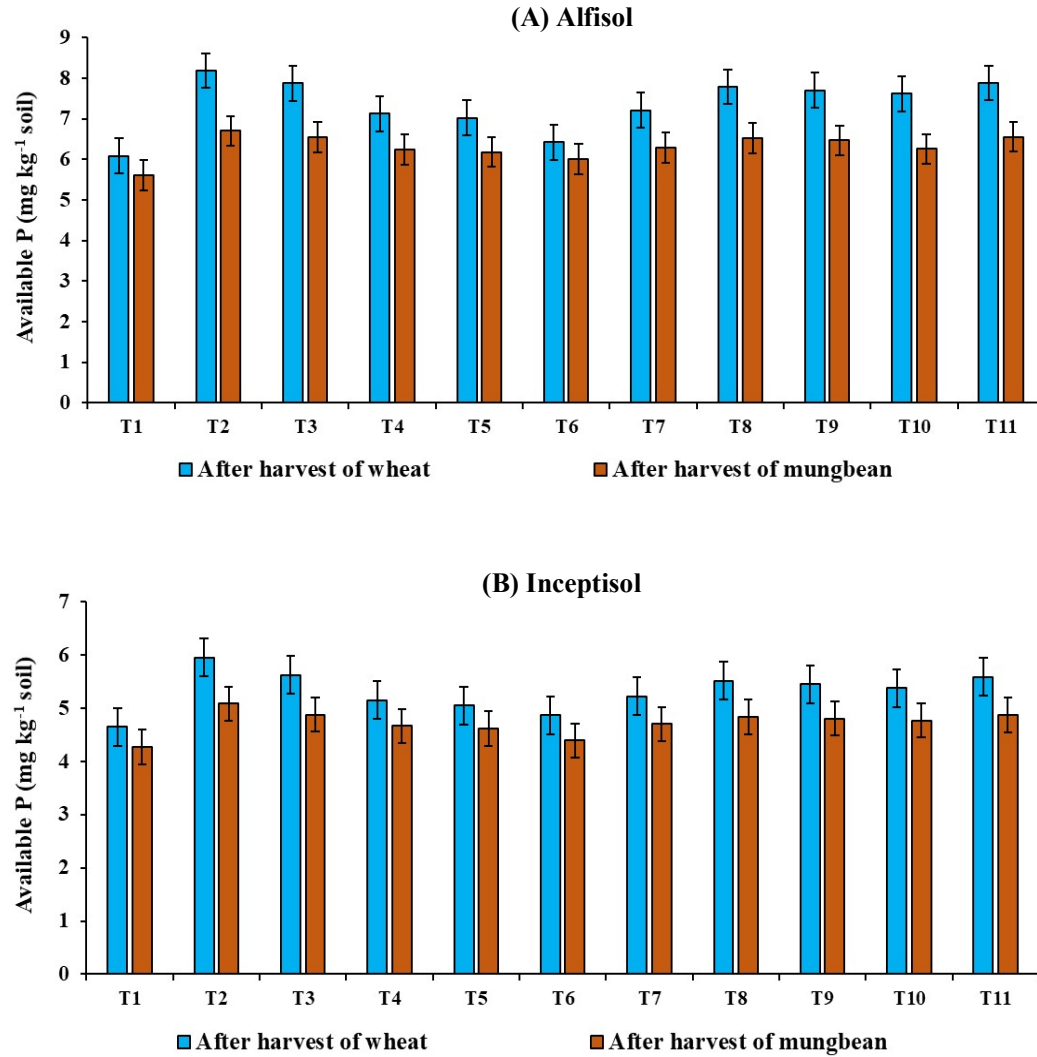


Figure 4.12. Available P (mg kg⁻¹) in soil after the harvest of wheat and mungbean crops as impacted by different treatments in (A) Alfisol and (B) Inceptisol. Error bars indicate LSD values ($P < 0.05$).

****T1** = Control (no P), **T2** = 100% P, **T3** = 75% P, **T4** = SBA @Si₂₅₀ + PSM, **T5** = RHA @Si₂₅₀ + PSM, **T6** = CCA@Si₁₂₅ + PSM, **T7** = CCA@Si₂₅₀ + PSM, **T8** = SBA @Si₂₅₀ + PSM + 50% P, **T9** = RHA @Si₂₅₀ + PSM + 50% P, **T10** = CCA @Si₁₂₅ + PSM + 50% P, **T11** = CCA @Si₂₅₀ + PSM + 50% P

Table 4.11. Available P (mg kg⁻¹) as impacted by different combinations of Si-rich agro-wastes, PSM and P fertilization in Alfisol and Inceptisol

Treatment	Available P (mg kg ⁻¹) in Alfisol		Available P (mg kg ⁻¹) in Inceptisol	
	After harvest of wheat	After harvest of mungbean	After harvest of wheat	After harvest of mungbean
Control	6.08e	5.61e	4.65g	4.27d
100% P	8.18a	6.70a	5.95a	5.09a
75% P	7.87ab	6.55abc	5.62ab	4.88ab
SBA@Si ₂₅₀ +PSM	7.12d	6.24bcd	5.15def	4.66bc
RHA@Si ₂₅₀ +PSM	7.02d	6.18cd	5.05ef	4.62bc
CCA@Si ₁₂₅ +PSM	6.42e	6.01d	4.87fg	4.39cd
CCA@Si ₂₅₀ +PSM	7.21cd	6.28bcd	5.22cdef	4.70bc
SBA@Si ₂₅₀ +PSM+50%P	7.78ab	6.52abc	5.52bc	4.83ab
RHA@Si ₂₅₀ +PSM+50%P	7.70b	6.47abc	5.45bcd	4.80ab
CCA@Si ₁₂₅ +PSM+50%P	7.62bc	6.26bcd	5.38bcde	4.77ab
CCA@Si ₂₅₀ +PSM+50%P	7.88ab	6.55ab	5.59b	4.87ab

***Values in each column with no common lower-case letters indicate a significant difference at $P < 0.05$, according to Fisher's LSD test.*

The results showed that the soil after the harvest of wheat maintained the available P status in the low range. An application of 100% and 75% of the recommended doses of P, resulted in ~34.5% and ~29.4% increase in available P, over no P application (control), respectively. The treatments, namely: (SBA @Si₂₅₀+PSM), (RHA @Si₂₅₀+PSM), and (CCA @Si₂₅₀+PSM) significantly increased the available P (over no P application), and the values were statistically at par with each other. The treatments (CCA @Si₂₅₀+PSM+50%P) and (SBA @Si₂₅₀+PSM+50%P) increased the available P in the post-harvest soils to such an extent that was statistically at par with that of 75% P treatment.

4.8.2. Available P status after the harvest of mungbean

Data on the available P (Bray-1 extractable P) status of soil samples after the harvest of mungbean are presented in figure 4.12.A and table 4.11. The results showed that the soil after the harvest of mungbean maintained the available P status in the low range. Treatments namely, SBA@Si₂₅₀+PSM+50%P, RHA@Si₂₅₀+PSM+50%P, and CCA@Si₂₅₀+PSM+50%P exhibited good residual effects of the applied ashes; and the available P status of the post-harvest soils of these treatments was statistically at par with that of the 100% P treatment. The treatments namely, SBA@Si₂₅₀+PSM, RHA@Si₂₅₀+PSM and CCA@Si₂₅₀+PSM also significantly increased the available P over no P application (control); however, the increase was lesser than that of the previously-mentioned treatments (T8, T9 and T11).

4.9. Available P status in the post-harvest soil samples of Inceptisol

4.9.1. Available P status after the harvest of wheat

Data on the available P (Olsen-P) status of soil samples after the harvest of wheat are presented in figure 4.12(B) and table 4.11. The results showed that the soil after the harvest of wheat maintained the available P status in the marginally medium range. An application of 100% and 75% of the recommended doses of P, resulted in ~28.0% and ~20.9% increase in available P, over no P application (control). The treatments namely- (SBA @Si₂₅₀+PSM), (RHA @Si₂₅₀+PSM), and (CCA @Si₂₅₀+PSM) significantly increased the available P (over no P application), and the values were statistically at par with each other. The treatments, namely: (SBA @Si₂₅₀+PSM+50%P), (RHA @Si₂₅₀+PSM+50%P), and (CCA @Si₂₅₀+PSM+50%P) increased the available P in the post-harvest soils to such an extent that was statistically at par with that of 75% P treatment.

4.9.2. Available P status after the harvest of mungbean

Data on the available P (Olsen-P) status of soil samples after the harvest of mungbean are presented in figure 4.12(B) and table 4.11. The results showed that the soil after the harvest of mungbean maintained the available P status in the marginally medium range. The treatments namely, SBA@Si₂₅₀+PSM+50%P, RHA@Si₂₅₀+PSM+50%P, and CCA@Si₂₅₀+PSM+50%P exhibited good residual effects RHA@Si₂₅₀+PSM, and CCA@Si₂₅₀+PSM also significantly increased the available P over no P application (control); however, the increase was lesser than that of the previously-mentioned treatments (T8, T9, and T11).

4.10. Available Si status in the post-harvest soil samples of Alfisol

4.10.1. Available Si status after the harvest of wheat

Data on the available Si (0.01 M CaCl₂-extractable) status of soil samples after the harvest of wheat are presented in figure 4.13(A) and table 4.12.

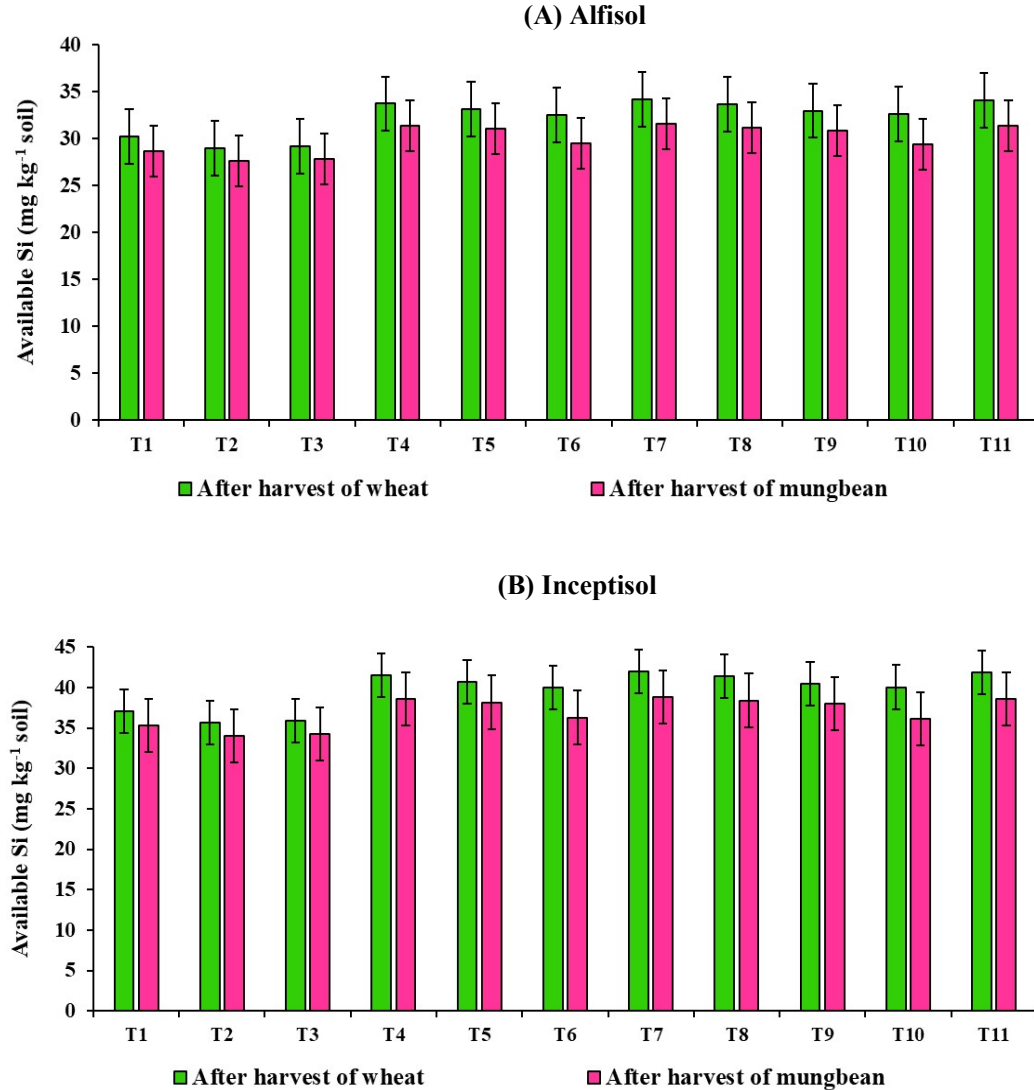


Figure 4.13. Available Si (mg kg⁻¹) in soil after the harvest of wheat and mungbean crops as impacted by different treatments in (A) Alfisol and (B) Inceptisol. Error bars indicate LSD values ($P < 0.05$).

****T1** = Control (no P), **T2** = 100% P, **T3** = 75% P, **T4** = SBA @Si₂₅₀ + PSM, **T5** = RHA @Si₂₅₀ + PSM, **T6** = CCA@Si₁₂₅ + PSM, **T7** = CCA@Si₂₅₀ + PSM, **T8** = SBA @Si₂₅₀ + PSM + 50% P, **T9** = RHA @Si₂₅₀ + PSM + 50% P, **T10** = CCA @Si₁₂₅ + PSM + 50% P, **T11** = CCA @Si₂₅₀ + PSM + 50% P

Table 4.12. Available Si (mg kg⁻¹) as impacted by different combinations of Si-rich agro-wastes, PSM and P fertilization in Alfisol and Inceptisol

Treatment	Available Si (mg kg ⁻¹) in Alfisol		Available Si (mg kg ⁻¹) in Inceptisol	
	After	After	After	After
	harvest of wheat	harvest of mungbean	harvest of wheat	harvest of mungbean
Control	30.23bc	28.70bc	37.10b	35.30bc
100% P	28.97c	27.63c	35.63b	34.01c
75% P	29.20c	27.83c	35.90b	34.23c
SBA @Si ₂₅₀ + PSM	33.73a	31.37ab	41.47a	38.57ab
RHA @Si ₂₅₀ + PSM	33.13a	31.03ab	40.70a	38.17ab
CCA @Si ₁₂₅ + PSM	32.50ab	29.47abc	39.93a	36.27abc
CCA @Si ₂₅₀ + PSM	34.19a	31.57a	42.00a	38.80a
SBA @Si ₂₅₀ + PSM +50%P	33.67a	31.17ab	41.37a	38.37ab
RHA @Si ₂₅₀ + PSM +50%P	32.97ab	30.87ab	40.47a	37.97ab
CCA @Si ₁₂₅ + PSM +50%P	32.60ab	29.37abc	40.03a	36.10abc
CCA @Si ₂₅₀ + PSM +50%P	34.10a	31.37ab	41.87a	38.57ab

***Values in each column with no common lower-case letters indicate a significant difference at $P < 0.05$, according to Fisher's LSD test.*

In the treatments containing no exogenous Si application (T1, T2, and T3), the available Si content in soil was the lowest. In the treatments, where exogenous Si application was there in terms of 250 mg Si kg⁻¹ soil (T4 to T11), the available Si contents in soil samples were significantly higher than in the rest three treatments (T1, T2, and T3). The available Si contents in the treatments ranging from T4 to T11 were statistically at par with each other.

4.10.2. Available Si status after the harvest of mungbean

Data on the available Si (0.01 M CaCl₂-extractable) status of soil samples after the harvest of mungbean are presented in figure 4.13(A) and table 4.12. In the treatments containing no exogenous Si application (T1, T2, and T3), the available Si content in soil was the lowest. In the treatments, where exogenous Si application was there through different ashes (T4 to T11), good residual effects of the applied ashes were

observed; and the available Si contents in soil samples of these treatments were significantly higher than in the rest three treatments (T1, T2, and T3). However, the available Si contents in the treatments ranging from T4 to T11 were statistically at par with each other.

4.11. Available Si status in the post-harvest soil samples of Inceptisol

4.11.1. Available Si status after the harvest of wheat

Data on the available Si (0.01 *M* CaCl₂-extractable) status of soil samples after the harvest of wheat are presented in figure 4.13(B) and table 4.12. In the treatments containing no exogenous Si application (T1, T2 and T3), the available Si content in soil was the lowest. In the treatments, where exogenous Si application was there in terms of 250 mg Si kg⁻¹ soil (T4 to T11), the available Si contents in soil samples contents in the treatments ranging from T4 to T11 were statistically at par with each other.

4.11.2. Available Si status after the harvest of mungbean

Data on the available Si (0.01 *M* CaCl₂-extractable) status of soil samples after the harvest of mungbean are presented in figure 4.13(B) and table 4.12. In the treatments containing no exogenous Si application (T1, T2 and T3), the available Si content in soil was the lowest. In the treatments, where exogenous Si application was there through different ashes (T4 to T11), good residual effects of the applied ashes were observed. The available Si contents in soil samples of the treatments T4, T5, T7, T8, T9 and T11 were statistically at par with each other, and the values were significantly higher than the rest other treatments (T1, T2, T3, T6 and T10).

4.12. Evaluation of the effectiveness of Si-rich ashes and PSM to supply P to wheat and mungbean crops

4.12.1. Yield of wheat

4.12.1.1. Yield of wheat in Alfisol

Data on the straw, grain, and total yield of wheat (g pot⁻¹) as impacted by the combined application of P fertilizer, Si-rich ashes and PSM are presented in table 4.13. The results showed that the no P treatment (control) had the lowest straw (8.15 g pot⁻¹), grain (5.29 g pot⁻¹), as well as total yield (13.44 g pot⁻¹) of wheat, which were significantly different from the rest of the other treatments, respectively. Application of 100% RDP along with full doses of N and K, *i.e.*, treatment T2 produced the

numerical highest straw (10.22 g pot⁻¹), grain (6.69 g pot⁻¹), and total yield (16.91 g pot⁻¹) of wheat. Combined application of 250 mg Si kg⁻¹ soil through ashes, PSM, and 50% P fertilizer (treatments T8, T9, and T11) resulted in the straw, grain, and total yields of wheat- which were statistically at par with that of the straw, grain, and total yields, respectively, obtained with 100% of the recommended doses of P *i.e.*, treatment T2. The straw, grain, as well as total yield of wheat as obtained by the combined application of 250 mg Si kg⁻¹ soil (through ashes) and PSM, without any P fertilizer (treatments T4, T5 and T7) were statistically at par with each other, respectively. Among the ashes, CCA application for supplementing 250 mg kg⁻¹ Si along with PSM and 50% RDP delivered the numerical highest wheat biomass (15.77 g pot⁻¹).

Table 4.13. Straw, grain and total biomass yield (g pot⁻¹) of wheat as impacted by different combinations of Si-rich agro-wastes, PSM and P fertilization in Alfisol

Treatment	Straw yield (g pot ⁻¹)	Grain yield (g pot ⁻¹)	Total biomass (g pot ⁻¹)
Control	8.15d	5.29d	13.44d
100% P	10.22a	6.69a	16.91a
75% P	8.96c	5.72cd	14.68cd
SBA @Si ₂₅₀ + PSM	9.47bc	6.03bc	15.50bc
RHA @Si ₂₅₀ + PSM	9.36bc	5.95bc	15.31bc
CCA @Si ₁₂₅ + PSM	8.82c	5.61cd	14.43cd
CCA @Si ₂₅₀ + PSM	9.54b	6.07b	15.62b
SBA @Si ₂₅₀ + PSM +50%P	9.87ab	6.28ab	16.15ab
RHA @Si ₂₅₀ + PSM +50%P	9.79ab	6.24b	16.03ab
CCA @Si ₁₂₅ + PSM +50%P	9.58ab	6.19b	15.77b
CCA @Si ₂₅₀ + PSM +50%P	9.93ab	6.36ab	16.29ab

***Values in each column with no common lower-case letters indicate a significant difference at P<0.05, according to Fisher's LSD test.*

4.12.1.2. Yield of wheat in Inceptisol

Data on the straw, grain, and total yield of wheat (g pot⁻¹) as impacted by the combined application of P fertilizer, Si-rich ashes, and PSM are presented in table

4.14. Results showed that the no P (control) had the lowest straw (9.21 g pot⁻¹), grain (6.02 g pot⁻¹), as well as total yield (15.23 g pot⁻¹) of wheat, which were significantly different from the rest of the other treatments, respectively. Application of 100% RDP along with full doses of N and K, *i.e.*, treatment T2 produced the numerical highest straw (11.41 g pot⁻¹), grain (7.45 g pot⁻¹), and total yield (18.86 g pot⁻¹) of wheat. Combined application of 250 mg Si kg⁻¹ soil through ashes, PSM, and 50% P fertilizer (treatments T8, T9 and T11) resulted in the total biomass yields of wheat- which were statistically at par with that of the total biomass yields obtained with 100% of the recommended doses of P *i.e.*, treatment T2. The straw, grain, as well as total yield of wheat as obtained by the combined application of 250 mg Si kg⁻¹ soil (through ashes) and PSM, without any P fertilizer (treatments T4, T5 and T7) were statistically at par with each other, respectively. Among the ashes, CCA application for supplementing 250 mg kg⁻¹ Si along with PSM and 50% RDP delivered the numerical highest wheat biomass (18.12 g pot⁻¹).

Table 4.14. Straw, grain and total biomass yield (g pot⁻¹) of wheat as impacted by different combinations of Si-rich agro-wastes, PSM and P fertilization in Inceptisol

Treatment	Straw yield (g pot ⁻¹)	Grain yield (g pot ⁻¹)	Total biomass (g pot ⁻¹)
Control	9.21d	6.02d	15.23d
100% P	11.41a	7.45a	18.86a
75% P	10.58b	6.77b	17.35bc
SBA @Si ₂₅₀ + PSM	10.55bc	6.70b	17.25bc
RHA @Si ₂₅₀ + PSM	10.42bc	6.61bc	17.04bc
CCA @Si ₁₂₅ + PSM	9.82cd	6.22cd	16.04cd
CCA @Si ₂₅₀ + PSM	10.63b	6.75b	17.38b
SBA @Si ₂₅₀ + PSM +50%P	11.00ab	6.99ab	17.99ab
RHA @Si ₂₅₀ + PSM +50%P	10.91ab	6.94b	17.85ab
CCA @Si ₁₂₅ + PSM +50%P	10.68ab	6.88b	17.56b
CCA @Si ₂₅₀ + PSM +50%P	11.07ab	7.05ab	18.12ab

***Values in each column with no common lower-case letters indicate a significant difference at P<0.05, according to Fisher's LSD test.*

4.12.2. Yield of mungbean

4.12.2.1. Yield of mungbean in Alfisol

Data on the straw, grain, and total yield of mungbean (g pot^{-1}) as impacted by the combined application of P fertilizer, Si-rich ashes and PSM are presented in table 4.15. As mungbean was grown on residual soil fertility without any external P nutrition, PSM, or ash, the yield did not vary significantly. However, the straw, grain, and total yields of mungbean in T11 were comparable to that of the straw, grain, and total yields of mungbean, respectively, in T2 and T3. The total biomass yield of mungbean under T8, T9, T10 and T11 was similar ($P < 0.05$). The highest straw (7.76 g pot^{-1}), grain (2.29 g pot^{-1}), and total biomass yield (10.05 g pot^{-1}), among the ashes, was obtained with T11. However, the grain and straw yield of mungbean obtained with ash application in different compositions was significantly higher than control (no P).

Table 4.15. Straw, grain, and total biomass yield (g pot^{-1}) of mungbean as impacted by different combinations of Si-rich agro-wastes, PSM and P fertilization in Alfisol

Treatment	Stover yield (g pot^{-1})	Grain yield (g pot^{-1})	Total biomass (g pot^{-1})
Control	5.89d	1.73d	7.63d
100% P	7.92a	2.33a	10.25a
75% P	7.73ab	2.27ab	10.00ab
SBA @Si ₂₅₀ + PSM	7.27bc	2.14bc	9.42bc
RHA @Si ₂₅₀ + PSM	7.21c	2.11c	9.32c
CCA @Si ₁₂₅ + PSM	7.21c	2.10c	9.31c
CCA @Si ₂₅₀ + PSM	7.37bc	2.16bc	9.53bc
SBA @Si ₂₅₀ + PSM +50%P	7.72abc	2.26abc	9.99abc
RHA @Si ₂₅₀ + PSM +50%P	7.66abc	2.24abc	9.90abc
CCA @Si ₁₂₅ + PSM +50%P	7.43abc	2.18abc	9.61abc
CCA @Si ₂₅₀ + PSM +50%P	7.76ab	2.29ab	10.05ab

***Values in each column with no common lower-case letters indicate a significant difference at $P < 0.05$, according to Fisher's LSD test.*

4.12.2.2. Yield of mungbean in Inceptisol

Data on the straw, grain, and total yield of mungbean (g pot^{-1}) as impacted by the combined application of P fertilizer, Si-rich ashes and PSM are presented in table 4.16. As mungbean was grown on residual soil fertility without any external P nutrition, PSM, or ash, the yield did not differ much. However, the straw, grain, and total yields of mungbean in T11 were comparable to that of the straw, grain, and total yields of mungbean, respectively, in T2 and T3. The total biomass yield of mungbean under T8, T9, T10 and T11 was similar ($P < 0.05$). The highest straw (8.65 g pot^{-1}), grain (2.52 g pot^{-1}), and total biomass yield (11.16 g pot^{-1}), among the ashes, was obtained with T11. However, the grain and straw yield of mungbean obtained with ash application in different compositions was significantly higher than control (no P).

Table 4.16. Straw, grain, and total biomass yield (g pot^{-1}) of mungbean as impacted by different combinations of Si-rich agro-wastes, PSM and P fertilization in Inceptisol

Treatment	Stover yield (g pot^{-1})	Grain yield (g pot^{-1})	Total biomass (g pot^{-1})
Control	6.73d	1.96d	8.69d
100% P	8.75a	2.55a	11.30a
75% P	8.55abc	2.50ab	11.05abc
SBA @Si ₂₅₀ + PSM	8.11bcd	2.36bc	10.47bc
RHA @Si ₂₅₀ + PSM	7.99c	2.33c	10.32c
CCA @Si ₁₂₅ + PSM	7.98c	2.33c	10.31c
CCA @Si ₂₅₀ + PSM	8.17bc	2.38bc	10.54bc
SBA @Si ₂₅₀ + PSM +50%P	8.56abc	2.49abc	11.05abc
RHA @Si ₂₅₀ + PSM +50%P	8.44abc	2.46abc	10.91abc
CCA @Si ₁₂₅ + PSM +50%P	8.26abc	2.40abc	10.66abc
CCA @Si ₂₅₀ + PSM +50%P	8.65ab	2.52ab	11.16ab

***Values in each column with no common lower-case letters indicate a significant difference at $P < 0.05$, according to Fisher's LSD test.*

4.12.3. Phosphorus uptake by wheat

4.12.3.1. Phosphorus uptake by wheat in Alfisol

Data on the straw, grain and total P uptake by wheat (mg pot^{-1}) as impacted by the combined application of P fertilizer, Si-rich ashes and PSM are presented in table

4.17. The highest straw (12.79 mg pot⁻¹), grain (19.34 mg pot⁻¹), as well as total P uptake (32.13 mg pot⁻¹) by wheat was observed in T2 treatment, *i.e.* 100% P fertilization. However, the lowest P uptake was observed in the control (no P) treatment. Interestingly, the application of T4 (SBA@Si₂₅₀+PSM) and T5 (RHA@Si₂₅₀+PSM) markedly enhanced the P uptake of wheat over control. However, the application of T8, T9, T10 and T11 resulted in similar P uptake, where T11 had the numerical highest P uptake among them. Despite P uptake within the wheat straw was similar for T2 and T11, grain P uptake was significantly lower for T11 as compared to T2.

Table 4.17. Straw, grain, and total P uptake (mg pot⁻¹) by wheat as impacted by different combinations of Si-rich agro-wastes, PSM and P fertilization in Alfisol

Treatment	Straw P uptake (mg pot ⁻¹)	Grain P uptake (mg pot ⁻¹)	Total P uptake (mg pot ⁻¹)
Control	7.83f	11.71g	19.54g
100% P	12.79a	19.34a	32.13a
75% P	11.92bc	17.78b	29.70bc
SBA @Si ₂₅₀ + PSM	11.14cd	16.17de	27.31de
RHA @Si ₂₅₀ + PSM	10.92de	15.87ef	26.79ef
CCA @Si ₁₂₅ + PSM	10.30e	14.89f	25.19f
CCA @Si ₂₅₀ + PSM	11.32bcd	16.46cde	27.77cde
SBA @Si ₂₅₀ + PSM +50%P	11.79bc	17.63b	29.42bc
RHA @Si ₂₅₀ + PSM +50%P	11.61bcd	17.38bc	29.00bcd
CCA @Si ₁₂₅ + PSM +50%P	11.55bcd	17.03bcd	28.58bcde
CCA @Si ₂₅₀ + PSM +50%P	12.06ab	18.06b	30.12b

***Values in each column with no common lower-case letters indicate a significant difference at P<0.05, according to Fisher's LSD test.*

4.12.3.2. Phosphorus uptake by wheat in Inceptisol

Data on the straw, grain, and total P uptake by wheat (mg pot⁻¹) as impacted by the combined application of P fertilizer, Si-rich ashes, and PSM are presented in table 4.18. The highest straw (13.02 mg pot⁻¹), grain (23.27 mg pot⁻¹), as well as total P uptake (36.30 mg pot⁻¹) by wheat was observed in T2 treatment, *i.e.* 100% P

fertilization. However, the lowest P uptake was observed in the control (no P) treatment. Application of T4 (SBA@Si₂₅₀+PSM) and T5 (RHA@Si₂₅₀+PSM) markedly enhanced the P uptake of wheat over control. However, the application of T8, T9, T10 and T11 resulted in similar P uptake, where T11 had the highest P uptake among them. Despite P uptake within the wheat straw was similar for T2 and T11, grain P uptake was significantly lower for T11 as compared to T2.

Table 4.18. Straw, grain and total P uptake (mg pot⁻¹) by wheat as impacted by different combinations of Si-rich agro-wastes, PSM and P fertilization in Inceptisol

Treatment	Straw P uptake (mg pot ⁻¹)	Grain P uptake (mg pot ⁻¹)	Total P uptake (mg pot ⁻¹)
Control	9.50g	15.31g	24.81g
100% P	13.02a	23.27a	36.30a
75% P	12.05bc	20.96b	33.01b
SBA @Si ₂₅₀ + PSM	11.19de	18.98de	30.17de
RHA @Si ₂₅₀ + PSM	10.95ef	18.61ef	29.56ef
CCA @Si ₁₂₅ + PSM	10.32f	17.44f	27.76f
CCA @Si ₂₅₀ + PSM	11.39cde	19.33cde	30.72cde
SBA @Si ₂₅₀ + PSM +50%P	11.89bcd	20.79b	32.68bc
RHA @Si ₂₅₀ + PSM +50%P	11.69bcde	20.49bc	32.18bcd
CCA @Si ₁₂₅ + PSM +50%P	11.65bcde	20.05bcd	31.70bcde
CCA @Si ₂₅₀ + PSM +50%P	12.19b	21.25b	33.44b

***Values in each column with no common lower-case letters indicate a significant difference at $P<0.05$, according to Fisher's LSD test.*

4.12.4. Phosphorus uptake by mungbean

4.12.4.1. Phosphorus uptake by mungbean in Alfisol

Data on the straw, grain, and total P uptake by mungbean (mg pot⁻¹) as impacted by the combined application of P fertilizer, Si-rich ashes, and PSM are presented in table 4.19. As mungbean was grown on residual soil fertility without any external P nutrition, PSM, or ash, the P uptake did not differ much. However, the grain P uptake by mungbean in T11 was comparable to T2 and T3. Total P uptake by mungbean under T8, T9, T10 and T11 was similar ($P<0.05$). The highest straw (12.26 mg pot⁻¹),

grain (6.33 mg pot⁻¹), as well as total P uptake (18.59 mg pot⁻¹) by mungbean, among the ashes, was obtained with T11. However, the grain, straw, as well as total P uptake by mungbean obtained with ash application in different compositions was significantly higher than control (no P).

Table 4.19. Straw, grain and total P uptake (mg pot⁻¹) by mungbean as impacted by different combinations of Si-rich agro-wastes, PSM and P fertilization in Alfisol

Treatment	Stover P uptake (mg pot ⁻¹)	Grain P uptake (mg pot ⁻¹)	Total P uptake (mg pot ⁻¹)
Control	8.73e	4.59f	13.32f
100% P	12.86a	6.57a	19.43a
75% P	12.15ab	6.27abc	18.42ab
SBA @Si ₂₅₀ + PSM	10.99d	5.80de	16.79de
RHA @Si ₂₅₀ + PSM	10.73d	5.65e	16.38e
CCA @Si ₁₂₅ + PSM	10.75d	5.67e	16.42e
CCA @Si ₂₅₀ + PSM	11.28cd	5.91cde	17.19cde
SBA @Si ₂₅₀ + PSM +50%P	12.05bc	6.19abcd	18.24abc
RHA @Si ₂₅₀ + PSM +50%P	11.81bc	6.10bcd	17.91bcd
CCA @Si ₁₂₅ + PSM +50%P	11.52bcd	6.00bcde	17.52bcde
CCA @Si ₂₅₀ + PSM +50%P	12.26ab	6.33ab	18.59ab

***Values in each column with no common lower-case letters indicate a significant difference at $P<0.05$, according to Fisher's LSD test.*

4.12.4.1. Phosphorus uptake by mungbean in Inceptisol

Data on the straw, grain, and total P uptake by mungbean (mg pot⁻¹) as impacted by the combined application of P fertilizer, Si-rich ashes and PSM are presented in table 4.20. As mungbean was grown on residual soil fertility without any external P nutrition, PSM, or ash, the P uptake did not differ much. However, the grain P uptake by mungbean in T11 was comparable to T2 and T3. Total P uptake by mungbean under T8, T9, T10 and T11 was similar ($P<0.05$). The highest straw (14.57 mg pot⁻¹), grain (7.28 mg pot⁻¹), as well as total P uptake (21.86 mg pot⁻¹) by mungbean, among the ashes, was obtained with T11. However, the grain, straw, as well as total P uptake by mungbean obtained with ash application in different compositions was significantly higher than the control (no P).

Table 4.20. Straw, grain, and total P uptake (mg pot⁻¹) by mungbean as impacted by different combinations of Si-rich agro-wastes, PSM and P fertilization in Inceptisol

Treatment	Stover P uptake (mg pot ⁻¹)	Grain P uptake (mg pot ⁻¹)	Total P uptake (mg pot ⁻¹)
Control	10.65f	5.43f	16.07f
100% P	14.97a	7.50a	22.47a
75% P	14.29ab	7.19abc	21.49abc
SBA @Si ₂₅₀ + PSM	13.08de	6.68de	19.75de
RHA @Si ₂₅₀ + PSM	12.72e	6.53e	19.24e
CCA @Si ₁₂₅ + PSM	12.69e	6.51e	19.20e
CCA @Si ₂₅₀ + PSM	13.34cde	6.80cde	20.14cde
SBA @Si ₂₅₀ + PSM +50%P	14.24abc	7.13abcd	21.37abc
RHA @Si ₂₅₀ + PSM +50%P	13.88bcd	7.02abcd	20.90bcd
CCA @Si ₁₂₅ + PSM +50%P	13.72bcd	6.91bcde	20.62bcde
CCA @Si ₂₅₀ + PSM +50%P	14.57ab	7.28ab	21.86ab

***Values in each column with no common lower-case letters indicate a significant difference at $P < 0.05$, according to Fisher's LSD test.*

4.13. Effect of different treatments on the fractions of P in Alfisol

Distribution of P into different fractions viz. inorganic P fractions as well as organic P in Alfisol as influenced by different treatments are discussed below:

4.13.1. Inorganic P fractions

The distribution of P into various inorganic fractions in the Alfisol after the harvest of the mungbean crop was determined and presented in figure 4.14. The findings are presented below:

4.13.1.1. Soluble and loosely bound P

The magnitude of the soluble and loosely bound P (SL-P) fraction in the collected bulk sample of Alfisol was 3.03 mg kg⁻¹ soil; whereas, the SL-P fraction was further reduced to 2.48 mg kg⁻¹ soil, in the control (no P) treatment, after the harvest of the mungbean crop. Data related to the per cent increase in the SL-P fraction over control (no P) treatment, as impacted by different treatments, is given in table 4.21. Maximum increase in the SL-P fraction over control, occurred in the case of 100% P

treatment, followed by 75% P treatment. In the treatments containing 50% P fertilization, the increase in SL-P fraction was significantly higher than that of the treatments having no external P fertilization (*i.e.* only Si and PSM application).

4.13.1.2. Aluminium bound P

The magnitude of the aluminium-bound P (Al-P) fraction in the collected bulk sample of Alfisol was 47.5 mg kg⁻¹ soil; whereas, the Al-P fraction was further reduced to 45.7 mg kg⁻¹ soil, in the control (no P) treatment, after the harvest of the mungbean crop. Data related to the per cent decrease in the Al-P fraction over control (no P) treatment, as impacted by different treatments, is given in table 4.21.

Table 4.21. Per cent changes in different fractions of inorganic P (mg kg⁻¹) in the soil as impacted by different treatments in Alfisol

Treatment	Per cent increase in SL-P over control	Per cent decrease in Al-P over control	Per cent decrease in Fe-P over control	Per cent decrease in ReS-P over control	Per cent decrease in Ca-P over control
100% P	32.36a	-3.26j	-2.73j	-2.15h	-5.24f
75% P	26.97b	-2.38i	-1.82i	-1.67g	-4.12e
SBA @Si ₂₅₀ +PSM	15.30f	4.84b	6.31b	0.20b	2.12a
RHA @Si ₂₅₀ +PSM	13.01g	4.16c	5.76c	0.12c	1.82b
CCA @Si ₁₂₅ +PSM	8.55h	3.40d	5.16d	0.09c	1.62b
CCA @Si ₂₅₀ +PSM	17.45ef	5.28a	6.82a	0.35a	2.31a
SBA @Si ₂₅₀ +PSM+50%P	21.46d	2.60f	3.85e	-0.10d	0.26c
RHA @Si ₂₅₀ +PSM+50%P	16.36f	1.93g	3.17f	-0.21f	0.17cd
CCA @Si ₁₂₅ +PSM+50%P	18.55e	2.98e	2.73g	-0.10e	0.19cd
CCA @Si ₂₅₀ +PSM+50%P	25.09c	3.68d	3.94e	-0.01d	0.35c

****** Values in each column with no common lower-case letters indicate a significant difference at $P < 0.05$, according to Fisher's LSD test.

SL-P = Soluble and loosely bound P; Al-P = Aluminium-bound P; Fe-P = Iron-bound P; ReS-P = Reductant-soluble P; Ca-P = Calcium-bound P

Notably, in the case of the treatments, namely: 100% P and 75% P, there was a net increase in the Al-P fraction, over control, as indicated by the negative values of per cent decrement. Besides these two treatments, the rest other treatments showed

decrease in the Al-P fraction over the control (no P) treatment. The maximum decrease in the Al-P fraction over control, occurred in the case of CCA@Si₂₅₀+PSM treatment, followed by SBA@Si₂₅₀+PSM treatment, followed by RHA@Si₂₅₀+PSM treatment. However, in the treatments containing 50% P fertilization, the per cent decrement in Al-P fraction was significantly lesser than that of the treatments having no external P fertilization (*i.e.* only Si and PSM application).

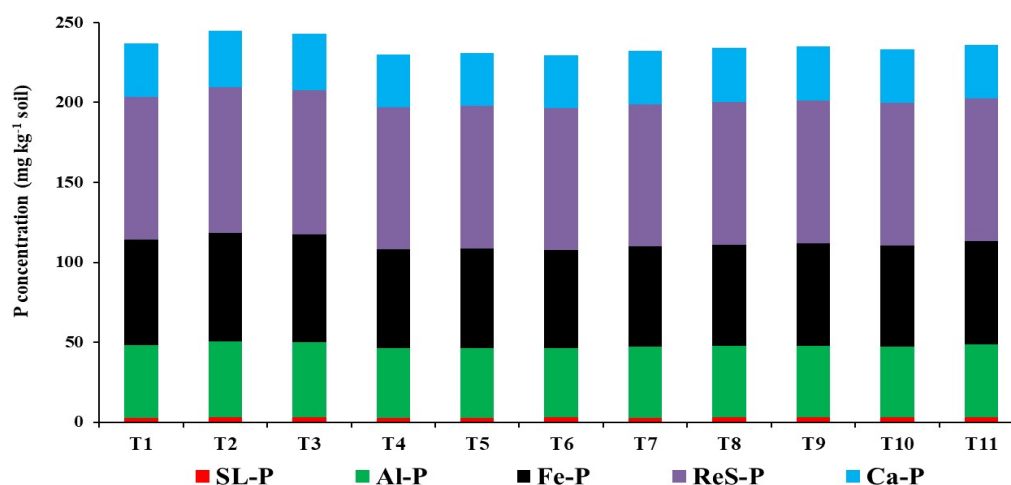


Figure 4.14. Inorganic P fractions as impacted by different combinations of Si-rich agro-wastes, PSM, and P fertilization in Alfisol

****** SL-P= Soluble and loosely bound P; Al-P= Aluminium-bound P; Fe-P= Iron-bound P; ReS-P = Reductant-soluble P; Ca-P= Calcium-bound P

#**T1**= Control (no P), **T2** =100% P, **T3** = 75% P, **T4** = SBA @Si₂₅₀ +PSM, **T5** = RHA @Si₂₅₀+PSM, **T6** = CCA@Si₁₂₅+PSM, **T7** = CCA@Si₂₅₀+PSM, **T8** = SBA @Si₂₅₀+PSM+ 50% P, **T9** = RHA @Si₂₅₀ + PSM+ 50% P, **T10** = CCA @Si₁₂₅ + PSM+ 50% P, **T11** = CCA @Si₂₅₀ + PSM+ 50% P

4.13.1.3. Iron bound P

The magnitude of the iron-bound P (Fe-P) fraction in the collected bulk sample of Alfisol was 68.3 mg kg⁻¹ soil; whereas, the Fe-P fraction was further reduced to 66.1 mg kg⁻¹ soil, in the control (no P) treatment, after the harvest of the mungbean crop. Data related to the per cent decrease in the Fe-P fraction over control (no P) treatment, as impacted by different treatments, is given in table 4.21. Notably, in the case of the treatments namely, 100% P and 75% P, there was a net increase in the Fe-P fraction, over control, as indicated by the negative values of per cent decrement. Besides these two treatments, the rest other treatments showed decrease in the Fe-P fraction over the control (no P) treatment. The maximum decrease in the Fe-P fraction over control,

occurred in the case of CCA@Si₂₅₀+PSM treatment, followed by SBA@Si₂₅₀+PSM treatment, followed by RHA@Si₂₅₀+PSM treatment. However, in the treatments containing 50% P fertilization, the per cent decrement in Fe-P fraction was only Si and PSM application).

4.13.1.4. Reductant soluble P

The magnitude of the reductant soluble P (ReS-P) fraction in the collected bulk sample of Alfisol was 89.7 mg kg⁻¹ soil; whereas, it was slightly reduced to 89.1 mg kg⁻¹ soil, in the control (no P) treatment, after the harvest of the mungbean crop. Data related to the per cent decrease in the ReS-P fraction over control (no P) treatment, as impacted by different treatments, are given in table 4.21. Notably, in the case of the treatments namely, 100% P and 75% P, there was a net increase in the ReS-P fraction, over control (no P), as indicated by the negative values of per cent decrement. Also, in the treatments containing 50% P fertilization, there was a net increase in the ReS-P fraction, over control (no P). Whereas, in the case of the treatments having no external P fertilization (*i.e.* only Si and PSM application), there was a net decrease in the ReS-P fraction, over control. The maximum decrease in the ReS-P fraction over control, occurred in the case of CCA@Si₂₅₀+PSM treatment, followed by SBA@Si₂₅₀+PSM treatment and RHA @Si₂₅₀+PSM treatment.

4.13.1.5. Calcium bound P

The magnitude of the calcium-bound P (Ca-P) fraction in the collected bulk sample of Alfisol was 34.4 mg kg⁻¹ soil; whereas, the Ca-P fraction was further reduced to 33.7 mg kg⁻¹ soil, in the control (no P) treatment, after the harvest of the mungbean crop. Data related to the per cent decrease in the Ca-P fraction over control (no P) treatment, as impacted by different treatments, are given in table 4.21. Notably, in the case of the treatments namely, 100% P and 75% P, there was a net increase in the Ca-P fraction, over control, as indicated by the negative values of per cent decrement. Besides these two treatments, the rest other treatments showed decrease in the Ca-P fraction over the control (no P) treatment. The maximum per cent decrease in the Ca-P fraction over control, occurred in the case of both CCA@Si₂₅₀+PSM treatment and SBA@Si₂₅₀+PSM treatment, followed by RHA@Si₂₅₀+PSM treatment. However, in the treatments containing 50% P fertilization, the per cent decrement in Ca-P fraction was significantly lesser than that of the treatments having no external P fertilization (*i.e.* only Si and PSM application).

4.13.1.6. Per cent solubilization of total inorganic P

Total inorganic P (P_{ing}) was calculated by taking the sum of all the inorganic P fractions in the soil. Data related to the per cent decrease, *i.e.* per cent solubilization of the P_{ing} fraction over control (no P) treatment, as impacted by different treatments, are given in figure 4.15. Notably, in the case of the treatments, namely: 100% P and 75% P, there was a net increase (fixation) in the P_{ing} fraction, over control, as indicated by the negative values. Besides these two treatments, the rest other treatments showed net solubilization of the P_{ing} fraction over the control (no P) treatment. The maximum solubilization of the P_{ing} fraction over control, occurred in the case of CCA@Si₂₅₀+PSM treatment, followed by SBA@Si₂₅₀+PSM treatment, followed by RHA@Si₂₅₀+PSM treatment. However, in the treatments containing 50% P fertilization, the per cent solubilization of the P_{ing} fraction was significantly lesser than that of the treatments having no external P fertilization (*i.e.* only Si and PSM application). The value of per cent solubilization of the P_{ing} fraction over control, ranged from 0.50% to 3.21% of total inorganic P in soil.

4.13.2. Organic P

The magnitude of the organic P (P_{org}) fraction in the collected bulk sample of Alfisol was 89.8 mg kg⁻¹ soil; whereas, it was slightly reduced to 88.6 mg kg⁻¹ soil, in the control (no P) treatment, after the harvest of the mungbean crop. Data related to the per cent decrease, *i.e.* per cent mineralization of the P_{org} fraction over control (no P) treatment, as impacted by different treatments, are given in figure 4.15. The maximum per cent mineralization of the P_{org} fraction over control, occurred in the case of CCA@Si₂₅₀+PSM treatment, followed by SBA@Si₂₅₀+PSM treatment, followed by RHA@Si₂₅₀+PSM) treatment. The minimum value of per cent mineralization of the P_{org} fraction over control, was recorded in the case of 100% P treatment, followed by 75% P treatment. The value of per cent mineralization of the P_{org} fraction over control, ranged from 0.55% to 2.69% of total organic P in soil.

4.14. Effect of different treatments on the fractions of P in Inceptisol

Distribution of P into different fractions *viz.* inorganic P fractions as well as organic P in Inceptisol as influenced by different treatments are discussed in the following sections.

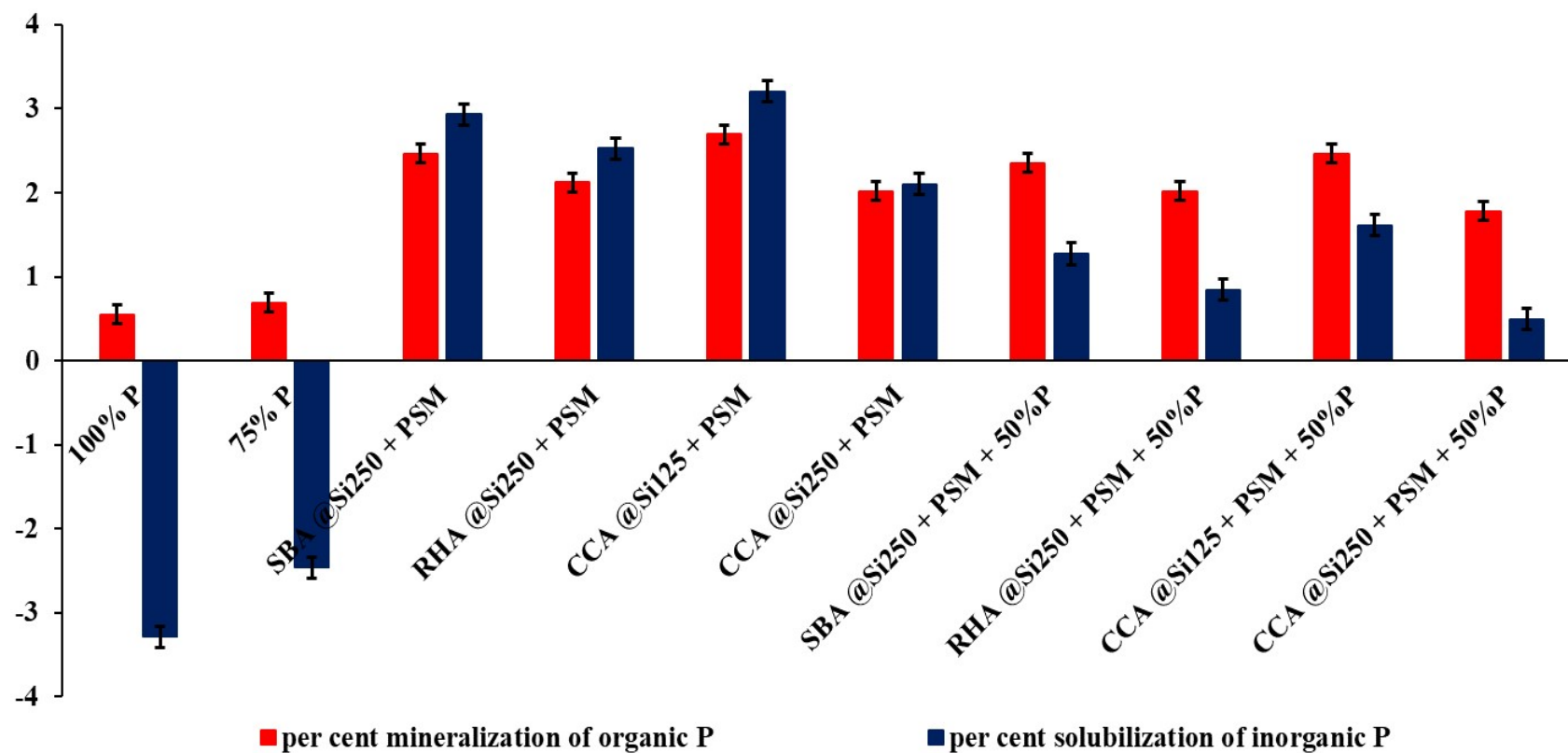


Figure 4.15. Per cent mineralization of organic P as well as per cent solubilization of inorganic P as impacted by different treatments in Alfisol

4.14.1. Inorganic P fractions

The distribution of P into various inorganic fractions in the Inceptisol after the harvest of the mungbean crop was determined and presented in figure 4.16. The findings are presented below:

4.14.1.1. Soluble and loosely bound P

The magnitude of the soluble and loosely bound P (SL-P) fraction in the collected bulk sample of Inceptisol was 5.52 mg kg⁻¹ soil; whereas, the SL-P fraction was further reduced to 3.91 mg kg⁻¹ soil, in the control (no P) treatment, after the harvest of the mungbean crop. Data related to the per cent increase in the SL-P fraction over control (no P) treatment, as impacted by different treatments, are given in table 4.22.

Table 4.22. Per cent changes in different fractions of inorganic P (mg kg⁻¹) in the soil as impacted by different treatments in Inceptisol

Treatment	Per cent increase in SL-P over control	Per cent decrease in Al-P over control	Per cent decrease in Fe-P over control	Per cent decrease in ReS-P over control	Per cent decrease in Ca-P over control
100% P	27.21a	-0.91j	-0.59g	-1.66h	-1.43i
75% P	23.77b	-0.50i	-0.12f	-1.26g	-1.14h
SBA @Si ₂₅₀ +PSM	12.51e	5.88b	6.54b	0.13b	1.48a
RHA @Si ₂₅₀ +PSM	10.07f	5.13c	5.50c	0.09c	1.18b
CCA @Si ₁₂₅ +PSM	8.01g	3.81d	5.23c	0.16b	1.05c
CCA @Si ₂₅₀ +PSM	13.38e	6.64a	7.14a	0.28a	1.54a
SBA @Si ₂₅₀ +PSM+50%P	21.25c	3.45e	4.71d	-0.16d	0.64e
RHA @Si ₂₅₀ +PSM+50%P	19.14d	2.89f	3.66e	-0.14f	0.48f
CCA @Si ₁₂₅ +PSM+50%P	14.17e	2.47g	3.39e	-0.22e	0.44f
CCA @Si ₂₅₀ +PSM+50%P	24.20b	4.02d	5.30c	-0.01d	0.80d

****Values in each column with no common lower-case letters indicate a significant difference at $P < 0.05$, according to Fisher's LSD test.**

#SL-P= Soluble and loosely bound P; Al-P= Aluminium-bound P; Fe-P= Iron-bound P; ReS-P= Reductant-soluble P; Ca-P= Calcium-bound P

The maximum increase in the SL-P fraction over control, occurred in the case of 100% P treatment, followed by 75% P treatment. In the treatments containing 50% P fertilization, the increase in SL-P fraction was significantly higher than that of the treatments having no external P fertilization (*i.e.* only Si and PSM application).

4.14.1.2. Aluminium bound P

The magnitude of the aluminium-bound P (Al-P) fraction in the collected bulk sample of Inceptisol was 56.3 mg kg⁻¹ soil; whereas, the Al-P fraction was further reduced to 54.7 mg kg⁻¹ soil, in the control (no P) treatment, after the harvest of the mungbean crop. Data related to the per cent decrease in the Al-P fraction over control (no P) treatment, as impacted by different treatments, is given in table 4.22. Notably, in case of the treatments namely, 100% P and 75% P, there was a net increase in the Al-P fraction, over control, as indicated by the negative values of per cent decrement. Besides these two treatments, the rest other treatments showed a decrease in the Al-P fraction over the control (no P) treatment. The maximum decrease in the Al-P fraction over control, occurred in the case of CCA@Si₂₅₀+PSM treatment, followed by SBA@Si₂₅₀+PSM treatment, followed by RHA@Si₂₅₀+PSM treatment. However, in the treatments containing 50% P fertilization, the per cent decrement in Al-P fraction was significantly lesser than that of the treatments having no external P fertilization (*i.e.* only Si and PSM application).

4.14.1.3. Iron bound P

The magnitude of the iron-bound P (Fe-P) fraction in the collected bulk sample of Inceptisol was 40.1 mg kg⁻¹ soil; whereas, the Fe-P fraction was further reduced to 38.9 mg kg⁻¹ soil, in the control (no P) treatment, after the harvest of the mungbean crop. Data related to the per cent decrease in the Fe-P fraction over control (no P) treatment, as impacted by different treatments, are given in table 4.22. It is evident that in the treatments namely, 100% P and 75% P, there was a net increase in the Fe-P fraction, over control, as indicated by the negative values of per cent decrement. Besides these two treatments, the rest other treatments showed decrease in the Fe-P fraction over the control (no P) treatment. The maximum decrease in the Fe-P fraction over control, occurred in the case of CCA@Si₂₅₀+PSM treatment, followed by SBA@Si₂₅₀+PSM treatment, followed by RHA@Si₂₅₀+PSM treatment. However, in the treatments containing 50% P fertilization, the per cent decrement in Fe-P fraction

was significantly lesser than that of the treatments having no external P fertilization (*i.e.* only Si and PSM application).

4.14.1.4. Reductant soluble P

The magnitude of the reductant soluble P (ReS-P) fraction in the collected bulk sample of Inceptisol was 72.1 mg kg⁻¹ soil; whereas, it was slightly reduced to 71.7 mg kg⁻¹ soil, in the control (no P) treatment, after the harvest of the mungbean crop. Data related to the per cent decrease in the ReS-P fraction over control (no P) treatment, as impacted by different treatments, is given in table 4.22.

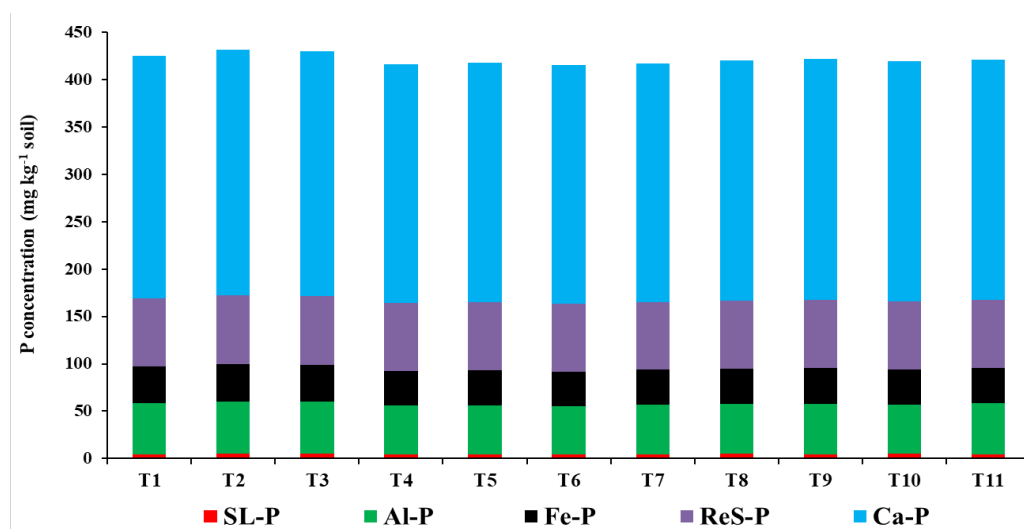


Figure 4.16. Inorganic P fractions as impacted by different combinations of Si-rich agro-wastes, PSM, and P fertilization in Inceptisol

** *SL-P*= Soluble and loosely bound P; *Al-P*= Aluminium-bound P; *Fe-P*= Iron-bound P; *ReS-P* = Reductant-soluble P; *Ca-P*= Calcium-bound P

#**T1** = Control (no P), **T2** = 100% P, **T3** = 75% P, **T4** = SBA @Si₂₅₀ +PSM, **T5** = RHA @Si₂₅₀+PSM, **T6** = CCA@Si₁₂₅+PSM, **T7** = CCA@Si₂₅₀+PSM, **T8** = SBA @Si₂₅₀+PSM+ 50% P, **T9** = RHA @Si₂₅₀ + PSM+ 50% P, **T10** = CCA @Si₁₂₅ + PSM+ 50% P, **T11** = CCA @Si₂₅₀ + PSM+ 50% P

In the case of the treatments namely, 100% P and 75% P, there was a net increase in the ReS-P fraction, over control (no P), as indicated by the negative values of per cent decrement. Also, in the treatments containing 50% P fertilization, there was a net increase in the ReS-P fraction, over control (no P). Whereas, in the case of the treatments having no external P fertilization (*i.e.* only Si and PSM application), there was a net decrease in the ReS-P fraction, over control. The maximum decrease in the

ReS-P fraction over control, occurred in the case of CCA@Si₂₅₀+PSM treatment, followed by SBA@Si₂₅₀+PSM treatment and RHA@Si₂₅₀+PSM treatment.

4.14.1.5. Calcium bound P

The magnitude of the calcium-bound P (Ca-P) fraction in the collected bulk sample of Inceptisol was 258.7 mg kg⁻¹ soil; whereas, the Ca-P fraction was further reduced to 255.9 mg kg⁻¹ soil, in the control (no P) treatment, after the harvest of the mungbean crop. Data related to the per cent decrease in the Ca-P fraction over control (no P) treatment, as impacted by different treatments, are given in table 4.22. Results showed that in case of the treatments 100% P and 75% P, there was a net increase in the Ca-P fraction, over control, as indicated by the negative values of per cent decrement. Besides these two treatments, the rest of the treatments showed decrease in the Ca-P fraction over the control (no P). The maximum per cent decrease in the Ca-P fraction over control, occurred in the case of both CCA@Si₂₅₀+PSM and SBA@Si₂₅₀+PSM treatments, followed by RHA@Si₂₅₀+PSM treatment. However, in the treatments containing 50% P fertilization, the per cent decrement in Ca-P fraction was significantly lesser than that of the treatments having no external P fertilization (*i.e.* only Si and PSM application).

4.14.1.6. Per cent solubilization of total inorganic P

Total inorganic P (P_{ing}) was calculated by taking the sum of all the inorganic P fractions in the soil. Data related to the per cent decrease, *i.e.* per cent solubilization of the P_{ing} fraction over control (no P) treatment, as impacted by different treatments, is given in figure 4.17. Notably, in the case of the treatments 100% P and 75% P, there was a net increase (fixation) in the P_{ing} fraction, over control, as indicated by the negative values. Besides these two treatments, the rest other treatments showed net solubilization of the P_{ing} fraction over the control (no P) treatment. The maximum solubilization of the P_{ing} fraction over control, occurred in the case of CCA@Si₂₅₀+PSM treatment, followed by SBA@Si₂₅₀+PSM treatment, followed by RHA@Si₂₅₀+PSM treatment. However, in the treatments containing 50% P fertilization, the per cent solubilization of the P_{ing} fraction was significantly lesser than that of the treatments having no external P fertilization (*i.e.* only Si and PSM application). The value of per cent solubilization of the P_{ing} fraction over control, ranged from 0.78% to 2.23% of total inorganic P in soil.

4.14.2. Organic P

The magnitude of the organic P (P_{org}) fraction in the collected bulk sample of Inceptisol was 174.6 mg kg^{-1} soil; whereas, it was slightly reduced to 173.4 mg kg^{-1} soil, in the control (no P) treatment, after the harvest of the mungbean crop. Data related to the per cent decrease, *i.e.* per cent mineralization of the P_{org} fraction over control (no P) treatment, as impacted by different treatments, are given in figure 4.17. The maximum per cent mineralization of the P_{org} fraction over control, occurred in the case of CCA@Si₂₅₀+PSM treatment. The minimum value of per cent mineralization of the P_{org} fraction over control, was recorded in the case of 100% P treatment followed by 75% P treatment. The value of per cent mineralization of the P_{org} fraction over control, ranged from 0.41 to 2.58% of total organic P in soil.

4.15. Assessing the contributions of different independent variables towards total yield and P uptake of wheat and mungbean crops

4.15.1. Principal component analysis

The bi-plots of principal component analysis (PCA) in the case of Alfisol and Inceptisol are presented in figures 4.18.A and 4.18.B, respectively. The PCA showed similar trends in both soils. The PCA revealed that 3 components were important for explaining the variables up to ~98.4%, in both the soils. In both soils, the variables present in PC-1 were yield and uptake-related parameters of wheat as well as of mungbean, along with the soluble and loosely bound P fraction. In PC-2, the variables which appeared were different fractions of P, namely: Al-P, Fe-P, ReS-P, Ca-P, organic P, and total P. In PC-3, only the variable named 'Available Si in soil' marked its presence. In case of Alfisol; PC-1, PC-2, and PC-3 contributed to 78.0%, 14.3%, and 6.14% of the total variation. Whereas, in case of Inceptisol; PC-1, PC-2 and PC-3 contributed to 58.3, 32.1 and 7.99% of the total variation.

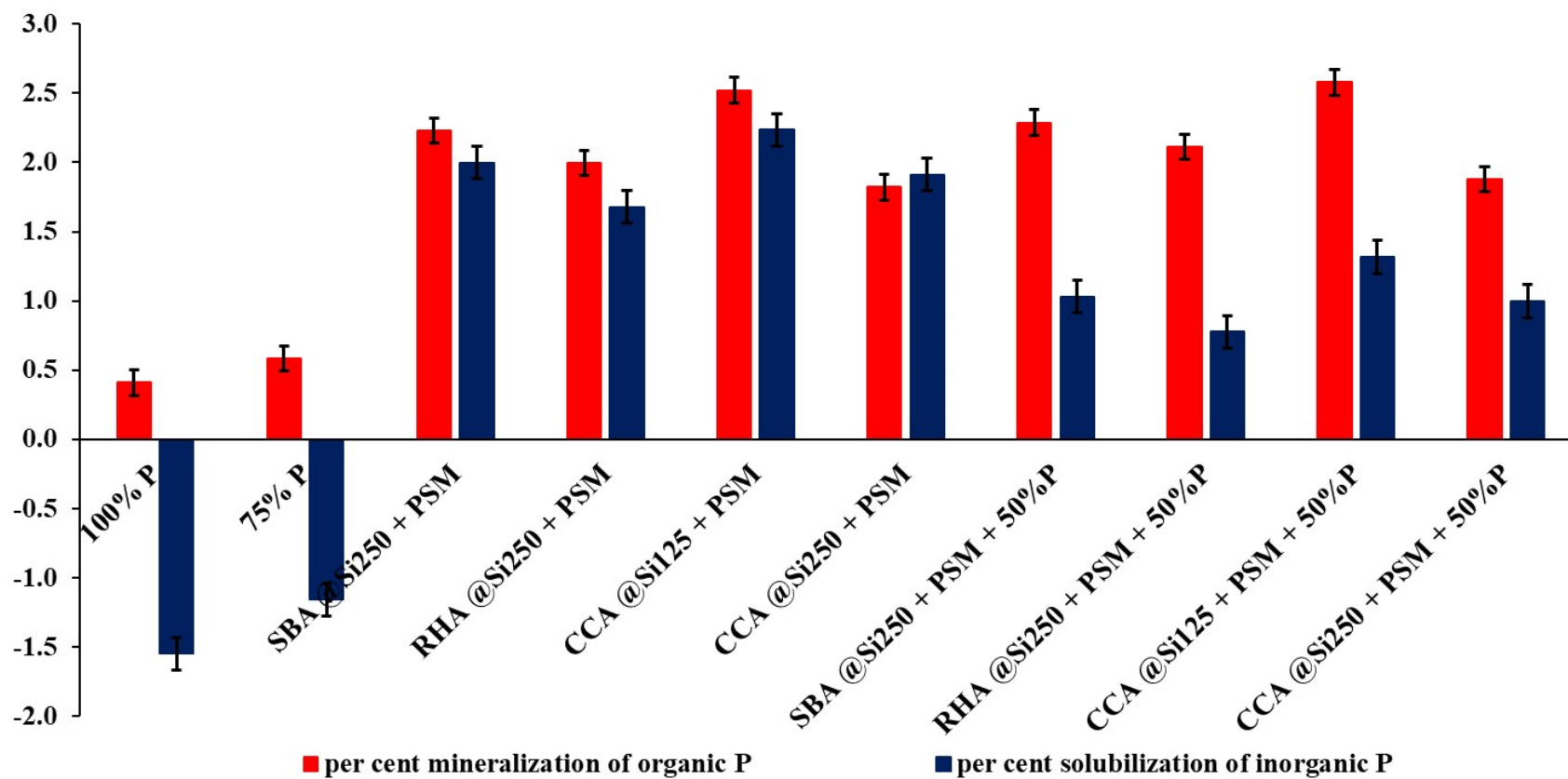


Figure 4.17. Per cent mineralization of organic P as well as per cent solubilization of inorganic P as impacted by different treatments in Inceptisol

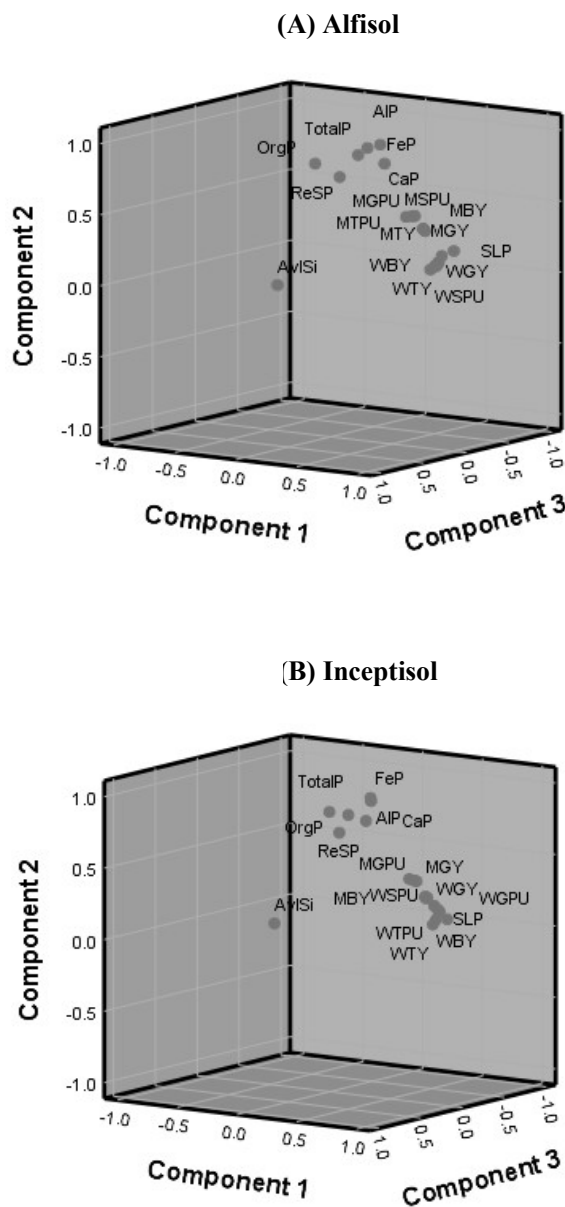


Figure 4.18. Bi-plot of principal component analysis (PCA) in (A) Alfisol and (B) Inceptisol

AvlSi = Available Si, WBY = Wheat biomass yield, WGY = Wheat grain yield, WTY = Wheat total yield, MBY = Mungbean biomass yield, MGY = Mungbean grain yield, MTY = Mungbean total yield, WGPU = Wheat grain P uptake, WTPU = Wheat total P uptake, MGPU = Mungbean grain P uptake, MSPU = Mungbean stover P uptake, MTPU = Mungbean total P uptake, SLP = Soluble and loosely bound P; AIP = Aluminium-bound P; FeP = Iron-bound P; ReSP = Reductant-soluble P; CaP = Calcium-bound P, OrgP = Total soil organic P, TotalP = Total soil P

4.15.2. Hierarchical cluster analysis

The dendrograms of hierarchical cluster analysis in the case of Alfisol and Inceptisol are presented in figures 4.19 and 4.20, respectively. Hierarchical cluster analysis revealed two broad variable groups representing yield and Si availability indicating the marked importance of Si in impacting crop yield. The trend was similar in both soils.

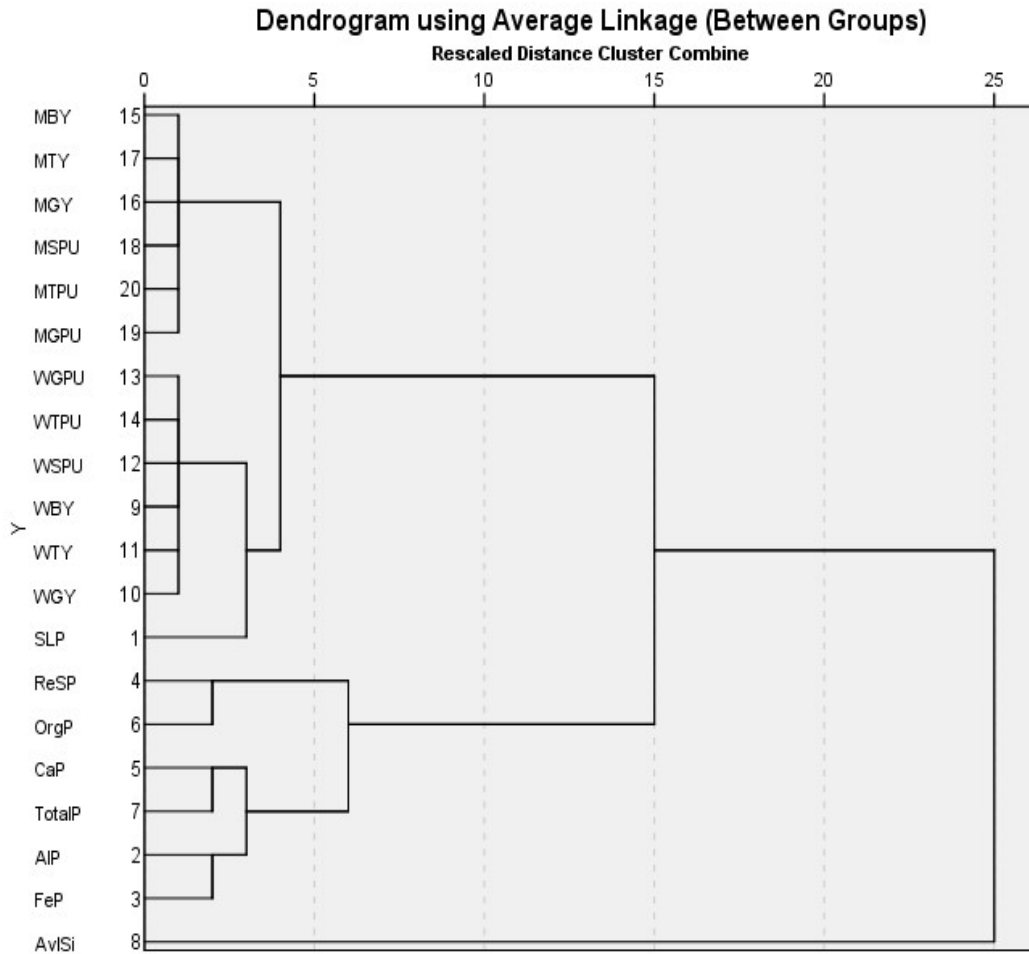


Figure 4.19. Dendrogram of hierarchical cluster analysis in Alfisol

AvlSi = Available Si, WBY = Wheat biomass yield, WGY = Wheat grain yield, WTY = Wheat total yield, MBY = Mungbean biomass yield, MGY = Mungbean grain yield, MTY = Mungbean total yield, WGPU = Wheat grain P uptake, WTPU = Wheat total P uptake, MGPU = Mungbean grain P uptake, MSPU = Mungbean stover P uptake, MTPU = Mungbean total P uptake, SLP= Soluble and loosely bound P; AlP = Aluminium-bound P; FeP = Iron-bound P; ReSP = Reductant-soluble P; CaP = Calcium-bound P, OrgP = Total soil organic P, TotalP = Total soil P

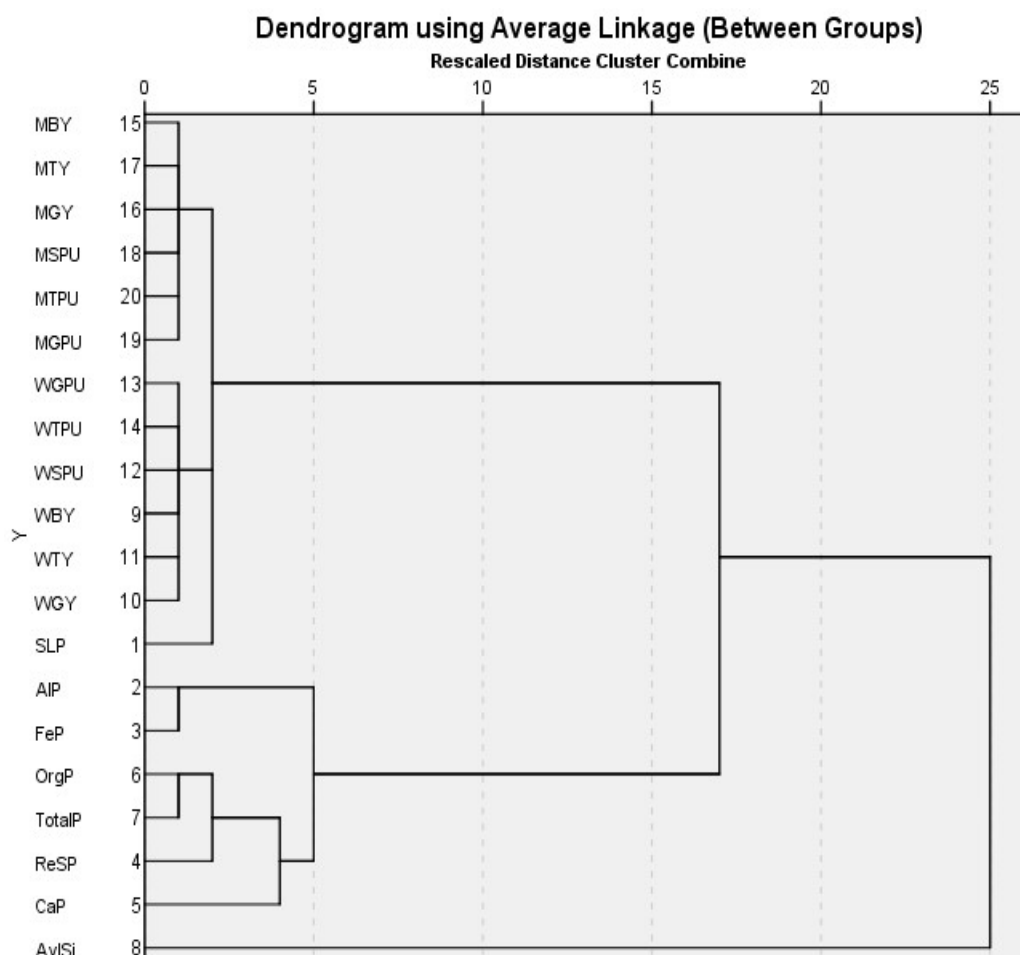


Figure 4.20. Dendrogram of hierarchical cluster analysis in Inceptisol

AvlSi = Available Si, WBY = Wheat biomass yield, WGY = Wheat grain yield, WTY = Wheat total yield, MBY = Mungbean biomass yield, MGY = Mungbean grain yield, MTY = Mungbean total yield, WGPU = Wheat grain P uptake, WTPU = Wheat total P uptake, MGPU = Mungbean grain P uptake, MSPU = Mungbean stover P uptake, MTPU = Mungbean total P uptake, SLP= Soluble and loosely bound P; AIP = Aluminium-bound P; FeP = Iron-bound P; ReSP = Reductant-soluble P; CaP = Calcium-bound P, OrgP = Total soil organic P, TotalP = Total soil P

4.15.3. Stepwise multiple linear regression

An attempt was made to quantify the contribution of different soil P fractions as well as Si availability in soil towards the total yield of wheat and mungbean in Alfisol and Inceptisol through multiple linear regression analysis (Tables 4.23- 4.26).

4.15.3.1. Multiple linear regression in Alfisol

It was evident from the regression analysis that as high as 95% variation in total yield of wheat in Alfisol could be explained by soluble and loosely bound P (SL-P) as well as the Si availability in the post-harvest soil; out of which, SL-P alone could explain 91% variation (Table 4.23). It was also observed that the soluble and loosely bound P, available Si, reductant soluble P (ReS-P), and calcium-bound P were able to explain 98% variation in the total yield of the mungbean crop, which was grown to assess the residual effect of applied Si-rich ashes (Table 4.24). However, stepwise removal of parameters revealed the SL-P and ReS-P to be the most important parameters impacting mungbean yield, as these two parameters combinedly could explain 93% variation in the total yield of the mungbean (Table 4.24).

Table 4.23. Stepwise regression equations relating different independent variables with total yield of wheat in Alfisol

Model no.	Regression equation	r ²	P
1	Total yield of wheat= 3.48 + 0.95 (SL-P)	0.909**	<0.01
2	Total yield of wheat= -1.936 + 0.92 (SL-P) + 0.21 (Avl Si)	0.951**	<0.01

*SL-P= soluble and loosely bound P; Avl Si= Available Si (0.01 M CaCl₂-extractable) in soil; ** Significant at 1% probability level*

Table 4.24. Stepwise regression equations relating different independent variables with total yield of mungbean in Alfisol

Model no.	Regression equation	r ²	P
1	Total yield of mungbean = 4.13 + 0.92 (SL-P)	0.841**	<0.01
2	Total yield of mungbean = -0.28 + 0.73 (SL-P) + 0.35 (ReS-P)	0.930**	<0.01
3	Total yield of mungbean= -0.74 + 0.75 (SL-P) + 0.27 (ReS-P) + 0.12 (Avl Si)	0.939**	<0.01
4	Total yield of mungbean = -1.52 + 0.52 (SL-P) + 0.99 (ReS-P) + 0.57 (Avl Si) + 1.22 (Ca-P)	0.981**	<0.01

** SL-P= soluble and loosely bound P; ReS-P= reductant-soluble P; Ca-P= calcium-bound P; Avl Si= Available Si (0.01 M CaCl₂-extractable) in soil; ** Significant at 1% probability level*

4.15.3.2. Multiple linear regression in Inceptisol

It was evident from the regression analysis that as high as 94% variation in total yield of wheat in Inceptisol could be explained by soluble and loosely bound P (SL-P) as well as the Si availability in the post-harvest soil; out of which, SL-P alone could explain 92% variation (Table 4.25). It was also observed that SL-P, available Si, reductant soluble P (ReS-P), Ca-bound P, Al-bound P, and Fe-bound P were able to explain 99.7% variation in the total yield of the mungbean crop, which was grown to assess the residual effect of applied Si-rich ashes (Table 4.26). However, stepwise removal of parameters revealed the SL-P and ReS-P to be the most important parameters impacting mungbean yield, as these two parameters combinedly could explain 98.7% variation in the total yield of the mungbean (Table 4.26).

Table 4.25. Stepwise regression equations relating different independent variables with total yield of wheat in Inceptisol

Model no.	Regression equation	r^2	P
1	Total yield of wheat= $3.03 + 0.96 (\text{SL-P})$	0.923**	<0.01
2	Total yield of wheat= $-0.059 + 0.15 (\text{SL-P}) + 0.03 (\text{Avl Si})$	0.940**	<0.01

* *SL-P= soluble and loosely bound P; Avl Si= Available Si (0.01 M CaCl₂-extractable) in soil; ** Significant at 1% probability level*

Table 4.26. Stepwise regression equations relating different independent variables with total yield of mungbean in Inceptisol

Model no.	Regression equation	r ²	P
1	Total yield of mungbean= 3.59 + 0.96 (SL-P)	0.928**	<0.01
2	Total yield of mungbean= -0.11 + 0.82 (SL-P) + 0.28 (ReS-P)	0.987**	<0.01
3	Total yield of mungbean= -0.24 + 0.83 (SL-P) + 0.22 (ReS-P) + 0.08 (Avl Si)	0.991**	<0.01
4	Total yield of mungbean= -1.59 + 0.82 (SL-P) + 0.05 (ReS-P) + 0.13 (Avl Si) + 0.15 (Ca-P)	0.993**	<0.01
5	Total yield of mungbean= -1.22 + 0.83 (SL-P) + 0.17 (Avl Si) + 0.10 (Ca-P) - 0.10 (Al-P)	0.995**	<0.01
6	Total yield of mungbean= -1.69 + 0.81 (SL-P) + 0.13 (Avl Si) + 0.16 (Ca-P) - 0.52 (Al-P) - 0.46 (Fe-P)	0.997**	<0.01

* *SL-P= soluble and loosely bound P; ReS-P= reductant-soluble P; Avl Si= available Si (0.01 M CaCl₂-extractable) in soil; Ca-P= calcium-bound P; Al-P= aluminium-bound P; Fe-P= iron-bound P; ** Significant at 1% probability level*

The results of the present investigation have been discussed critically in this chapter drawing support from the published pieces of literature.

5.1. Effect of Si-rich ashes and PSM on the availability of P in soil

In our experiment, bio-available P or solution P was derived from the solubilization of the inorganic P (P_{ing}) pool and the mineralization of organic P (P_{org}), with a major contribution from the P_{ing} pool. Thus, an exponential model was used to investigate the kinetics of cumulative P release in soil. Several researchers (Shariatmadari *et al.*, 2006; Alam *et al.*, 2022b, 2022c) have already used the same model to study the P-release kinetics in soil. The increase in soil solution P content due to the exogenous addition of Si (via Si-rich ashes) in the soil environment in the present study can be explained by one or more of the following mechanisms: (1) Firstly, Si (as mono silicic acid, H_4SiO_4) competes with P (as orthophosphate, H_2PO_4^-) for binding sites on the surface of Fe and Al minerals, with silicate having a slightly lower affinity for binding than phosphate. However, at higher doses of applied Si, the competition between Si and P may shift in favour of Si, thereby, replacing the previously adsorbed phosphate by silicate (Schaller *et al.*, 2019). (2) Secondly, Si application reduces the availability of heavy metals in soil, which indirectly increases the bioavailability of P (Etesami *et al.*, 2021). Otherwise, these heavy metals would have reacted with P present in the soil solution to form sparingly soluble compounds or insoluble precipitates, rendering the P non-labile and thus, unavailable to plants. (3) Thirdly, the organic C adsorbed on soil mineral surfaces can be displaced by applied Si. The released C will eventually provide energy to the soil microbes. It was also reported that bacteria utilize Si-based autotrophs to get the energy required to support CO_2 fixation (Das *et al.*, 1992). Moreover, applied Si was found to enhance the population and activity of PSMs such as phosphate solubilizing bacteria (PSB) and phosphate solubilizing fungi (PSF) in soil (Rangaraj *et al.*, 2014). Thus, enhanced activity and metabolism of the native soil microbes along with the exogenous applied microbe will lead to the better solubilization of recalcitrant P to increase the plant-available P.

Additionally, bacterial strains can dissolve insoluble P_{ing} compounds and mineralize P_{org} compounds to plant available forms like H_2PO_4^- and HPO_4^{2-} (Khan *et*

al., 2009; Alam *et al.*, 2022b). Bacterial metabolism produces a variety of low molecular weight organic acids. The PSM used in this experiment is a bacterial strain, *Lactococcus lactis*, essentially produces lactic acid as the principal by-product of its carbohydrate metabolism (de Lacerda *et al.*, 2016). The organic anions thus produced can increase the availability of P in soil solution by: (i) forming stable complexes with various cations (*e.g.*, Ca^{2+} , Fe^{2+} , Fe^{3+} , Al^{3+} , *etc.*) in soil rendering them unavailable for reaction with phosphate, (ii) competing with the phosphate anion for sorption sites in soil, and (iii) substituting for the sorbed phosphate on Fe- and Al-oxide surfaces via ligand exchange (Whitelaw, 1999; Etesami *et al.*, 2021). Additionally, PSB is capable of mineralizing complex organic forms of soil P via the secretion of phosphatase enzymes, resulting in P solubilization (Khan *et al.*, 2009).

Interestingly, the interaction of PSM $\times$ Si-dose was found to be significantly positive in the case of mediating the P bioavailability in soil solution (Tables 4.3 and 4.4). The Si addition into the soil through Si-rich ashes (or charred materials) eventually increases the abundance of reduced C, which acts as a source of nutrition for PSM. Also, highly porous materials preferred by bacteria for adsorption (Samonin and Elikova, 2004), are provided by the ashes. Moreover, the Si supplied through the ashes can enhance the population and activity of PSM in soil (Rangaraj *et al.*, 2014).

Among the Si-rich ashes, CCA maintained a higher level of P release than the other two ashes (SBA and RHA) during the 90 days of incubation in both soils. Among the Si-rich ashes, CCA had much lower per centage Si content than the other two ashes (Table 4.2). Therefore, in order to maintain the equivalent Si level in case of a particular Si dose applied through different ashes, the amount of CCA applied was much higher than the other two ashes. The addition of CCA (which is basically a charred material) eventually increased the abundance of reduced C, which acted as a source of nutrition for PSM. Moreover, highly porous materials preferred by the applied micobe for adsorption, were provided by the ashes. So, higher amount of applied CCA might have boosted the population and activity of the applied PSM in soil to a greater extent, as compared to the other two ashes.

5.2. Effect of Si-rich ashes and PSM on the availability of Si in soil

Soluble or soil solution Si originated mostly from the dissolution of both amorphous and crystalline forms of Si contained in the Si-rich ashes. Additionally, Si was dissolved

from silicate minerals already present in the soil. As silicate minerals dissolution follows zero-order kinetics, *i.e.*, linear kinetics (Wood and Walther, 1983), a linear model was chosen to analyze the Si release kinetics in soil. Several researchers (Obihara and Russell, 1972; Alam *et al.*, 2022b, 2022c) have earlier used the linear kinetics model to study the Si-release kinetics in soil.

Interestingly, it is evident from the present study that the PSM inoculation enhanced the soluble Si content in soil considerably during 90 days of incubation (Tables 4.3. and 4.4.). As a result of their basic metabolic processes such as the respiration and release of organic acids, PSMs are often able to weather soil silicate minerals as well (Brucker *et al.*, 2020). The PSM used in this experiment, a bacterial strain (*Lactococcus lactis*), essentially produces lactic acid as the principal by-product of its carbohydrate metabolism (de Lacerda *et al.*, 2016). On the other hand, microbial respiration generates CO₂, which generates H₂CO₃ through a hydrolysis reaction. The secreted organic acids and the carbonic acid, both are mild acids, which might have hastened the dissolution of Si from the applied Si-rich ashes. Recent reports (Rezakhani *et al.*, 2019) also indicate the ability of the PSM to increase the availability and subsequent uptake of Si by plants.

5.3. Adsorption-desorption behaviour of P in soils as impacted by Si-rich agro-wastes

5.3.1. Phosphorus adsorption

Phosphorus isotherms are used practically for indicating the replenishing ability of soils to supply P to the soil solutions, which is an important factor in the P-supplying capacity of soils to plants (Singh *et al.*, 2005). The current analysis had shed light on the adsorption capacity as well as the energy with which P is retained in the soil system. The present study showed that the amount of P adsorbed decreased significantly due to the application of Si-rich agro-wastes, with respect to untreated control (No P). Such a negative effect of applied Si on P adsorption has also been demonstrated by a few researchers (Obihara and Russell, 1972; Owino-Gerrho and Gascho, 2004; Sandim *et al.*, 2014; Haynes and Zhou, 2018). Usually, silicate and phosphate anions are thought to be adsorbed on hydroxylated ferric and aluminium surfaces in soil (Obihara and Russell, 1972). Through a process called ligand exchange, both of these anions are specifically adsorbed to such variable charge surfaces (Haynes and Zhou, 2018). Both

phosphate and silicate can form inner-sphere complexes with variable charge surfaces. According to Obihara and Russell (1972), once a certain amount of silicate is adsorbed or a certain concentration of silicate is reached, there is a possibility of a linear relationship between the amount of Si adsorbed and P desorbed. The SiO_4^{4-} ions, supplied by the Si sources, can replace PO_4^{3-} from adsorption sites. This is possible because Si adsorption is near maximal in the pH range 6-11, whereas P adsorption is quickly decreasing. Such findings imply that, in order to successfully reduce phosphate adsorption by prior silicate application, the soil pH would need to be relatively high (>6.0) (Ghosh *et al.*, 2023). Both the soils used in our study had an initial pH value of greater than 6. Another reason for decreased P adsorption with increasing levels of Si application is due to an increase in the pH of the soil solution. If the soil has very little phosphate adsorbed, the capacity of a silicate solution at a given concentration to desorb phosphate rises as the pH of the soil rises (Obihara and Russell, 1972). The Si-rich ash used in the present study is an amorphous substance, which releases different ionized metals into the soil system on decomposition. Principally, due to the presence of a higher amount of total alkali metals (Na, K) or alkaline earth metals (Ca, Mg) in the ashes, the pH values of these ashes are much higher (Xiao *et al.*, 2014). These biomass ashes, when applied in higher doses, can substantially increase the base saturation of the soil system, in turn, increasing the soil pH (Islabão *et al.*, 2014). Several studies have shown the potentiality of these biomass ashes in increasing the pH of the soil (Islabão *et al.*, 2014; Singh *et al.*, 2019). Various workers also attributed the reduction in phosphate adsorption to a concomitant increase in soil pH (Ma and Takahashi, 1990; Owino-Gerrho and Gascho, 2004; Barman *et al.*, 2020).

The P adsorption in the experimental soils was described using Freundlich and Langmuir adsorption isotherms. These adsorption models aid in comprehending the link between the amount of P adsorbed per unit soil weight and the concentration of P in soil solution. Both the Freundlich and Langmuir equations fit the adsorption data from the current experiment well, with high prediction coefficients, demonstrating that both equations could explain P adsorption in experimental soils to a reasonable amount. These equations had also been successfully used earlier by several other workers to describe P adsorption in different soils (Reddy *et al.*, 1980; Said and Dakermanji, 1993; Shao *et al.*, 2006; Pal, 2011; Gupta *et al.*, 2014; Jalali *et al.*, 2018). The bonding energy of adsorbed P as described by Langmuir parameter 'k' is most important in describing

the affinity of soil for P. A higher 'k' value indicates stronger P adsorption (Wang and Liang, 2014). In our study, it was observed that the 'k' value decreased with Si application, over control, in both Alfisol and Inceptisol. The value of 'k' was relatively higher in the case of Alfisol than that of Inceptisol. This indicates, P was held more tenaciously in Alfisol, as compared to Inceptisol. The presence of plentiful amounts of sesquioxides in Alfisol might have contributed towards a higher value of bonding energy. Hydrous-oxides of Fe and Al are found as a fine coating on the surfaces of clay minerals that have large surface areas and hold P more strongly (Pal, 2011). Generally, highly weathered soils with high contents of oxides, as in the case of Alfisol in our study, tend to adsorb high amounts of P, with little possibility of recovery of P adsorbed (Guedes *et al.*, 2016). That's why, the values of 'b' (maximum adsorption capacity) were much higher in the case of Alfisol, as compared to Inceptisol. Both the 'b' and maximum phosphate buffering capacity (MPBC) decreased gradually with increasing levels of applied Si. Application of Si, either by competitive adsorption or by an increase in pH of the soil solution decreased adsorption maxima across the soils. The partition of P between the solution and solid phase is regulated by MPBC (Shirvani *et al.*, 2005). The value of MPBC decreased with increased Si application, *i.e.* P concentration at a given level of labile P increased with Si application. The less buffered soil has lesser bonding energy indicating increased P concentration in the soil solution. These results suggest the application of silicate may decrease P adsorption, in turn, increasing the availability of P in soil.

5.3.1. Phosphorus desorption

It was apparent that the application of higher doses of Si sources (250 mg Si kg⁻¹ soil) increased the desorption of P with respect to control in both soils. It was apparent that only a small fraction of the adsorbed P was available for desorption. The hysteresis index (%) signifies the hysteric property of the adsorbed nutrient in the soil, with a higher value representing more hysteresis, *i.e.* more difficult release of the nutrient for plant need (Deng *et al.*, 2010). Distinct hysteresis between adsorption and desorption was discernible from the desorption index. The values of hysteresis index (%) were higher in Alfisol, as compared to Inceptisol. The P was held more tenaciously in Alfisol during the adsorption process, therefore, it tended to release a smaller proportion of the adsorbed P during desorption. The P retention mechanisms in the oxides difficult the desorption process, because the energy required to remove the central atoms of the

crystal structure is greater than the energy required for these to be formed (Sparks, 2003). The application of higher doses of Si sources (250 mg Si kg⁻¹ soil) also decreased the hysteresis index (%) of P with respect to control in both soils. When no competing anion is there in soil solution, soils with high contents of oxides or having high specific areas tend to adsorb high amounts of P, with little possibility of recovery of P adsorbed. However, the exogenous Si application can act in preventing the irreversible retention of P and increasing nutrient recovery chances. Application of higher doses of the Si sources (250 mg Si kg⁻¹ soil) decreased the adsorption of P as well as increased the desorption of P with respect to control in both soils. Thus, the treatments receiving external Si application had a higher potential to release the adsorbed P to meet the P requirements for crop needs.

5.4. Impact of combined application of Si-rich ashes, PSM and P fertilization on different fractions of P in soil

5.4.1. Inorganic P fractions

Fractionation analysis elucidates the distribution of any nutrient in soil into different distinct fractions, and the availability of these fractions to plants varies according to their varied chemical nature. The soluble and loosely bound P (SL-P) fraction denotes P present in soil solution or loosely (*i.e.* non-specifically) bonded on ion exchange sites that are readily available for plant uptake (Alam *et al.*, 2020). The application of different combinations of Si-rich ashes, PSM and P fertilization increased the SL-P fraction significantly. However, the maximum increase in the SL-P fraction (over no-P control), occurred in the case of 100% P treatment, followed by 75% P, in both the soils. It was quite expected, as these treatments involved the application of higher doses of water-soluble forms of P. On the other hand, Al-P and Fe-P fractions represent P which is tightly held on Fe- and Al-oxide surfaces in soil, respectively, via chemisorption/ligand adsorption. These two fractions help maintain steady levels of plant-available P in soil and can undergo desorption to recharge the SL-P fraction (Zhang and Mackenzie, 1997). The application of different combinations of Si-rich ashes, PSM and P fertilization decreased the Fe-P and Al-P fractions in post-harvest soils. Both the applied Si (through Si-rich ashes) and PSM dissolved the Fe- and Al-bound P fractions in the present investigation, which in turn, contributed to the SL-P fraction. According to Sigg and Stumm (1981), the electric charge on the surface of Fe minerals causes silicic acid to release protons (H⁺) therein. Thus, Si adsorption

eventually transforms the Fe mineralogy near the mineral surfaces into colloidal Fe-silicates or Fe-hydroxy silicates. Thereby, Si adsorption ultimately shifts the Fe mineralogy into colloidal Fe-silicates or Fe-hydroxy silicates in close proximity to the mineral surfaces. Silicon, thus, can displace the phosphate adsorbed to Fe and Al minerals, if higher doses of exogenous Si are applied. Organic anions produced by microbes, on the other hand, can compete with phosphate for adsorption sites on Fe and Al oxides, and ligand exchange mechanisms can also replace sorbed phosphate from Al and Fe oxide surfaces, making phosphate available in soil solution (Whitelaw, 1999). The application of P at 100% and 75% of recommended doses caused a net increase in the Al-P and Fe-P fractions, over control. The increment occurred in these two fractions with P fertilization, as added excess fertilizer P beyond the crop requirement can be stored into these fractions, which in turn maintain the levels of plant-available P through the desorption process (Zhang and MacKenzie, 1997).

The reductant soluble P (ReS-P) and calcium-bound P (Ca-P) fractions are generally considered as a non-labile P pool in soil. The fraction of P which is not extracted by successive neutral salts, fluoride, alkali, or acid treatments is found in the ReS-P fraction and is mainly attributed to P present in the structure of layer silicate clays (Jackson, 1973). The Ca-P primarily denotes the primary mineral-P such as apatite, although, minor amounts of mono-, di- and octa-calcium phosphate that may occur as transitional forms (Chang and Jackson, 1957). The ReS-P and Ca-P fractions are potentially available pools of P, which can be available in soil when conditions permit and thus, generally are considered bioavailable pools in long-term (Johnston and Syers, 2009; Alam *et al.*, 2022a). In the mungbean crop, there was no external addition of P-fertilizer and it was grown to study the residual effect of the applied treatments to the first crop of wheat. In that case, the ReS-P fraction and Ca-P fraction also contributed to the SL-P fraction, from where the crop got the P nutrition. Basically, the SL-P is supposed to be in dynamic equilibrium with the Fe-P and Al-P fractions. The Fe-P and Al-P fractions, in turn, remain in a slow equilibrium with the ReS-P and Ca-P fractions, which gradually becomes plant available with time (Johnston and Syers, 2009). Additionally, the secretion of different low molecular weight organic acids due to microbial metabolism, and the generation of H_2CO_3 as a result of microbial respiration, which in turn, help in the solubilization of Ca-phosphates. The Ca-P fraction contributed merely 10.4% of the total P in the case of Alfisol; whereas it

constituted ~42.7% of the total P in the Inceptisol. However, the solubilization of the Ca-P was lesser in the Inceptisol, as compared to the Alfisol. At high pH, Ca binds P resulting in the co-precipitation of less soluble Ca-phosphates and Ca-carbonates. This starts at a pH of ~7 under elevated Ca availability in soils (Tunesi *et al.*, 1999). The Si-rich ashes used in the present study comprised of amorphous substances, which are rich in alkaline earth metals (Ca, Mg). Thus, higher doses of ashes application might have co-precipitated the solubilized P (present in soil solution) to some extent, in the Inceptisol. Additionally, at soil pH levels in the range of that of the Inceptisol of IARI (pH 8.12), precipitation of carbonates can occur and the soluble P can be occluded on the surface of calcium carbonate precipitates.

5.4.2. Organic P

Of the total soil P pool, about 50% of P is in organic forms (Richardson, 2001), which varies between 4% and 90% in most soils (Yadav and Verma, 2012). In our experiment, the organic P pool constituted ~27.2% and ~29.0% of the total P in Alfisol and Inceptisol, respectively. The PSM can mineralize the organic P in soil via phosphatase enzyme secretion. Exogenous Si can be used to boost PSM activity and population in soil (Rangaraj *et al.*, 2014). Moreover, the application of Si through charred material or ashes in soil eventually enhances the availability of reduced C as a source of nutrition for PSM. Additionally, the bacteria prefer highly porous materials for adsorption (Samonin and Elikova, 2004), and all the ashes used in this study are the best fitted materials in this category. Thus, it is clear that Si acted as a stimulant in increasing the population and activity of PSM, which resulted in enhanced mineralization of organic P via increased microbial phosphatase secretion.

5.5. Impact of combined application of Si-rich ashes, PSM and P fertilization on the growth parameters of crops

Combined application of Si-rich ashes and PSM, with or without P fertilizer, positively influenced the grain and total yield of wheat. Also, a good residual effect of these treatments was observed in the subsequent mungbean crop. In the 'results' section, it was observed that the combined application of fertilizer P, Si sources and PSM significantly increased the plant available P in soil. Silicon is generally not considered as an essential element; however, it is considered as a beneficial element. Several researchers have reviewed the recent advances in the beneficial effects of Si on plant

growth and grain quality under nutrient-deficient conditions (Liu *et al.*, 2017; Neu *et al.*, 2017). Both the soils used in our study (Alfisol and Inceptisol) had marginally medium to low status of plant-available P, where P deficiency was a limiting factor for plant yield. Applied Si has been reported to alleviate many environmental stresses, including P deficiency stress in soil. Several authors have reported the positive effect of applied Si in increasing plant P availability in P-deficient soils (Schaller *et al.*, 2019; Barman *et al.*, 2020; Alam *et al.*, 2022b, 2022c). Applied Si increased the plant availability of P in the soils, in turn, leading to enhanced crop yields. On the other hand, the positive effects of P fertilization on the shoot and total biomass yields of different crops have been reported in the literature (Yousefi *et al.*, 2011; Sharma *et al.*, 2012; Alam *et al.*, 2022a). The improvement in growth parameters of the wheat crop may be due to the stimulating effect of P on plant metabolic processes such as cell division, root elongation, and improved function of ATP and ADP (Sharma and Parmar, 1998; Sharma *et al.*, 2012). Moreover, PSM inoculation leads to improved enzyme activities in the rhizosphere soil and thus better nutrient availability to the plants. They are also known to produce plant growth regulators such as ethylene, auxin, gibberellin, cytokinin, *etc.* (Khan *et al.*, 2009). Such positive effects of PSM inoculation on crop yield and P uptake have already been reported in literature (Yousefi *et al.*, 2011; Wang *et al.*, 2014; Pradhan *et al.*, 2018; Alam *et al.*, 2022a).

5.6. Stepwise regression equations relating different independent variables with the total yield of wheat and mungbean

In the present investigation, contributions of different independent variables (soil inorganic P fractions, soil organic P, available Si in post-harvest soil) towards total yield, in wheat, as well as mungbean crops, were quantified through regression analysis. The relationships of various independent variables with yield parameters showed similar trends in both the soils (Alfisol and Inceptisol) for a particular crop; however, showed dissimilar trends in different crops. The different results obtained in two different crops may be due to the fact that the treatments were applied to wheat crop only and mungbean crop was grown to study the residual effect of the applied treatments. In both the soils, soluble and loosely bound P (SL-P) and available Si in soil contributed positively to the total yield of the wheat crop. The SL-P fraction denotes P present in soil solution or loosely (*i.e.* non-specifically) bonded on ion exchange sites that are readily available for plant uptake (Alam *et al.*, 2020). Generally, SL-P is

considered as the most labile form of P, which directly can influence plant yield and P uptake (Alam *et al.*, 2022b). This might be the reason for a high positive contribution of SL-P fraction towards the total yields of wheat, as well as mungbean crops. On the other hand, although not considered as an essential element, Si has a positive impact on plant growth and development. Applied Si has been reported to alleviate many environmental stresses, including P deficiency stress in soil. Several authors have reported the positive effect of applied Si in increasing plant P availability in P-deficient soils (Schaller *et al.*, 2019; Barman *et al.*, 2020; Alam *et al.*, 2022b, 2022c). Both the soils used in our study (Alfisol and Inceptisol) had marginally medium to low status of plant-available P, where P deficiency was a limiting factor for plant yield. Applied Si increased the plant availability of P in the soils, in turn, leading to enhanced crop yields. That's why plant-available Si in the post-harvest soils turned out to be an important parameter imparting high positive contribution towards the total yields of crops.

However, it was also observed that the SL-P and reductant soluble P (ReS-P) were the most important parameters impacting mungbean yield, in both soils. The fraction of P which is not extracted by successive neutral salts, fluoride, alkali or acid treatments is found in ReS-P fraction and is mainly attributed to P present in structure of layer silicate clays (Jackson, 1973). The ReS-P is generally considered as a non-labile P pool in soil. This is a potentially available pool of P, which can be available in soil when conditions permit and thus, generally is considered a bioavailable pool in long-term (Johnston and Syers, 2009; Alam *et al.*, 2022b). In the mungbean crop, no external addition of P fertilizer was there and it was grown to study the residual effect of the applied treatments. In that case, the ReS-P fraction also contributed to the SL-P fraction, from where the crop got the P nutrition. Basically, the SL-P is supposed to be in dynamic equilibrium with the Fe-P and Al-P fractions. The Fe-P and Al-P fractions, in turn, remain in a slow equilibrium with the ReS-P fraction, which gradually becomes plant available with time (Johnston and Syers, 2009). Therefore, the ReS-P fraction also, along with the SL-P fraction, positively impacted mungbean yield.

5.7. Linkage between principal component analysis (PCA), hierarchical cluster analysis (dendrogram), and stepwise regression equations:

Principal component analysis (PCA) revealed the available Si to be present in PC-3 which is orthogonal to PC-1. Whereas, the dendrogram revealed available Si and yield to be important group variables. This indicates a mechanistic process undergoing in soil

which was confirmed by the stepwise regression analysis, where available Si was an important variable in the regression equation. This directly marks the role of Si in influencing crop yield. However, available Si was present in PC-3; and P fractions such as Fe-P, Al-P and Ca-P were present in PC-2. Thus, understandably, Si is influencing crop yield by moderating concentrations of Fe-P, Al-P and Ca-P. Hence, it appeared in stepwise regression analysis.

The research work entitled “**Enhancing soil phosphorus availability to wheat (*Triticum aestivum*) and mungbean (*Vigna radiata*) using silicon-rich agricultural wastes and phosphate solubilizing microorganism**” was carried out with the following objectives: (i) to monitor the release pattern of phosphorus in Alfisol and Inceptisol as affected by silicon-rich agricultural wastes and phosphate solubilizing microorganism, (ii) to study the effect of silicon-rich agricultural wastes on adsorption-desorption behaviour of phosphorus in soils, (iii) to assess the effect of applied silicon-rich agricultural wastes and phosphate solubilizing microorganism on phosphorus availability to wheat (*Triticum aestivum*) and mungbean (*Vigna radiata*) crops, and (iv) to find out the changes in different fractions of soil phosphorus as affected by silicon-rich agricultural wastes and phosphate solubilizing microorganism. For this purpose, bulk surface soils (0-15 cm depth) of Alfisol and Inceptisol orders having a high amount of total phosphorus (P) with concomitant low to marginally medium plant-available P were collected from Ranchi (Jharkhand) and IARI research farm (New Delhi), respectively. The soils from Ranchi and New Delhi were having pH of 6.32 and 8.12, respectively.

A 90-day incubation study was conducted at 25 °C to assess the P and silicon (Si) release kinetics from the soil samples treated with Si-rich agro-wastes (ashes) and phosphate solubilizing microorganism (PSM). Liquid pure culture of the PSM, *Lactococcus lactis* ($\sim 10^9$ cfu mL⁻¹), was used for this study. A factorial completely randomized design with 3 factors namely, Si sources [three levels: sugarcane bagasse ash (SBA), rice husk ash (RHA), and corn cob ash (CCA)], PSM (two levels: without PSM and with PSM); and Si doses [three levels: no Si (Si₀), 125 (Si₁₂₅) and 250 (Si₂₅₀) mg Si kg⁻¹ soil] was followed. In both soils, an exponential model was selected to study the P release kinetics in the soil; whereas, a linear model was selected to study the Si release kinetics in the soil. In Alfisol, PSM increased the solution P and soluble Si level by ~22.2 and 1.88 per cent, respectively, over no PSM; whereas, Si₁₂₅ and Si₂₅₀ increased solution P by ~60.4 and 77.1 per cent, as well as soluble Si by ~41.5 and 55.5 per cent, respectively, over Si₀. In Inceptisol, the PSM increased solution P and soluble Si by ~17.2 and 1.46 per cent, respectively, over no PSM; whereas, Si₁₂₅ and Si₂₅₀ increased solution P by ~44.3 and 57.1 per cent, as well as soluble Si by ~39.0 and 50.8

per cent, respectively, over Si_0 . Among different Si sources, CCA maintained a significantly higher level of mean solution P after 90 days of incubation, than SBA and RHA, in both Alfisol and Inceptisol. Moreover, the interaction of $\text{PSM} \times \text{Si}$ doses was found significant ($P < 0.05$) in both soils.

To study the effect of Si-rich agricultural wastes on the adsorption-desorption behaviour of P in soil, a separate incubation experiment was carried out. Soil samples were treated with the highest dose of Si (*i.e.* 250 mg Si kg^{-1} soil) at 25 °C for 90 days. Then the soil samples were air-dried and processed. These processed soil samples were further subjected to equilibration with solutions containing graded concentrations of P in 0.01 M CaCl_2 solution. Both the Freundlich and Langmuir equations fit the adsorption data from the current experiment well, with high prediction coefficients, demonstrating that both the equations could explain P adsorption in the experimental soils to a reasonable amount. Application of higher doses of the Si sources (250 mg Si kg^{-1} soil) decreased the adsorption of P (by 12-22% in Alfisol and 7-18% in Inceptisol) as well as increased the desorption of P (by 31-47% in Alfisol and 11-20% in Inceptisol) with respect to control in both soils. Application of Si sources decreased the adsorption maxima as well as affinity constant values in both soils. Among different treatments, the application of CCA to supply 250 mg Si kg^{-1} soil, caused the maximum decrement in the amount of P adsorbed, in both soils. In Alfisol, the hysteresis index varied from 87.5% in control to 81.9% in the treatment containing CCA at 250mg Si kg^{-1} soil. On the other hand, in Inceptisol, the hysteresis index varied from 95.2% in control to 90.7% in the treatment containing CCA at 250 mg Si kg^{-1} soil.

Based on the P-release pattern under the incubation study, the best-performing treatments were further tested in pot culture experiments for their ability to supply P for plant uptake in a wheat-mungbean cropping sequence. The different treatments were applied to wheat crop only and mungbean was grown to study the residual effect of the applied treatments. The sequential fractionation of soil P (Kuo, 1996) was done in the post-harvest soils after the harvest of the mungbean crop to find out the changes in different fractions of soil P. Administration of Si-rich ashes with PSM significantly improved P bioavailability to wheat and mungbean in the pot-culture experiment. Application of CCA containing 250 mg Si kg^{-1} in combination with PSM and 50% recommended dose of P (RDP) enhanced plant available P by 29.6% for wheat and 16.8% for mungbean in Alfisol; and by 20.2% for wheat and 14.1% for mungbean in

Inceptisol. In both Alfisol and Inceptisol, the soluble and loosely bound P (SL-P) was increased significantly due to the combined application of Si-rich ashes and PSM; whereas, the Fe-P, Al-P as well as Ca-P fractions were solubilized resulting in the increase in SL-P. In the case of mungbean crop, which was grown on residual soil fertility, the reductant soluble P (ReS-P) fraction also contributed to crop yield. In Alfisol, overall, 0.50 to 3.21% of total inorganic P in soil was solubilized; as well as, 0.55 to 2.69% of total organic P in soil was mineralized, with respect to control. Whereas, in Inceptisol, overall, 0.78 to 2.23% of total inorganic P in soil was solubilized; as well as, 0.41 to 2.58% of total organic P in soil was mineralized, with respect to control. Hierarchical cluster analysis revealed two broad variable groups representing yield and Si availability indicating the marked importance of Si in impacting crop yield. Principal component analysis (PCA) revealed the available Si to be present in PC-3 which is orthogonal to PC-1. Whereas, the dendrogram revealed available Si and yield to be important group variables. This indicates a mechanistic process undergoing in soil environment which was confirmed by the stepwise regression analysis, where available Si was an important variable in the regression equation. This directly marks the role of Si in influencing crop yield. However, available Si was present in PC-3; and P fractions such as Fe-P, Al-P and Ca-P were present in PC-2. Thus, understandably, Si is influencing crop yield by moderating concentrations of Fe-P, Al-P and Ca-P.

Combined application of Si-rich ashes, PSM and reduced dose of P fertilizer significantly boosted the yield of the wheat crop, as well as showed a good residual effect in the subsequent mungbean crop. Among the Si-rich ashes, the performance of CCA was the best. Application of CCA containing 250 mg Si kg⁻¹ in combination with PSM and 50% RDP also boosted wheat yield by at least 17% and mungbean yield by at least 28% in those soils. Hence, the application of CCA containing 250 mg Si kg⁻¹ in combination with PSM and 50% RDP can sustain wheat productivity equivalent to 75% P. Thus, it could save 25% of P-fertilizer. It also maintained higher residual P status than the control (no P) during mungbean cultivation.

Based on the above observations, finally we can conclude that:

- In both Alfisol and Inceptisol, the application of Si through different Si-rich ashes along with PSM significantly enhanced P mobilization. Among different Si sources, corn cob ash (CCA) containing 250 mg Si kg⁻¹ in combination with

PSM mobilized a greater (~1.99 and 2.32 times in Inceptisol and Alfisol, respectively) amount soil P as a consequence of greater Si concentration in soils. Hence, the combined application of Si and PSM had a synergistic effect on P mobilization.

- Application of higher doses of the Si sources (250 mg Si kg⁻¹ soil) decreased the adsorption of P (by 12-22% in Alfisol and 7-18% in Inceptisol) as well as increased the desorption of P (by 31-47% in Alfisol and 11-20% in Inceptisol) with respect to control in both soils. Application of Si sources decreased the adsorption maxima as well as affinity constant value in both soils. These observations led to the inference that the application of Si-rich ashes, such as SBA, RHA and CCA could potentially trigger P solubilization and minimize P adsorption to supply P demand of crops.
- Administration of Si-rich ashes with PSM significantly improved P bioavailability to wheat and mungbean in the pot-culture experiment. Application of CCA containing 250 mg Si kg⁻¹ in combination with PSM and 50% RDP enhanced plant available P by 29.6% for wheat and 16.8% for mungbean in Alfisol; and by 20.2% for wheat and 14.1% for mungbean in Inceptisol.
- Application of CCA containing 250 mg Si kg⁻¹ in combination with PSM and 50% RDP also boosted wheat yield by at least 17% and mungbean yield by at least 28% in those soils. Hence, the application of CCA containing 250 mg Si kg⁻¹ in combination with PSM and 50% RDP can sustain wheat productivity equivalent to 75% P. Thus, it could save 25% of P-fertilizer. It also maintained higher residual P status than the control (no P) during mungbean cultivation.
- In both Alfisol and Inceptisol, the soluble and loosely bound P (SL-P) was increased significantly due to the combined application of Si-rich ashes and PSM; whereas, the Fe-P, Al-P as well as Ca-P fractions were solubilized to result in the increase in SL-P.
- In the case of mungbean crop, which was grown on residual soil fertility, the reductant soluble P (ReS-P) fraction also contributed to crop yield significantly.
- So, the present study provides a cost-effective and environmental-friendly strategy to facilitate P availability in low-P Alfisol and Inceptisol. Most

importantly, these Si-rich agro-wastes, thus, can be converted to a valuable wealth, by means of supplementing and reducing the requirement of costly phosphatic fertilizers for crop production. However, such findings should be tested for various soils and crops in field investigations for further understanding.

Enhancing soil phosphorus availability to wheat (*Triticum aestivum*) and mungbean (*Vigna radiata*) using silicon-rich agricultural wastes and phosphate solubilizing microorganism

The deficiency of phosphorus (P) largely limits crop production substantially in agricultural soils globally. Interestingly, soils do not necessarily have a low total P content, however, a significant portion of this P is fixed in plant-unavailable forms. It is imperative to find suitable strategies to utilize the native fixed soil P, as continuous mining of rock phosphate (RP) for P-fertilizer production has put non-renewable, finite deposits of RP on the verge of depletion. Phosphate solubilizing microorganism (PSM) and silicon (Si)-rich agro-wastes (as Si sources) were investigated with the aim of searching for eco-friendly and cost-effective strategies to solubilize the recalcitrant soil P in agriculture. Laboratory incubation and pot-culture experiments were conducted using bulk surface (0-15 cm) soils of Alfisol (pH= 6.32) from Ranchi (Jharkhand) and Inceptisol (pH= 8.12) from IARI (New Delhi) having low available P status. A 90-days incubation experiment was carried out in these two soils at 25 °C with field capacity soil moisture to assess the P and Si release kinetics. A factorial completely randomized design with 3 factors namely, Si sources [three levels: sugarcane bagasse ash (SBA), rice husk ash (RHA) and corn cob ash (CCA); PSM (two levels: without PSM and with PSM); and Si doses [three levels: no Si (Si_0), 125 (Si_{125}) and 250 (Si_{250}) mg Si kg⁻¹ soil] was followed. In Alfisol, the PSM increased solution P and soluble Si level by ~22.2 and 1.88 per cent, respectively, over no PSM; whereas, Si_{125} and Si_{250} increased solution P by ~60.4 and 77.1 per cent, as well as soluble Si by ~41.5 and 55.5 per cent, respectively, over Si_0 . In Inceptisol, the PSM increased solution P and soluble Si by ~17.2 and 1.46 per cent, respectively, over no PSM; whereas, Si_{125} and Si_{250} increased solution P by ~44.3 and 57.1 per cent, as well as soluble Si by ~39.0 and 50.8 per cent, respectively, over Si_0 . Moreover, the interaction of PSM×Si doses was found significant in both soils. Application of higher doses of the Si sources (250 mg Si kg⁻¹ soil) decreased the adsorption of P (by 12-22% in Alfisol and 7-18% in Inceptisol) as well as increased the desorption of P (by 31-47% in Alfisol and 11-20% in Inceptisol) with respect to control in both soils. Application of Si sources decreased the adsorption maxima as well as affinity

constant value in both soils. Administration of Si-rich ashes with PSM significantly improved P bioavailability to wheat and mungbean in the pot-culture experiment. Application of CCA containing 250 mg Si kg⁻¹ in combination with PSM and 50% of the recommended dose of P (RDP) enhanced plant available P by 29.6% for wheat and 16.8% for mungbean in Alfisol; and by 20.2% for wheat and 14.1% for mungbean in Inceptisol. In both the soils, the soluble and loosely bound P (SL-P) was increased significantly due to the combined application of Si-rich ashes and PSM; whereas, the Fe bound P, Al bound P as well as Ca bound P fractions were solubilized to result in the increase in SL-P. In the case of the mungbean crop, which was grown on residual soil fertility, the reductant soluble P (ReS-P) fraction also contributed to crop yield. Application of corn cob ash (CCA) containing 250 mg Si kg⁻¹ in combination with PSM and 50% RDP boosted wheat yield by at least 17% and mungbean yield by at least 28% in those soils. Hence, the application of CCA containing 250 mg Si kg⁻¹ in combination with PSM and 50% RDP can sustain wheat productivity equivalent to 75% RDP. So, the present study provides a cost-effective and environmental-friendly strategy to facilitate P availability in low-P Alfisol and Inceptisol. However, such findings should be tested for various soils and crops in field investigations for further understanding.

Keywords: Silicon-rich agro-wastes, Phosphorus fractionation, Phosphorus release kinetics, Phosphorus solubilization, Phosphate solubilizing microorganism

सिलिकॉन संपन्न कृषि अपशिष्टों और फॉस्फेट घोलक सूक्ष्मजीवों का उपयोग करके गेहूं (*ट्रिटिकम एस्टीवम*) और मूंग (*विग्रा रेडियाटा*) के लिए मृदा फास्फोरस उपलब्धता को बढ़ाना

कृषि मृदाओं में फॉस्फोरस की कमी वैश्विक स्तर पर फसल उत्पादन को काफी हद तक सीमित कर देती है। रोचक बात यह है कि जरूरी नहीं कि मिट्टी में कुल फॉस्फोरस कम हो, क्योंकि इस फॉस्फोरस का एक महत्वपूर्ण हिस्सा पौधे के लिए अनुपलब्ध रूपों में पाया जाता है। मृदा में स्थिर पैतृक फॉस्फोरस का उपयोग करने के लिए उपयुक्त रणनीति खोजना अनिवार्य है, क्योंकि फॉस्फोरस उर्वरक उत्पादन के लिए रॉक फॉस्फेट के निरंतर खनन ने इसके गैर-नवीकरणीय, सीमित स्रोतों को रिक्तिकरण के कगार पर खड़ा कर दिया है। अघुलनशील मृदा फॉस्फोरस को घोलने के लिए पर्यावरण के अनुकूल और लागत प्रभावी रणनीतियों की खोज करने के उद्देश्य से फॉस्फेट घोलक सूक्ष्मजीव और सिलिकॉन युक्त कृषि-अपशिष्ट (सिलिकॉन स्रोतों के रूप में) की जांच की गई। कम उपलब्ध फॉस्फोरस वाली अल्फिसोल (पीएच = 6.32) और इंसेप्सिसोल (पीएच = 8.12) की सतही मृदा (0-15 सेमी) का उपयोग करके प्रयोगशाला और पॉट-कल्चर प्रयोग किए गए। फॉस्फोरस और सिलिकॉन की रिलीज कैनेटीक्स का आकलन करने के लिए मृदा में नमी की मात्रा क्षेत्र क्षमता पर बनाए रखते हुए 25 डिग्री सेल्सियस पर 90 दिनों तक प्रयोगशाला में इनक्यूबेशन प्रयोग किया गया। इस प्रयोग के लिए तीन कारकों के साथ एक तथ्यात्मक पूर्णतः यादृच्छिक बनावट, अर्थात्: सिलिकॉन स्रोत [तीन स्तर: गन्ने के खोई की राख, धान के भूसी की राख, और मक्का के भुट्टे की राख, फॉस्फेट घोलक सूक्ष्मजीव (दो स्तर: सूक्ष्मजीव के बिना, और सूक्ष्मजीव के साथ); और सिलिकॉन खुराक [तीन स्तर: बिना सिलिकॉन (सिलिकॉन₀), 125 (सिलिकॉन₁₂₅) और 250 (सिलिकॉन₂₅₀) मिलीग्राम सिलिकॉन प्रति किलोग्राम मृदा] का पालन किया गया। अल्फिसोल में, फॉस्फेट घोलक सूक्ष्मजीव ने घुलनशील फॉस्फोरस और सिलिकॉन का स्तर बिना सूक्ष्मजीव की तुलना में क्रमशः ~22.2% और 1.88% बढ़ा दिया; जबकि, सिलिकॉन₁₂₅ और सिलिकॉन₂₅₀ ने सिलिकॉन₀ की तुलना में घुलनशील फॉस्फोरस को क्रमशः 60.4 और 77.1%, साथ ही घुलनशील सिलिकॉन को ~41.5 और 55.5% बढ़ा दिया। इंसेप्सिसोल में, फॉस्फेट घोलक सूक्ष्मजीव ने बिना सूक्ष्मजीव की तुलना में घुलनशील फॉस्फोरस और घुलनशील सिलिकॉन में क्रमशः ~17.2 और 1.46%, की वृद्धि की; जबकि, सिलिकॉन₁₂₅ और सिलिकॉन₂₅₀ ने सिलिकॉन₀ की तुलना में घुलनशील फॉस्फोरस को ~44.3 और 57.1%, साथ ही घुलनशील सिलिकॉन को क्रमशः ~39.0 और 50.8% तक बढ़ा दिया। इसके अलावा, फॉस्फेट घोलक सूक्ष्मजीव × सिलिकॉन खुराक की परस्पर क्रिया दोनों मृदाओं में महत्वपूर्ण पाई गई। सिलिकॉन स्रोतों की उच्च खुराक (250 मिलीग्राम सिलिकॉन प्रति किलोग्राम मृदा) के उपयोग से फॉस्फोरस का अधिशोषण (अल्फिसोल में 12-22% तक और इंसेप्सिसोल में 7-18% तक) कम हो गया, साथ ही दोनों मृदाओं में नियंत्रण की तुलना में फॉस्फोरस (अल्फिसोल में 31-47% और इंसेप्सिसोल में 11-20% तक) की वृद्धि हुई। सिलिकॉन स्रोतों के अनुप्रयोग ने दोनों मृदाओं में अधिशोषण के साथ-साथ आत्मीयता स्थिरांक के मान में कमी की। फॉस्फेट घोलक सूक्ष्मजीव के साथ सिलिकॉन संपन्न राख के प्रयोग ने पॉट-कल्चर प्रयोग में गेहूं और मूंग में फॉस्फोरस की जैवउपलब्धता में काफी सुधार किया। फॉस्फेट घोलक सूक्ष्मजीव के साथ संयोजन में 250

मिलीग्राम सिलिकॉन प्रति किलोग्राम युक्त मक्का के भुट्टे की राख और फॉस्फोरस की अनुशंसित खुराक के 50% खुराक के प्रयोग से अल्फिसोल में गेहूं के लिए 29.6% एवं मूंगबीन के लिए 16.8%; और इंसेटिसोल में गेहूं के लिए 20.2% एवं मूंग के लिए 14.1% उपलब्ध फॉस्फोरस में सुधार हुआ। दोनों मृदाओं में, सिलिकॉन संपन्न राख और सूक्ष्मजीव के संयुक्त अनुप्रयोग के कारण घुलनशील और शिथिल बंधित फॉस्फोरस में काफी वृद्धि हुई; जबकि, आयरन बंधित फॉस्फोरस, एल्युमिनियम बंधित फॉस्फोरस के साथ-साथ कैल्शियम बंधित फॉस्फोरस अंशों के घुलने के परिणामस्वरूप शिथिल बंधित फॉस्फोरस में वृद्धि हुई। मूंग की फसल के मामले में, जो अवशिष्ट मृदा की उर्वरता पर उगाई गई थी, कम घुलनशील फॉस्फोरस अंश ने भी फसल की उपज में योगदान दिया। फॉस्फेट घोलक सूक्ष्मजीव और 50% आरडीपी के संयोजन में 250 मिलीग्राम सिलिकॉन प्रति किलोग्राम युक्त मक्का के भुट्टे की राख के उपयोग से इन मृदाओं में गेहूं की उपज में कम से कम 17% और मूंग की उपज में कम से कम 28% की वृद्धि हुई। इसलिए, फॉस्फेट घोलक सूक्ष्मजीव और 50% आरडीपी के संयोजन में 250 मिलीग्राम सिलिकॉन प्रति किलोग्राम युक्त मक्का के भुट्टे की राख का अनुप्रयोग 75% आरडीपी के बराबर गेहूं उत्पादकता को बनाए रख सकता है। इसलिए, वर्तमान अध्ययन फॉस्फोरस न्यून अल्फिसोल और इंसेटिसोल में फॉस्फोरस की उपलब्धता बढ़ाने के लिए एक लागत प्रभावी और पर्यावरण के अनुकूल रणनीति प्रदान करता है। हालांकि, आगे की समझ के लिए इन निष्कर्षों का परीक्षण विभिन्न प्रकार की मृदा और फसलों के लिए खेत में किया जाना चाहिए।

मुख्य शब्द: सिलिकॉन संपन्न कृषि अपशिष्ट, फॉस्फोरस विभाजन, फॉस्फोरस रिलीज कैनेटीक्स, फॉस्फोरस घुलनशीलता, फॉस्फेट घोलक सूक्ष्मजीव

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