

DYNAMICS OF SOIL PHOSPHORUS IN RELATION TO CARBON UNDER DIFFERENT CROPPING SYSTEMS

Dissertation

**Submitted to the Punjab Agricultural University
in partial fulfillment of the requirements
for the degree of**

**DOCTOR OF PHILOSOPHY
in
SOIL SCIENCE
(Minor Subject: Chemistry)**

By

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(L-2011-A-44-D)**

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CERTIFICATE-I

This is to certify that the thesis entitled “**DYNAMICS OF SOIL PHOSPHORUS IN RELATION TO CARBON UNDER DIFFERENT CROPPING SYSTEMS**” submitted for the degree of Ph.D., in the subject of **Soil Science** (Minor subject: **Chemistry**) of the Punjab Agricultural University, Ludhiana, is a bonafide research work carried out by **Dhram Prakash (L-2011-A-44-D)** under the supervision of **Dr. G S Saroa** upto 31st March 2015 and under my supervision thereafter for the completion of Ph.D. degree and that no part of this thesis has been submitted for any other degree.

The assistance and help received during the course of investigation have been fully acknowledged.

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CERTIFICATE-II

This is to certify that the thesis entitled “**DYNAMICS OF SOIL PHOSPHORUS IN RELATION TO CARBON UNDER DIFFERENT CROPPING SYSTEMS**” submitted by **Dhram Prakash (L-2011-A-44-D)** to the Punjab Agricultural University, Ludhiana, in partial fulfillment of the requirements for the degree of Ph.D., in the subject of **Soil Science** (Minor subject: **Chemistry**) has been approved by the Student’s Advisory Committee along with Head of the Department after an oral examination on the same.

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ABSTRACT

Dynamics of phosphorus in soils were studied in relation to nutrient management and land-use practices. The nutrient management practices evaluated included source (rock phosphate and single superphosphate) and rates of P application in rice-wheat system; and integrated nutrient management (INM) and organic farming practices in basmati-wheat system in field experiments conducted at the research farm of Punjab Agricultural University, Ludhiana. The land-uses studied included rice-wheat, maize-wheat, cotton-wheat and poplar based agroforestry systems at farmers' fields in different districts of Punjab. After seven cycles of rice-wheat cropping, farmyard manure (FYM) and rock phosphate (RP) application increased available P and soil organic carbon (SOC) by 72% and 98%, respectively over control. Inorganic P constituted the largest proportion (88-92%) of total P in soil and relative abundance of different inorganic P fractions in soils followed the order Ca-Al associated > Fe associated > humic bound > water soluble P. In basmati-wheat system, application of recommended rates of NPK and adoption of INM improved available P in soil over unamended control by 75 and 100%, respectively. The comparison of three organic sources revealed that available P was the highest in soil receiving 400 kg N ha⁻¹ through FYM followed by rice straw compost and the lowest in vermicompost-amended plots. Application of FYM significantly increased inorganic, organic and total P, SOC and labile C pools compared to INM treatments. The INM increased inorganic, organic and total P by 77, 82 and 78%, respectively over NPK. Humic-bound organic P constituted major proportion (39.5-49.5%) and water soluble organic P comprised the smallest proportion (0.83-2.5%) of organic P in soils under basmati-wheat system. Beneficial effects of different treatments on soil properties were higher in surface soil (0-7.5 cm), which decreased with soil depth. Generally, soil P fractions were positively correlated with soil C pools. Cumulative P released in 96 hours of equilibration increased with manure and fertilizer application either alone or in combination. Phosphorus release kinetics were best described by Elovich and power function equations ($R^2 \geq 0.98$). Results of land-use studies showed that agroforestry systems had relatively higher proportion of organic P (27%) compared to sole cropping (6-7.7%). Soil organic C was the highest (0.58%) under agroforestry and was significantly correlated with soil P fractions under sole cropping systems. Soil properties viz. clay, organic C, CaCO₃ and available P content significantly influenced soil P sorption and release kinetics. Phosphorus release decreased with increase in clay and CaCO₃ content. On the contrary, P release increased with increase in available P and organic C. The results suggested that P availability will be higher in coarse-textured, non-calcareous soils having higher levels of organic C and available P. Therefore, for efficient P management it is important to take into account soil texture, the existing soil P level, organic C content and calcareousness of soil. Practices that increase SOC content and ameliorate CaCO₃ could lead to improved P use efficiency.

Keywords: Fertilizer P, Farmyard manure, Cropping system, Agroforestry, Available P, Soil phosphorus pools, Soil carbon pools, Calcium carbonate

Signature of the major advisor

Signature of the student

ਖੋਜ ਪ੍ਰਬੰਧ ਦਾ ਸਿਰਲੇਖ	: ਵੱਖੋ-ਵੱਖਰੇ ਫ਼ਸਲੀ ਚੱਕਰਾਂ ਅਧੀਨ ਕਾਰਬਨ ਦੇ ਲਿਹਾਜ਼ ਨਾਲ ਮਿੱਟੀ ਵਿੱਚ ਫ਼ਾਸਫ਼ੋਰਸ ਦੀ ਗਤੀਸ਼ੀਲਤਾ
ਵਿਦਿਆਰਥੀ ਦਾ ਨਾਂ	: ਧਰਮ ਪ੍ਰਕਾਸ਼
ਅਤੇ ਦਾਖ਼ਲਾ ਨੰਬਰ	: (ਐਲ-੨੦੧੧-ਏ-੪੪-ਡੀ)
ਮੁੱਖ ਵਿਸ਼ਾ	: ਭੂਮੀ ਵਿਗਿਆਨ
ਸਹਿਯੋਗੀ ਵਿਸ਼ਾ	: ਰਸਾਇਣ ਵਿਗਿਆਨ
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ਯੂਨੀਵਰਸਿਟੀ ਦਾ ਨਾਮ	: ਪੰਜਾਬ ਖੇਤੀਬਾੜੀ ਯੂਨੀਵਰਸਿਟੀ, ਲੁਧਿਆਣਾ

ਸਾਰ

ਮੌਜੂਦਾ ਖੋਜ ਦੌਰਾਨ ਪੌਸ਼ਟਿਕ ਪ੍ਰਬੰਧਨ ਅਤੇ ਭੂਮੀ-ਵਰਤੋਂ ਦੀਆਂ ਵਿਧੀਆਂ ਦੇ ਲਿਹਾਜ਼ ਨਾਲ ਮਿੱਟੀ ਵਿੱਚ ਫ਼ਾਸਫ਼ੋਰਸ ਦੀ ਗਤੀਸ਼ੀਲਤਾ ਦਾ ਅਧਿਐਨ ਕੀਤਾ ਗਿਆ। ਪੰਜਾਬ ਖੇਤੀਬਾੜੀ ਯੂਨੀਵਰਸਿਟੀ, ਲੁਧਿਆਣਾ ਦੇ ਖੋਜ ਫਾਰਮ ਵਿਖੇ ਖੋਜ ਤਜਰਬੇ ਦੌਰਾਨ ਪੌਸ਼ਟਿਕ ਪ੍ਰਬੰਧਨ ਲਈ ਮੁਲਾਂਕਿਤ ਕੀਤੀਆਂ ਗਈਆਂ ਵਿਧੀਆਂ ਵਿੱਚ ਝੋਨਾ-ਕਣਕ ਫ਼ਸਲੀ ਚੱਕਰ ਵਿੱਚ ਸਰੋਤ (ਚਟਾਨ ਫ਼ਾਸਫ਼ੋਰਸ ਅਤੇ ਇਕਹਿਰਾ ਸੂਪਰਫ਼ਾਸਫੇਟ) ਅਤੇ ਫ਼ਾਸਫ਼ੋਰਸ ਦੀ ਵਰਤੋਂ ਦੀਆਂ ਦਰਾਂ; ਸੰਗਠਿਤ ਪੌਸ਼ਟਿਕ ਪ੍ਰਬੰਧਨ (ਆਈ.ਐਨ.ਐਮ.) ਅਤੇ ਅਤੇ ਬਾਸਮਤੀ-ਕਣਕ ਫ਼ਸਲੀ ਚੱਕਰ ਲਈ ਜੈਵਿਕ ਵਿਧੀ ਰਾਹੀਂ ਖੇਤੀ ਸ਼ਾਮਲ ਸਨ। ਪੰਜਾਬ ਦੇ ਵੱਖੋ-ਵੱਖਰੇ ਖੇਤਰਾਂ ਵਿੱਚ ਕਿਸਾਨਾਂ ਦੇ ਖੇਤਾਂ ਵਿਖੇ ਝੋਨਾ-ਕਣਕ, ਮੱਕੀ-ਕਣਕ, ਨਰਮਾ-ਕਣਕ ਅਤੇ ਪਾਪਲਰ ਅਧਾਰਿਤ ਵਣ-ਖੇਤੀ ਪ੍ਰਣਾਲੀ ਅਧੀਨ ਭੂਮੀ ਵਰਤੋਂ ਦਾ ਅਧਿਐਨ ਕੀਤਾ ਗਿਆ। ਝੋਨਾ-ਕਣਕ ਫ਼ਸਲੀ ਪ੍ਰਣਾਲੀ ਦੇ ਸੱਤ ਚੱਕਰਾਂ ਉਪਰੰਤ ਰੂੜੀ ਖਾਦ (FYM) ਅਤੇ ਚਟਾਨ ਫ਼ਾਸਫੇਟ (RP) ਦੀ ਵਰਤੋਂ ਨਾਲ ਉਪਲਬਧ ਫ਼ਾਸਫ਼ੋਰਸ ਅਤੇ ਮਿੱਟੀ ਵਿੱਚਲੀ ਜੈਵਿਕ ਕਾਰਬਨ (SOC) ਦੀ ਮਿਕਦਾਰ ਵਿੱਚ ਕ੍ਰਮਵਾਰ 72% ਅਤੇ 98% ਦਾ ਵਾਧਾ ਹੋਇਆ। ਮਿੱਟੀ ਵਿੱਚ ਕੁੱਲ ਫ਼ਾਸਫ਼ੋਰਸ ਵਿੱਚ ਅਜੈਵਿਕ ਫ਼ਾਸਫ਼ੋਰਸ ਦਾ ਅਨੁਪਾਤ ਸਭ ਤੋਂ ਵਧੇਰੇ (88.1-92.0%) ਸੀ ਅਤੇ ਅਜੈਵਿਕ ਫ਼ਾਸਫ਼ੋਰਸ ਦੇ ਵੱਖੋ-ਵੱਖਰੇ ਅੰਸ਼ਾਂ ਦੀ ਮਾਤਰਾ ਦਾ ਕ੍ਰਮ ਕੈਲਸ਼ੀਅਮ-ਅਲੂਮੀਨੀਅਮ ਅਧਾਰਿਤ > ਆਇਰਨ ਅਧਾਰਿਤ > ਹਿਊਮਕ-ਬੰਧਿਤ > ਪਾਣੀ ਵਿੱਚ ਘੁਲਣਸ਼ੀਲ ਫ਼ਾਸਫ਼ੋਰਸ ਸੀ। ਬਾਸਮਤੀ-ਕਣਕ ਪ੍ਰਣਾਲੀ ਵਿੱਚ, ਅਸੰਸ਼ੋਧਤ ਕੰਟਰੋਲ ਦੇ ਮੁਕਾਬਲੇ, NPK ਦੀਆਂ ਸਿਫਾਰਿਸ਼ ਦਰਾਂ ਅਤੇ INM ਦੀ ਵਰਤੋਂ ਨਾਲ ਮਿੱਟੀ ਵਿੱਚ ਫ਼ਾਸਫ਼ੋਰਸ ਦੀ ਮਿਕਦਾਰ ਵਿੱਚ ਕ੍ਰਮਵਾਰ 75 ਅਤੇ 100% ਦਾ ਸੁਧਾਰ ਹੋਇਆ। ਤਿੰਨ ਜੈਵਿਕ ਸਰੋਤਾਂ ਦੀ ਤੁਲਨਾ ਤੋਂ ਇਹ ਤੱਥ ਸਾਹਮਣੇ ਆਏ ਕਿ ਜਿਸ ਮਿੱਟੀ ਵਿੱਚ ਰੂੜੀ ਖਾਦ ਰਾਹੀਂ 400 ਕਿ.ਗ੍ਰਾ. ਨਾਈਟ੍ਰੋਜਨ ਪ੍ਰਤੀ ਹੈਕਟੇਅਰ ਦੀ ਵਰਤੋਂ ਕੀਤੀ ਗਈ ਸੀ ਉਸ ਵਿੱਚ ਉਪਲਬਧ ਫ਼ਾਸਫ਼ੋਰਸ ਦੀ ਮਿਕਦਾਰ ਸਭ ਤੋਂ ਵਧੇਰੇ ਸੀ ਅਤੇ ਵਰਮੀ-ਕੰਪੋਸਟ ਦੀ ਵਰਤੋਂ ਵਾਲੇ ਪਲਾਟਾਂ ਵਿੱਚ ਉਪਲਬਧ ਫ਼ਾਸਫ਼ੋਰਸ ਦੀ ਮਿਕਦਾਰ ਸਭ ਤੋਂ ਘੱਟ ਪਾਈ ਗਈ। INM ਉਪਚਾਰਾਂ ਦੇ ਮੁਕਾਬਲੇ ਰੂੜੀ ਖਾਦ ਦੀ ਵਰਤੋਂ ਨਾਲ ਅਜੈਵਿਕ, ਜੈਵਿਕ ਅਤੇ ਕੁੱਲ ਫ਼ਾਸਫ਼ੋਰਸ, ਮਿੱਟੀ ਵਿੱਚਲੀ ਜੈਵਿਕ ਕਾਰਬਨ ਅਤੇ ਤਬਦੀਲੀ ਯੋਗ ਕਾਰਬਨ ਪੂਲਾਂ ਦੀ ਮਿਕਦਾਰ ਵਿੱਚ ਅਰਥਪੂਰਨ ਵਾਧਾ ਹੋਇਆ। INM ਦੀ ਵਰਤੋਂ ਨਾਲ ਅਜੈਵਿਕ, ਜੈਵਿਕ ਅਤੇ ਕੁੱਲ ਫ਼ਾਸਫ਼ੋਰਸ ਦੀ ਮਿਕਦਾਰ ਵਿੱਚ ਕ੍ਰਮਵਾਰ 77, 82 ਅਤੇ 78% ਦਾ ਵਾਧਾ ਹੋਇਆ। ਬਾਸਮਤੀ-ਕਣਕ ਫ਼ਸਲੀ ਚੱਕਰ ਅਧੀਨ ਮਿੱਟੀ ਵਿੱਚ ਜੈਵਿਕ ਫ਼ਾਸਫ਼ੋਰਸ ਦੇ ਹਿਊਮਕ-ਬੰਧਿਤ ਜੈਵਿਕ ਫ਼ਾਸਫ਼ੋਰਸ ਦਾ ਹਿੱਸਾ ਸਭ ਤੋਂ ਵਧੇਰੇ (39.5-49.5%) ਸੀ ਅਤੇ ਪਾਣੀ ਵਿੱਚ ਘੁਲਣਸ਼ੀਲ ਜੈਵਿਕ ਫ਼ਾਸਫ਼ੋਰਸ ਦਾ ਹਿੱਸਾ ਸਭ ਤੋਂ ਘੱਟ (0.83-2.5%) ਸੀ। ਮਿੱਟੀ ਦੇ ਗੁਣਾਂ ਉਪਰ ਵੱਖੋ-ਵੱਖਰੇ ਉਪਚਾਰਾਂ ਦਾ ਸਭ ਤੋਂ ਵਧੇਰੇ ਲਾਭ ਉਪਰੀ ਸਤ੍ਹਾ ਦੀ ਮਿੱਟੀ ਨੂੰ (0-7.5 ਸੈ.ਮੀ.) ਮਿਲਿਆ, ਜੋ ਕਿ ਮਿੱਟੀ ਦੀ ਗਹਿਰਾਈ ਦੇ ਵਧਣ ਨਾਲ ਘੱਟ ਹੁੰਦਾ ਗਿਆ। ਮਿੱਟੀ ਵਿੱਚ ਕਾਰਬਨ ਪੂਲਾਂ ਨਾਲ ਮਿੱਟੀ ਵਿੱਚਲੇ ਫ਼ਾਸਫ਼ੋਰਸ ਅੰਸ਼ਾਂ ਦਾ ਸਬੰਧ ਧਨਾਤਮਕ ਸੀ। ਸੰਤੁਲਨ ਦੇ 96 ਘੰਟਿਆਂ ਉਪਰ ਸੰਚਿਤ ਫ਼ਾਸਫ਼ੋਰਸ ਮੁਕਤੀ ਸਭ ਤੋਂ ਵਧੇਰੇ ਸੀ ਜਿਸ ਵਿੱਚ ਰੂੜੀ ਖਾਦ ਅਤੇ ਰਸਾਇਣਕ ਖਾਦਾਂ ਦੀ ਇਕੱਠੀਆਂ ਜਾਂ ਸਾਂਝੀ ਵਰਤੋਂ ਨਾਲ ਵਾਧਾ ਹੋਇਆ। ਇਲੇਵਿੱਚ ਅਤੇ ਪਾਵਰ ਫੰਕਸ਼ਨ ਸਮੀਕਰਣਾਂ ($R^2 \geq 0.98$) ਰਾਹੀਂ ਫ਼ਾਸਫ਼ੋਰਸ ਮੁਕਤੀ ਕਾਈਨੈਟਿਕਸ ਨੂੰ ਚੰਗੀ ਤਰ੍ਹਾਂ ਸਪਸ਼ਟ ਕੀਤਾ ਗਿਆ। ਭੂਮੀ-ਵਰਤੋਂ ਦੇ ਅਧਿਐਨ ਤੋਂ ਪਤਾ ਚੱਲਿਆ ਕਿ ਇਕਹਿਰੀ ਫ਼ਸਲੀ ਪ੍ਰਣਾਲੀ (6-7.7%) ਦੇ ਮੁਕਾਬਲੇ ਵਣ-ਅਧਾਰਿਤ ਖੇਤੀ ਪ੍ਰਣਾਲੀ ਵਿੱਚ ਜੈਵਿਕ ਫ਼ਾਸਫ਼ੋਰਸ ਦੀ ਮਿਕਦਾਰ (27%) ਵਧੇਰੇ ਸੀ। ਵਣ-ਅਧਾਰਿਤ ਖੇਤੀ ਪ੍ਰਣਾਲੀ ਅਧੀਨ ਭੂਮੀ ਵਿਚਲੇ ਜੈਵਿਕ ਕਾਰਬਨ ਦੀ ਮਕਦਾਰ ਸਭ ਤੋਂ ਵਧੇਰੇ (0.58%) ਦਰਜ ਕੀਤੀ ਗਈ ਅਤੇ ਮਿੱਟੀ ਵਿੱਚਲੀ ਫ਼ਾਸਫ਼ੋਰਸ ਨਾਲ ਇਸਦਾ ਅਰਥਪੂਰਨ ਸਬੰਧ ਵੇਖਿਆ ਗਿਆ। ਫ਼ਾਸਫ਼ੋਰਸ ਗ੍ਰਹਿਣ ਅਤੇ ਮੁਕਤੀ ਉਪਰ ਮਿੱਟੀ ਦੇ ਗੁਣਾਂ ਜਿਵੇਂ ਕਿ ਚਿਕਨੀ ਮਿੱਟੀ, ਜੈਵਿਕ ਕਾਰਬਨ, CaCO_3 ਅਤੇ ਉਪਲਬਧ ਫ਼ਾਸਫ਼ੋਰਸ ਦੀ ਮਿਕਦਾਰ ਦਾ ਅਰਥਪੂਰਨ ਪ੍ਰਭਾਵ ਵੇਖਿਆ ਗਿਆ। ਚਿਕਨੀ ਮਿੱਟੀ ਅਤੇ CaCO_3 ਅਤੇ ਦੀ ਮਿਕਦਾਰ ਵਿੱਚ ਵਾਧਾ ਹੋਣ ਨਾਲ ਫ਼ਾਸਫ਼ੋਰਸ ਮੁਕਤੀ ਵਿੱਚ ਕਮੀ ਆਈ। ਦੂਜੇ ਪਾਸੇ, ਉਪਲਬਧ ਫ਼ਾਸਫ਼ੋਰਸ ਅਤੇ ਜੈਵਿਕ ਕਾਰਬਨ ਦੀ ਮਿਕਦਾਰ ਵਿੱਚ ਵਾਧਾ ਹੋਣ ਨਾਲ ਫ਼ਾਸਫ਼ੋਰਸ ਮੁਕਤੀ ਵਿੱਚ ਵਾਧਾ ਹੋਇਆ। ਅਧਿਐਨ ਦੇ ਨਤੀਜਿਆਂ ਤੋਂ ਇਹ ਤੱਥ ਸਾਹਮਣੇ ਆਏ ਕਿ ਵਧੇਰੇ ਜੈਵਿਕ ਕਾਰਬਨ ਅਤੇ ਉਪਲਬਧ ਫ਼ਾਸਫ਼ੋਰਸ ਵਾਲੀ ਮੋਟੇ ਕਣਾਂ ਵਾਲੀ, ਕੈਲਸ਼ੀਅਮ ਰਹਿਤ ਮਿੱਟੀ ਵਿੱਚ ਫ਼ਾਸਫ਼ੋਰਸ ਉਪਲਬਧਤਾ ਵਧੇਰੇ ਹੋਵੇਗੀ। ਇਸ ਲਈ, ਕੁਸ਼ਲ ਫ਼ਾਸਫ਼ੋਰਸ ਪ੍ਰਬੰਧਨ ਲਈ, ਮਿੱਟੀ ਦੀ ਬਣਤਰ, ਮਿੱਟੀ ਵਿੱਚ ਮੌਜੂਦਾ ਫ਼ਾਸਫ਼ੋਰਸ ਦੇ ਪੱਧਰ, ਜੈਵਿਕ ਕਾਰਬਨ ਦੀ ਮਿਕਦਾਰ ਅਤੇ ਮਿੱਟੀ ਵਿੱਚ ਚੂਨੇ ਦੀ ਮਿਕਦਾਰ ਨੂੰ ਧਿਆਨ ਵਿੱਚ ਰੱਖਣਾ ਬਹੁਤ ਮਹੱਤਵਪੂਰਨ ਹੈ। ਜੈਵਿਕ ਕਾਰਬਨ ਦੀ ਮਿਕਦਾਰ ਵਿੱਚ ਵਾਧਾ ਕਰਨ ਵਾਲੀਆਂ ਅਤੇ ਕੈਲਸ਼ੀਅਮ ਕਾਰਬੋਨੇਟ ਦੀ ਮਿਕਦਾਰ ਵਿੱਚ ਕਮੀ ਕਰਨ ਵਾਲੀਆਂ ਵਿਧੀਆਂ ਦੀ ਵਰਤੋਂ ਨਾਲ ਫ਼ਾਸਫ਼ੋਰਸ ਦੀ ਸੁਚੱਜੀ ਵਰਤੋਂ ਵਿੱਚ ਸੁਧਾਰ ਲਿਆਂਦਾ ਜਾ ਸਕਦਾ ਹੈ।

ਮੁੱਖ ਸ਼ਬਦ: ਰਸਾਇਣਕ ਫ਼ਾਸਫ਼ੋਰਸ, ਰੂੜੀ ਖਾਦ, ਫ਼ਸਲੀ ਪ੍ਰਣਾਲੀ, ਵਣ-ਖੇਤੀ, ਉਪਲਬਧ ਫ਼ਾਸਫ਼ੋਰਸ, ਮਿੱਟੀ ਵਿੱਚ ਫ਼ਾਸਫ਼ੋਰਸ ਦੇ ਪੂਲ, ਮਿੱਟੀ ਵਿੱਚ ਕਾਰਬਨ ਦੇ ਪੂਲ, ਕੈਲਸ਼ੀਅਮ ਕਾਰਬੋਨੇਟ

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CHAPTER I

INTRODUCTION

Phosphorus (P) is one of the major nutrients required for plant growth, and its deficiency has been reported world-wide. More than 5.7 billion hectare cropland across the world has insufficient P concentration for optimal crop production (Batjes 1997). World population is projected to reach over nine billion by the year 2050, and ensuring food security while mitigating environmental impacts represents a major agricultural challenge. Therefore, higher productivity must be reached through sustainable production by taking into account soil fertility (Bedoussac *et al* 2015). Majority of soils in the world contain sufficient amounts of total P (200-3,000 mg P kg⁻¹ soil), but only a small proportion (<1%) is available to plants, because of its physico-chemical behaviour and interaction at the soil mineral interface (Stewart and Tiessen 1987, Richardson *et al* 2005). While some soils have low P availability due to a small amount of total P, the others are deficient in plant-available P despite the presence of a considerable amount of total P (Muhammad *et al* 2008). In India, 42% soils are deficient and 38% are medium in plant available P. In Punjab, despite the addition of 379 thousand tonnes of phosphatic fertilizers to the soils annually, about 29% soils are deficient and 49% are medium in plant available P (Singh and Grover 2011, FAI 2012).

Because of its complex chemistry, P dynamics in soil are controlled by combinations of dissolution-precipitation, sorption-desorption and mineralization-immobilization reactions (Frossard *et al* 2000). Long-term P application through organic and inorganic fertilizers plays an important role in P supply for plant growth. About 10-20 % of fertilizer P is used by crops in the year of its application and the rest is retained in soil. The unused P is converted to less soluble forms through reactions with aluminium (Al) and iron (Fe) in acid soils and calcium (Ca) in neutral to alkaline and calcareous soils (Holford 1997, McLaughlin *et al* 1988). Transformations of native and applied P in soil from moderately labile and non-labile P fractions to labile forms also depend on P extraction by plants. Therefore, determination of available P alone may not reflect such changes (Hedley *et al* 1982, Aulakh *et al* 2003). In slightly weathered and sub-tropical soils calcium associated inorganic P can be gradually converted into available P (Guo *et al* 2000). Humic-bound P pool acts as a P sink when the system is fertilized and as a source when available P is being depleted (Beck and Sanchez 1994). Soils low in organic matter may contain less than 3% of their total P in the organic form, but high organic matter soils may contain 50% or more of their total P content in the organic form (Griffith 2011). Therefore, determination of soil P fractions by sequential P fractionation could increase our understanding of sink and sources of P in soil (Verma *et al* 2005). Adsorption and precipitation reactions render 85-90% of the added P unavailable for plants. The adsorbed or precipitated P forms are stable, but they are susceptible to dissolution and can

become available to plants depending to the environmental conditions (Khan and Joergensen 2009, Wright 2009). The plant unavailable P gets converted to various organic and inorganic-P fractions depending upon soil characteristics, which govern soil P availability to the growing plants (Trivedi *et al* 2010).

Rice (*Oryza sativa*)-wheat (*Triticum aestivum*) is the dominant cropping system in the Indo-Gangetic Plains (IGP) of India. This is an exhaustive cropping system leading to nutrients mining. According to Benbi and Biswas (1999), P availability in soils is related to the amount of P added to soils. Generally, inorganic fertilizers viz. urea, single super phosphate (SSP), di-ammonium phosphate (DAP), and muriate of potash are applied to correct nutrients deficiencies. However, high prices of chemical fertilizers render these beyond the reach of poor farmers in India. Phosphatic fertilizers are obtained from acidulation of rock phosphate (RP). In India, it is estimated that there are 260 million tonnes (0.19 per cent of the world) of RP deposits (FAI 2002). Out of the total RP resource, the country has a predominance of low-grade RP having only 15.27 Mt of high-grade RP (Kumari and Phogat 2008) and the remaining low-grade RP is unacceptable to P fertilizer industry due to its very low P_2O_5 content. The cost of applying conventional water soluble P fertilizer is high in India because their manufacture requires importing high grade rock phosphate (RP). Because of lower solubility of RP, it needs longer time to be dissolved in neutral to alkaline soils. Therefore, to improve the availability of phosphorus contained in RP application of farmyard manure (FYM) along low-grade RP has been advocated (Akanke *et al* 2011, Deshpande *et al* 2015). Several workers have reported the beneficial effects of conjoint application RP and organic amendments such as FYM and rice straw compost on microbial biomass P, available P, organic P, total P, acid and alkaline phosphatase activities in soils under rice-wheat system (Kaur and Reddy 2015, Meena and Biswas 2015). Production of CO_2 during the process of decomposition of organic manures results in the formation of weak organic acids such as carbonic acid, citric, oxalic, tartaric etc., which solubilise RP leading to release of phosphate into soil solution (Biswas and Narayanasamy 2006, Pypers *et al* 2007). In comparison to low profitability of many annually applied fertilization strategies with imported P, alternative P sources, for example rock phosphate and FYM applications may be a possible alternative to enhance the P availability in neutral to alkaline soils.

Recently, organic farming has been recommended as an alternative form of agriculture to obtain high-quality food in an environment friendly manner. The key characteristics of organic farming include protecting the long-term fertility of soils by maintaining soil organic matter (SOM) levels through inclusion of legumes, effective recycling of crop residues and livestock wastes (Yadav *et al* 2013). Organic farming has been introduced in the state of Punjab recently and is gaining wide popularity. Total area under organic farming was 3320 ha (0.38 percent of the total area under organic farming in India) during 2008 in Punjab (Singh and Grover 2011). The favourable effect of organic amendments on soil

organic carbon (SOC) is well-known but their effect of soil P fractions is relatively unknown. An improvement in SOC enhances soil microbial biomass and thereby alters P availability through mineralization-immobilization processes (Chen *et al* 2003). Soil P transformations are primarily mediated by microbial activity, which is influenced by a combination of factors including land-use, soil type and nutrient management (Chen *et al* 2008, Wright 2009). Inorganic P released from soil microbial biomass and mineralization of soluble organic P contributes to plant available P pool. Therefore, land-use changes, which influence SOC accumulation in soil, may also impact plant P availability (Bandaranayake *et al* 2003). It has been reported that soils under grassland had a significantly higher concentration of total P, microbial biomass P and organic P than the croplands (Chen *et al* 2003). Agroforestry has been advocated as an important strategy for C sequestration in soil (Benbi *et al* 2012, Wotherspoon *et al* 2014). It has been shown that soils under agroforestry systems have greater C stocks and C rehabilitation capacity than the croplands because of greater addition of leaf and root biomass to soil (Benbi *et al* 2015a). However, their effect on P accumulation and transformations in soil is not known.

The rate of P uptake by plant roots depends on P concentration in soil solution. The sorbed-P as such cannot be taken-up by plant roots unless it is released into the soil solution. The rate at which P is released from the soil colloidal complex and its replenishment in the soil solution to maintain critical solution P concentration ($0.2 \mu\text{g P mL}^{-1}$) is influenced by soil properties (Fox and Kamprath 1970) such as clay (Serrano *et al* 2014), soil organic C (SOC) content, available P concentration and CaCO_3 content (Trivedi *et al* 2010, Hadgu *et al* 2014, Mashal *et al* 2014). Clay tends to sorb P because of the existence of large number of positively charged functional groups attached on colloidal matrix that interact and bind the negatively charged phosphate (PO_4^-) ions in soil (Singh and Gilkes 1991). A significant relationship between clay content and sorption coefficients estimated from Langmuir and Freundlich isotherms have shown the importance of clay content (Solis and Torrent 1989, Pinto *et al* 2013). Replenishment of P concentration in soil solution occurs predominately through the release of P from clay and organic matter (Jalali and Ranjbar 2010). This controls short- and long-term P availability in soils (Messiga *et al* 2012). In soils with higher amount of available P, most of the active sorption sites on colloidal matrix are occupied, which leads to greater release of P (McDowell and Sharpley 2001). In calcareous soils, large surface area of CaCO_3 results in rapid precipitation of P, which affects its release for plant growth (Tisdale *et al* 2002). The effect of calcium carbonate in influencing P sorption is greater in coarse-textured than the fine-textured soils (Vig *et al* 2000). Time-dependent P release from soil requires understanding of mechanisms involved in reaction by the use of empirical models. Several researchers have reported the effect of fertilizer and manure application on P release and sorption-desorption kinetics (Saroa *et al* 1990, Gaston *et al* 2003, Gorgin *et al* 2011). Most of these studies on P release and sorption-

desorption focussed mainly on the effect of one soil property with little emphasis on variation in another soil property.

Phosphorus transformations in soils depend upon nutrient management, land-use change, cropping system, and soil properties such as texture, SOC, CaCO_3 and available P status. Knowledge about the factors influencing the transformations and availability of applied or residual P is essential for developing sustainable P management strategies. The dynamics of applied fertilizer P under different land-uses viz. rice-wheat, maize-wheat, cotton-wheat cropping and agroforestry with varying rate of SOM turnover is known to a lesser extent. Therefore, the present study was conducted with the following objectives.

- 1) To study the effect of fertilizer management practices on the dynamics of inorganic and organic P fractions in soils under rice-wheat and basmati-wheat cropping
- 2) To study P and SOC dynamics in soils under rice-wheat, maize-wheat, cotton-wheat and agroforestry systems
- 3) To study the dynamics of inorganic P in soils with variable physical and chemical properties
- 4) To study the dynamics of SOC and P in texturally different soils under variable moisture and temperature regimes

CHAPTER II

REVIEW OF LITERATURE

Phosphorus (P) is one of the major nutrients required for plant growth, but low soil P availability is a major nutritional constraint for crop production in many agro-ecosystems. Because of its complex chemistry, each phosphate ion forms multiplicity of compounds of different composition and variable solubilities, therefore, rendering it most immobile nutrient in soil. Immediately after fertilizer-P application to the soil, P undergoes series of transformations, owing to its high reactivity with soil matrix. Thus, P build-up in soil is more than its recovery by the plants (Aulakh and Pasricha 1999). Research data from field experiments and farming practices suggest that to maintain an agriculturally optimum soil fertility level, the supply in excess of crop uptake of 10-30 kg P ha⁻¹ yr⁻¹ is necessary to compensate for fixation and immobilization (Aarts *et al* 2000). Therefore, appropriate evaluation of P availability in a soil is a pre-requisite for providing reliable P-fertilizer recommendation and ensuring the long-term sustainable management of agro-ecosystems (Frossard *et al* 2000). Phosphorus dynamics in the soils is controlled by the combinations of dissolution-precipitation, sorption-desorption and mineralization-immobilization reactions (Frossard *et al* 2000) which in turn are influenced by soil properties such as soil texture, SOC, CaCO₃ (Trivedi *et al* 2010, Hadgu *et al* 2014) and available P that respond to agricultural management and land-use change (Aguiar *et al* 2013). The change with time in applied P in soil is governed by organic matter content, application of organics, cropping systems and nature of fertilizer. Soil P availability and efficiency of applied P may be improved through an understanding of soil P dynamics in relation to management practices in a cropping system (Reddy *et al* 1999). Among different agricultural management practices, nutrient management (Song *et al* 2007), cropping systems (Oberson *et al* 2011, Aguiar *et al* 2013) and land-use change (Chen *et al* 2003, Aguiar *et al* 2013) are the best management practices (BMPs) that have a profound influence on soil P dynamics. The management practices that increase soil organic matter levels also influence P availability and related dynamics (Messiga *et al* 2012). Improvement in SOC with organic manure application enhances soil microbial biomass, and thereby alters P availability through mineralization-immobilization reactions (Chen *et al* 2003, Sigua *et al* 2009). Application of organic manure to soil along with inorganic-P fertilizers causes; a significant improvement in organic P and inorganic P fractions (Ranatunga *et al* 2013), reduction in sorption (Prasad and Mathur 1997, Varinderpal-Singh *et al* 2006, Song *et al* 2007), conversion of non-labile P to labile-P pool (Hundal *et al* 1988) and prevention of the formation of meta-stable compounds like β -tri-calcium phosphate and hydroxyl apatite in the soil (Toor and Bahl 1999, Singh *et al* 2010). Higher concentration of available P in fertilizer-P applied soils under rice-wheat cropping compared to the maize-wheat cropping (Oberson *et al* 2011) has been reported to be the result of alternate wetting and

drying of soils under rice-based cropping system, causing a release of large flush of available P. Improved P nutrition for cereals grown on low-P soils in a legume-based cropping system compared to cereal-cereal mono-cropping has also been reported (Aulakh *et al* 2003, Oberson *et al* 2011). Aguiar *et al* (2013) compared several land-use systems and reported significantly higher P concentration in rice-wheat cropping than pasture, secondary forest and alley cropping and relate the variation in P concentration among different land-use systems to the regular application of fertilizer-P in rice-wheat cropping. Because of large addition of aerial and below ground crop biomass coupled with reduced tillage, grassland soils had a significantly higher concentration of total P, microbial biomass P and organicP than cropland soils (Chen *et al* 2003). The literature to the present study is reviewed under the following heads and sub-heads:

- 2.1. Effect of nutrient management practices on soil P and organic carbon dynamics
- 2.2. Effect of cropping systems/ land-use on soil P and organic carbon dynamics
- 2.3. Effect of soil properties on P availability
 - 2.3.1. Effect of texture
 - 2.3.2. Effect of CaCO_3
 - 2.3.3. Effect of soil organic carbon (SOC)
 - 2.3.4. Effect of available P status
- 2.4. Effect of moisture and temperature on soil nutrient availability
 - 2.4.1. Influence of moisture and temperature regimes on soil P dynamics
 - 2.4.2. Influence of moisture regime on Fe, Mn and SOC in soils

2.1 Effect of nutrient management practices on soil P and carbon dynamics

Integrated use of organic manures and inorganic P sources results in enhanced fertilizer-P use efficiency and sustainability of the agricultural production. Long-term application of poultry litter results in P build-up in close proximity of even in high P sorbing soils (Gaston *et al* 2003). Stevenson (1982) reported that OM, being a source of organic P, influences availability of P in different ways such as (i) insoluble Ca, Fe and Al phosphates may be converted to soluble forms through the formation of chelates and decomposed products of OM (ii) humate may compete with phosphate ions for sorption sites thereby decrease the P fixation (iii) during decomposition of OM, released CO_2 which in turn, may increase the solubility of Ca and Mg (iv) OM produced organic acids may cover colloidal sesqui-oxides surface, thereby tends to reduce P fixations.

Saroa and Vig (1992) reported the mobilization of residual P using inorganic and organic extractants. Their result indicated the superiority of organic anions to that of inorganic in mobilizing residual/native P from soil at any reaction time. Amongst organic acids fulvic acid was more efficient and the order of P replacing ability of the anions was fulvate > citrate > lactate > chloride. The release of P from

solid phase was a slow process. The P mobilization data conformed to the pseudo-first order integrated rate equation. The mobility of surface P was relatively higher with organic extractants than inorganic. Saroa *et al* (1990) reported that regular application of fertilizer P at optimum rate of each crop in different cropping systems results in considerable buildup of residual P and accordingly soil solution P concentration may be enriched. Benbi and Biswas (1999) demonstrated that continuous differential fertilization (100% N, P and K) increased Olsen-P in the surface soil layer from initial value of 8.6 kg P ha⁻¹ to 78.3 kg P ha⁻¹ after 22 cycle of maize-wheat-cowpea cropping. Stroia *et al* (2013) evaluated the effect of fertilization on soil P availability, observed that available P values ranged between 4.9-13.4 mg kg⁻¹, were higher than the previous year which were 3.2-7.8 mg kg⁻¹, fertilization increased the P availability over last year which followed order: N₁P₀ < N₀P₀ < N₀P₁ < N₁P₁ which was due to the residual effect of phosphorus application. Yaduvanshi *et al* (2013) reported 76% increase in available P in plots which received NPK+GM and NPK+FYM, and 28% in only NPK treated plots over its initial value (11.88 kg ha⁻¹) at the end of 12 yrs rice-wheat cropping system.

Turtola and Yli-Halla (1999) reported that application of animal waste can raise soil P concentration far in excess to crop nutrition needs. Benbi and Biswas (1999) reported that the application of FYM in conjunction with 100% NPK led to significant greater accumulation of available P as compare to 100%NPK alone, despite the higher level of total-P removal in former treatment than in the later. Majumdar *et al* (2007) studied the effect of rock phosphate, super phosphate and conjoint of both with FYM on soil P in a typic hapludalf of Meghalaya, observed increase in SOC as well as available P in soil increased by 11.5-19.9% over the initial status in various treatments after 5 years of cropping. P build-up was higher in plots which received 60 kg P₂O₅ ha⁻¹ through SSP alone or with FYM > 60 kg P₂O₅ ha⁻¹ as SSP + RP (1:1) conjoint use with FYM or without FYM. Nishanth and Biswas (2007) showed a sharp increase in release of water-soluble P from all the composts at 8th to 12th day of leaching, thereafter, it decreased gradually. Maximum release of water-soluble P was obtained in ordinary compost than enriched composts during the initial stages of leaching, but their differences narrowed down at later stages.

According to Reddy *et al* (1999), regular application of fertilizer P to each crop progressively increased the Olsen-P relative to initial level upto 0-15 cm soil depth, in both unmanured (0.9-9.6 mg kg⁻¹) and higher concentration in manured (15.7-25.1 mg kg⁻¹) plots under soybean-wheat system, because manure application reduced P sorption and solubilized the native P in soil.

Increased P availability in soils under controlled laboratory and field conditions with the application of crop residue from cereal (Aulakh *et al* 1992, Yadvinder-Singh *et al* 1988) and oilseed crops (Kabba and Aulakh 2004) has also been observed in several studies. Likewise, the effect of green-manure (Hundal *et al* 1988), crop residues (Hundal and Thind 1992) FYM, pressmud (Singh *et al* 2010) and

sludge (Sui and Thompson 2000, Singh and Singh 2011) on increased P availability has also been well documented. Tolanur and Badanur (2003) observed that integrated use of FYM and inorganic P fertilizers increased the P availability to crop and mineralization of organic P due to microbial action and enhanced mobility of P. Addition of organic manure like FYM, crop residue along with inorganic fertilizer had a beneficial effect in increasing the P availability.

Natalwadmath *et al* (2003) found that soils under long term experiment received organic manure conjointly with N and P resulted 21% increase in soil organic carbon over CK. The increase in P range 4.8 to 33.5 kg ha⁻¹ was recorded under the plots which were dressed with organic manure with NPK. There are reports that the application of organic manures besides increasing soil P availability (Ballamy *et al* 1995, Toor and Bahl 1999, Sui and Thompson 2000) also reduces the need for inorganic fertilizer (Toor and Bahl 1997, Singh *et al* 2010). A complete supplementation of inorganic P with conjoint application of organic manures and inorganic P has also been reported under controlled laboratory conditions (Toor and Bahl 1997, Singh *et al* 2010). Even under field conditions, Hargopal-Singh *et al* (2004) also reported a complete saving of costly P fertilizers in rice-wheat cropping. The effect of FYM on available P in sandy loam soil having pH 8.2 and Olsen's P 6.4 kg ha⁻¹ was demonstrated by (Dhillon and Dev 1986) concluded that inclusion of FYM leads to remarkable increased in available P under both aerobic and anaerobic moisture regimes. This might be due to CO₂ liberation and production of various organic acids. Further, Erich *et al* (2002) concluded that soil under potato cropping system having higher available P and desorbed P amended with compost and manure than CK. Toor and Bahl (1997) and Singh *et al* (2010) reported that the synergistic effect of fertilizer-P conjointly used with organic manures on P availability has been reported to be more than sum of the increase from either applied singly. It could be explained by the fact that the manure-P might be equally or even more available than fertilizer-P (Meek *et al* 1979, Gale *et al* 2000). According to Sharpley *et al* (1989), 75-80% of the manure-P becomes available over time.

According to Prasad and Singhanian (1989) application of manure may serve the source of available P for long duration than application of fertilizers (Dhillon *et al* 2004) alone. These information's were further supported by Laboski and Lamb (2003), conducted an long term incubation study and investigated available P from fertilizer decreased with increase the incubation period than manure could be possibly production of organic substances that cover the sorption sites there by enhance available P. Bahl *et al* (1998) observed that P sorption as influenced by green manuring and cropping in non-calcareous, calcareous and acid soils of Punjab and Himanchal Pradesh. The extent and rate of P adsorption declined with P application and green manuring. It was also indicated by Vig and Dev (1979) reported that high boding energy values were responsible for low plant uptake of P. Soils with high P

adsorption maxima are able to supply sufficient P for wheat growth at a relatively lower saturation point than soils having low adsorption maxima.

A competitive adsorption between low molecular weight organic acids produced upon decomposition of organic matter and phosphate ions, delays P sorption on active surfaces (Hundal *et al* 1988, Violante and Gianfreda 1993, Stauntan and Leprince 1996, Geelhoed *et al* 1999). Organic acids results in the formation of stable complexes with Fe and Al (El-Baruni and Olsen 1979), and thus increases the solubility of calcium phosphates. Organic manures help in maintain crystalline products of phosphate in meta-stable or poorly crystalline form (Toor and Bahl 1997, Singh *et al* 2010), and there by leading to the release of large flush of available P. Younessi *et al* (2010) observed that application of both chemical and organic fertilizers increased the values of P diffusion coefficients of soils (R) and relatively higher values of determination coefficient (R^2), the initial and final P release rate indices and the values of P release rate constants (a and b) obtained from the power function equation as compared to the CK. Adding dairy manure and sewage sludge to soil increased the quantity of soil desorbable P with progress the time. They have also indicated that release of P from the soils was rapid at first few hours and continued more slowly until an apparent equilibrium was reached.

Vig and Milap-Chand (1993) reported the effect of sesbania aculeate green manure on labile and inorganic P in alkaline sandy loam and loamy sand soils and observed a significant decrease in 0.5 M NaHCO_3 extractable organic P after incubation for 100 days which was the result of its rapid mineralization to inorganic P. Manna *et al* (2006) observed that continuous application of fertilizer P invariably improved buildup of organic P, which may be mineralizing/solubilizing through rhizosphere microbial action and improved bio-available P to plants. Thus, in P-deficient soil, the addition of P and organic matter may help to build up organic P in the soil. Yashpal (1988) revealed that dhaincha green manure gives double advantage; on one hand, it reduced P sorption and on the other hand resulted enhanced P release. The increase in P desorption in amended over unamended soil ranged from 0.32 to 0.70 and 1.81 to 2.95 $\mu\text{g P g}^{-1}$ soil at applied P levels of 50 and 200 $\mu\text{g P g}^{-1}$ soil respectively. Singh and Jones (1976) reported that soil treated with organic residues that contained $<0.22\%$ P yielded less P on desorption than check treatment while more P was desorbed from the samples which were incubated with organic residues containing P in excess of 0.22 %. They made a conclusion that the P content of the organic residues had an effect on the amount of P desorbed from the soil. Jat and Ahlawat (2006) observed that application of 13 and 26 kg P ha^{-1} increased P (7.89-10.16%) content over CK, however, application of vermi-compost also increased available soil P status over no vermi-compost, application of vermi-compost might be due to its solubilization effect on the native P. Moreover, decomposition of vermicompost tended to the formation of CO_2 , which helps in the solubilization of the native phosphorus, forms the phospho-humic complexes.

Prasad and Mathur (1997) concluded that rate and extent of P adsorption was considerably lower in soils which received recommended NPK+FYM or lime. The adsorption maxima was highest in unfertilized plots and lowest in NPK+FYM plots followed by NP + lime, bonding energy constant (K) was highest where N was applied as ammonium sulphate in the NPK treatment. Tang and Armstrong (2008) reported a significant increase in all inorganic P fractions except HCl-inorganic P after 65- years of manure and fertilizer application. However, P buffering capacity and sorption maxima decreased with the increase in the concentration of Olsen P and resin-P with increasing rate of fertilizer P application. Singh and Singh (2011) reported a significant improvement in total P with sludge application either applied alone or conjointly with fertilizers. An enrichment of 18 kg total P ha⁻¹ in soil plough layer (0-15 cm) in alone sludge applied soil was reported in comparison 132 kg total P ha⁻¹ with integrated use of sludge and fertilizer. Singh and Singh (2011) reported that the extent of P-sorption was comparatively lower in the soils receiving P either source (sludge or fertilizers) applied alone or conjointly with fertilizers. They reported that P-sorption data are well described by both Langmuir ($r \geq 0.991^{**}$) and Freundlich ($r \geq 0.994^{**}$) sorption isotherms. Sludge application @ 10 t ha⁻¹ resulted in 9.6 and 21.0% decrease in Langmuir's sorption maxima constants ' b_1 ' and ' b_2 ', respectively and 33.3 and 13.0% in bonding energy constants ' k_1 ' and ' k_2 ', respectively over control. Appreciable decrease in Freundlich's sorption extent ' a ' and rate ' n ' (11.6 and 10.2%) in alone sludge dressed soil over control soil was observed. Pandian (2009) observed that desorption of sorbed P was higher in the manured soils (11.5%) than in the unmanured soils (4.1%).

Gorgin *et al* (2011) indicated that the P-desorption rate was initially rapid followed by slower until equilibrium was approached, P-desorption rate was greater in the poultry-manure-amended soils than in the pistachio-compost-treated soils, attributed to the greater contribution of mineralized P by poultry manure. The kinetic data were best described by power function and simple Elovich equations as evidenced by the relatively greater values of determination coefficient (r^2) and relatively lower values of the SE. Desorption rate constants of these equations indicated that the application of organic matter not only decreased phosphate retention of the soil but also increased phosphate desorption in the soil solution.

Yan *et al* (2013) studied the effect of differential fertilization on P availability in the soils under paddy-wheat system and they have observed that Olsen-P and total P in NPK along with manure @15 or 7.5 t ha⁻¹ y⁻¹ treated soils were significantly higher than those treated with NPK alone ($P < 0.05$). The contents of Olsen-P and total P were about four and two folds than those in the NPK plots. Ultimately, there was a greater increase of labile P than stable P with long-term manure application in the paddy soil.

Pizzeghello *et al* (2011) reported that soil P forms were affected by both quantity and quality of long-term P fertilizers and manure, observed 6-fold increase in Olsen-P in FYM soils over CK. Mineral fertilization also significantly increased ($p < 0.05$) the P extractable forms but with lower magnitude than

FYM. FYM positively influenced organic P, the manured soils showed aorganic P value 1.4-fold higher than CK.

Sharpley *et al* (2004) reported that after 10-25 yrs, manured soils had significantly more SOC, exchangeable Ca, and total P than CK soils, Melich-3 P ranged 10-42% of total P under manure treated soils, water soluble P was closely related to that extracted as Mehlich-3 P ($R^2=0.94$). Organic and inorganic P were significantly higher in manured soils, 49-80% of total P was inorganic P (27% was hydroxide inorganic P and 49% was acid inorganic P of inorganic P) than in CK soils, which comprised 43-74% inorganic P of total P. Large additions of manure increased the soil P, led to shift in P chemistry and reaction products from Al- and Fe-dominated product to Ca-minerals.

Nwoke *et al* (2004) made the comparison of either alone or together application of organic and inorganic fertilizers with CK, showed a significant increase in the amount of P fractions extractable with resin P, HCO_3 -inorganic P, NaOH-inorganic P, and NaOH-organic P there by increased P availability in inorganically treated plots, which come largely from organic NaOH-organic P pool, might buffer the resin P to a large extent through mineralization processes. However, together application of organic plus inorganics compared with only inorganic fertilized treatment indicated that FYM had no effect on these fractions, because the period of management was too short for differences to appear in these fractions. Takahashi and Anwar (2006) evaluated soil P fractions after 23 years of annual fertilizer application to the soil and reported that by application of P fertilizers, soil total P [Ca-P +Al-P +Fe-P] increased and unutilized P transformed mainly to Al-P and Fe-P.

Sharma and Verma (2000) found that among various inorganic P fractions, reduced P was the most dominant (45%), followed by Fe-P (33%) and Ca-P (10%). However, the addition of lantana over six years increases Al-P, Ca-P and red-P by 36, 29 and 9%, respectively. Jatav *et al* (2010) reported a significant increase in saloid-P, Al-P and Ca-P and decrease in Fe-P with integrated use of inorganic and organic fertilizers. Park *et al* (2004) have reported that the conjoint application of compost and chemical fertilizers significantly increased Fe-P and Al-P, but Ca-P content was significantly influenced, compared to the control. Huang *et al* (2011) observed that Ca-P, Al-P, Fe-P decreased in control, but increased significantly with P supplementation. Sihag *et al* (2005) reported that amount of P recovered as saloid-P, Al-P and Ca-P increased significantly with conjoint application of organic and inorganic P sources. However, the highest amount of all the P forms was recorded under FYM followed by green manuring and press-mud treatments. Bahl and Singh (1997) reported that saloid-P increased while Fe-P, Ca-P and Al-P decreased significantly with the application of green manure in alkaline and acidic soils. They have reported that saloid-P increased by 27% in an alkaline and 21% in an acidic soil.

After 111 years of manure and fertilizer application, Motavalli and Miles (2002) reported a significant increase in NaOH-extractable inorganic P (a more slowly available P fraction) than resin-

inorganic P and NaHCO_3 -inorganic P. However, Nziguheba *et al* (2000) reported that organic residues increased the concentration of NaOH-organic P by $\sim 7\text{-}14\%$. Continuous application of P at 150 kg ha^{-1} drastically increased the inorganic pools but did not affect the organic pools of P (NaHCO_3 and NaOH-organic P). Lee *et al* (2004) studied the changes in organic P fractions in paddy soil with long-term chemical fertilizers (NPK), straw-based compost (compost) and chemical fertilizers plus compost (NPK + compost) after 31 years. They reported a decrease in ratio of organic P to total P with the lapse of years. The conjoint application of NPK + compost accelerated the decrease in the organic P fractions, presumably due to the promotion of microbial activity in the plow layer, even though a high amount of organic P was added through compost. Guo *et al* (2011) investigated the influence of different P fertilizers [Kunyang phosphate rock (KPR), mono-calcium phosphate (MCP)] on different soil P fractions in the two soils dressed with NK and NPK. Resin-P, NaHCO_3 -P, and NaOH-P increased after MCP treatment compared with no P application. The KPR application only increased resin P and HCl-P and organic P fractions were stable and less affected by P application. The average of KPR P dissolved in the two soils across all P rates was 19% of the averaged amount of KPR P applied was lower than MCP, due to its low reactivity. This explained poor agronomic effectiveness of KPR with respect to MCP.

More and Ghonsikar (1988) compared the effect of organic and inorganic fertilizer application on P availability and concluded that greater P availability in soils which treated with poultry manure (PM) + SSP followed by conjoint addition of FYM and goat manure, whereas significantly lower available P than SSP alone. Jun *et al* (2010) reported that soil Olsen-P content increased by 3.7, 5.2, 11.2 and 20.6 mg P kg^{-1} after 21-year annual fertilizer P application at 20, 39, 59, and 79 kg P ha^{-1} , respectively. All inorganic P fractions but Ca_{10} -P were correlated with Olsen-P significantly and the direct contribution of Ca_8 -P (sparingly soluble P, but can be partly used by plants) was predominant, suggested that long-term annual superphosphate application facilitated the accumulation of soil Ca_8 -P, and thus improve soil P availability.

Roboredo *et al* (2012) concluded that acidification of pig slurry or its solid fraction (AS) led to higher increases in the most labile inorganic P fraction in soil, up to 87.4%, either in slurry or slurry solid fraction, however, without acidification increase was 75.8%. They have also observed the increase in other inorganic P fractions and indicated that acidification of slurry or its solid fractions may have promoted the dissolution of some labile, moderately labile, occluded and Ca associated P.

Traditional nutrient management practices, such as, organics application or together with inorganic fertilizers have almost been ignored after the introduction of chemical fertilizers and adoption of high yielding varieties under intensive cultivation, resulted decrease in SOM (Wang *et al* 2013). Main reservoirs in the terrestrial ecosystem of C refer to SOC (Tchienkoua and Zech 2004, Huang *et al* 2014) its decomposition largely governed by MBC, because soil microorganisms play a dominant role in SOM

mineralization (Tate 2000), which has been suggested as early and more sensitive indices to monitor longer-term trends in SOM, played a key role in maintaining function and sustainability. Soil C fractions were strongly influenced by the addition of organics, significantly highest concentration of MBC was found in GM treatment followed by FYM (Dash *et al* 2014) and P fertilized plots (Ghani *et al* 2003) compared to CK due to the change in quality and quantity of SOM.

Rasool *et al* (2008) reported that the application of FYM to maize increased mean value of SOC by 16% whereas NPK increased it by 21% than CK, upto a depth of 0-60 cm, It was a non-significant difference between both treatment, corresponding SOC increased was 20 and 10 % at the end of wheat crop. Their findings showed that increased in SOC was only till 45 cm soil depth.

Liang *et al* (2014) investigated that in soil, TOC increased with treatment: CK<NPK<FYM. SOC increased by 19% in the NPK relative to the CK. However, concentration in the FYM treatment was almost twice than CK. SOC concentration was the highest in the FYM+NPK treatment and lowest in the N fertilizer treatment. No significant differences were observed in the SOC concentrations in the CK, N and NPK treatments, indicated that the long-term application of inorganic fertilizers had no significant effect on SOC accumulation in tilled vegetable cropping systems, in which crop residue and roots were removed, but, the SOC concentration in the FYM treatments increased significantly. The SOC concentration in the FYM+NPK treatment was higher than those in the FYM and FYM+N treatments due to the balanced fertilization in former. Wang *et al* (2013) reported that TOC was obviously affected by organics application. NPK showed higher SOC values than CK, because, NPK had more organic materials input from stubbles and litters based on its high yield of biomass. The micro biomass and biodiversity in the soil with addition of organic material were higher than that without manure. Li *et al* (2009) conducted an experiment on long-term (17 yr) fertilization included treatments with fertilizer and pig manure with or without straw incorporated and reported that there was a dramatic increase in soil SOM from the initial level of 5.70 to 13.1-17.2 g kg⁻¹ in the final year. Especially for the straw retention plus pig manure (SM), NSM and NPKSM treatments, marked increase in soil SOM occurred over the CK due to the application of pig manure and incorporation of straw to the field. Kaur *et al* (2008) reported that under maize–wheat cropping system, continuous application of fertilizers increased SOC content from initial level of 0.20–0.52% with an application of FYM over the 34 yrs, irrespective of the treatments SOC increased in all fertilized plots as compared to initial value. At 0–7.5 cm depth, SOC was 61.3% greater under treatment dressed with 100%NPK+FYM as compared to CK. In 7.5– 15 cm soil layer, FYM treated plot had maximum organic carbon (4 g kg⁻¹) was significantly higher than 100% NPK (3.5 g kg⁻¹) and 100% NP (3.2 g kg⁻¹) treated plots. However, in 15–30 cm soil layer the change in SOC was not significant in different fertilizer treatments. Substantial build up in SOC was due to added source of carbon through FYM and addition of root biomass and crop residues for 34 years.

Yaduvanshi *et al* (2013) studied the effect of inorganic fertilizers singly and conjointly with organic manures on SOC. In the soils, where rice-wheat system was practised for 12 yrs (1994-95 to 2005-06) and observed that SOC was significantly greater in plots which treated with GM or FYM with NPK over that only inorganic fertilizer NPK dressed plots. The mean SOC increased to 4.05 g kg⁻¹ in organic manures treated plots as compared to that of 2.34 g kg⁻¹ in inorganic fertilizer treated treatments. However, SOC in plots received NPK+GM and NPK+FYM increased by 28.1 and 31.3%, respectively, concluded that the beneficial effect of integration of inorganic fertilizer and organic manures was related to the incorporation of organic material in the soil.

Fuentes *et al* (2013) reported that MBC under barley mono-cropping (*Hordeum vulgare* L.), with the addition of 120 kg N ha⁻¹, the MBC content was about 25% higher compared with the CK. This increase in MBC could be explained by the greater crop biomass observed in the fertilized plots compared with the unfertilized plots. According to research findings of Bhattacharyya *et al* (2008), treatments received FYM recorded significant increase in MBC compared to the plots that did not receive manure for the past 30 yrs. The NPK+FYM-treated plots recorded the highest MBC. The MBC was 73% higher than the CK. Increase in MBC under FYM amended soils could be attributed to several factors, such as higher moisture content, greater soil aggregation and higher SOC content. The FYM amended plots provided a steady source of SOC to support the microbial community compared to NPK-treated plots. FYM applied to soil has long been employed to enhance favourable soil conditions. Kaur *et al* (2008) reported that under maize-wheat cropping system, MBC ranged from 137-228 mg kg⁻¹ in 0–15 cm soil depth. It was 21.1, 34.5, 52.1 and 65.1% more under 100% N, 100% NP, 100% NPK and 100% NPK+FYM treated plots than CK, respectively. MBC increased significantly with an application of N fertilizer and comprised 4.5–5.7% of soil TOC, observed that the greater mineralizable and readily hydrolysable carbon due to manure application resulted in higher microbial activity and MBC. The decrease in microbial biomass could be due to the acidifying effect of N fertilizers applied in the form of urea alone, which probably resulted in the appearance of unfavourable conditions to many types of microorganisms, *i.e.* bacteria and actinomycetes.

Banger *et al* (2009) reported that the N alone or N and P did not have any significant effect on SOC. The application of inorganic fertilizers, integrated fertilization or organics resulted in build-up of SOC than in CK. The FYM increased the SOC by 27.6%, and 100% NPK increased SOC by 15.9% than CK. The MBC and WSC were relatively higher in the plots treated with FYM either singly or together with NPK. The average SOC, MBC and WSC were relatively higher in the upper 0–15 cm than in (15–30 cm) soil depth variation with respect to fertilizer treatments. Increased C under the FYM and inorganic treatments might be due to the addition of organic materials for several years from external sources as well as higher SOC in the surface layers is due to the fact that organic residues are usually incorporated in

the surface soil and the left over residues of shallow rooted crops like rice and cowpea also get accumulated in the top few centimetre of the soil.

Marinari *et al* (2010) compared the SOC and WSC in chemically fertilized and organic manured soils, significant differences of SOC and WSC content were observed between above soils. The content of WSC was significantly higher under organic management in comparison to inorganic fertilized soil due to fresh organic matter, such as green manure or slurry, may release soluble compound into the soil. Brar *et al* (2013) evaluated the effect of organic and inorganic fertilization on C pools, the experiment was carried out under rice-wheat cropping system and they have observed that the application of 100%NPK and 100%NPK + FYM significantly increased the soil labile-C and WSC as compared to the CK, 100%NPK + FYM tended to greater increase in labile-C and WSC than 100% NPK. Kaur *et al* (2008) concluded that averaged water-soluble carbon (WSC) accounted for 0.5–1.1% of TOC and increased significantly with an application of organic fertilizers along with inorganic fertilizers. In plots receiving balanced fertilization, water-soluble fractions were sustained better than in plots receiving continuous application of fertilizer N alone, due to the priming effect of fertilization.

Bhattacharyya *et al* (2008) reported that combined application of mineral and organic fertilizers in a rainfed soybean–wheat system and observed that SOC concentrations increased from the initial values in all the plots. After 30 yrs of application of NPK showed significantly higher SOC (8.0 g C kg^{-1}) over the CK (6.3 g C kg^{-1}) surface soil and also over either NP or NK, indicated the beneficial effect of a balanced fertilization in improving SOC status of the soil. Soils under the NPK + FYM-treated plots contained higher total SOC by 47% in the 0–15 cm soil layer over those under the NPK treated plots. Regular application of FYM in combination with NPK or N alone resulted in considerable accumulation of SOC in the 0–15 cm soil layer. SOC concentrations marginally improved from the start of the experiment in the unfertilized plots due to C addition through the roots and crop residues.

Ghani *et al* (2003) observed that HWSC was sensitive to land use. HWSC (mg C kg^{-1}) in sheep/beef pastures was (3400), dairy pastures (3000), cropping (maize and sweetcorn) (1000) and market gardening (vegetables and strawberries) soils (850). Lower HWSC in later two land use was due to cultivation over the last 12–18 yr. HWC was also sensitive to differences within an ecosystem, long-term continuous P fertilization had a significant positive effect on the HWC, which was significantly greater ($P < 0.05$) in plots which had received yearly applications of P for the last 25 yr than CK. They have also observed that HWC was positively correlated ($P < 0.001$) with soil MBC ($R^2 = 0.84$). The HWC was positively correlated with WSC and TOC. MBC values ranged between $80\text{--}1200 \text{ mg C g}^{-1}$ soil and HWC values ranged between $600\text{--}5400 \text{ mg C g}^{-1}$ soil. Considerably higher amounts of C in the HWC was due to the fact that it would have extracted not only the microbial biomass-C but also root exudates, soluble carbohydrates and amino acids (Gregorich *et al* 2003), C bound to soil enzymes would also be extracted

because most of the soil enzymes in these soils would be denatured at 80 °C. The application of inorganic fertilizers, by themselves or in combination, has been reported to significantly affect soil organic C fractions due to the significant increase in C input (Ma *et al* 2011).

Carbon mineralization is a crucial process of SOM dynamics in soils, depend on C input, determined the size of C accumulating in the soil (Benbi *et al* 2015b). Marinari *et al* (2010) observed that generally, C mineralization increased with incubation period, significantly higher in organics treated than inorganic treated soil, however, at DOK site C mineralization increased particularly after the first month of incubation, showing a different kinetic of mineralization process, which became rapid at 30 days of soil incubation when labile compounds were produced from the early step of OM decomposition, suggested a diverse composition of SOM and/or microbial community in DOK soil which probably caused by the use of unstabilized fresh organic manure (Miller *et al* 2004) because the composition of organic amendments, type of crop (Kumar and Goh 2002) and amount of SOM (Saggar *et al* 2000) affect C mineralization. Harmer and Marschner (2002) reported the type of organic substrates applied and diversity of the active soil microbial community had a large influence on CO₂-C production. This attributed to the consumption of labile substrates and decreased ability of the microbial population to mineralize the remaining, more recalcitrant material (Steinweg *et al* 2008). Dash *et al* (2014) reported that organics application to soil had a significant effect on CO₂ production because of the labile soil C inputs and increased in microbial activity, such as GM and FYM increased soil respiration than CK. However, regarding soil health and higher nutrient mineralization and availability, GM was the better adoptable option compared FYM, which enhanced labile C pools because presence of more humified material in FYM inhibited the microbial mineralization. They have also revealed that CO₂ production increased with time but the rate of CO₂ production decreased after 10 days of incubation.

Marinari *et al* (2010) reported that the cumulative CO₂ production (mg C–CO₂ g⁻¹ of SOC) was significantly higher in organically treated than chemically fertilized soils. The mineralization rate of C (qM) was higher in the systems which included legumes, such as alfalfa or grass clover, in the annual crop rotation. It might be due to that the leguminous residues have different composition with lower C/N ratio, leading to a faster mineralization process in soil with respect to non-leguminous crop residues.

Jha and Rattan (2007) reported that at termination of 64 days of incubation, CO₂ evolved was highest under mungbean-incorporated (321.4 mg 100 g⁻¹ soil) followed by sesbania-incorporated (312.2 mg 100 g⁻¹ soil) and wheat-straw-incorporated (292.9 mg 100 g⁻¹ soil), probably due to higher content of N in mungbean followed by sesbania and wheat straw. This indicates that the carbon mineralization was more limited by the availability of N (or possibly other nutrients) rather than organic carbon per se.

Chen *et al* (2014) observed that throughout the 80 days incubation, straw-amended treatments showed greater ($P < 0.001$) CO₂-C emissions than CK. the amount of straw-C mineralization from the soil

2 (long term manure fertilized soil) was more compared to the soil 1 (non-fertilized soil), indicated that straw amendment increased the mineralization of soil-derived C compared to non-amended soil. They also observed 9.3 g kg⁻¹ SOC in the soil 2 compared with 3.3 g kg⁻¹ SOC in the soil 1 and a greater microbial biomass in soil 2 compared to soil 1, concluded that due to the greater SOC and MBC soil 2 has greater potential for straw mineralization.

Mohanty *et al* (2013) conducted an incubation study with soils, collected from 41 years of rice-rice system under long term fertilization and observed that long term fertilization and moisture regime significantly affected C and N mineralization in soil. Long-term integrated (NPK+FYM and N+FYM) application in soils resulted in higher potentially mineralizable C (C₀), potentially mineralizable N (N₀), rates of mineralization (dC_{min}/dt and dN_{min}/dt), microbial and mineralization quotients as compared to either of them applied alone (N, NPK, and FYM), C mineralization was higher in aerobic system due to favourable conditions for microbial activities than submergence conditions and observed that C mineralization was tightly linked to N mineralization in soil through the activity of microbial pool and C:N ratio of substrate which regulated the supply of N in soil thereby influenced the crop growth and production, Ultimately, they suggested that combined application of organic and inorganic sources enhanced N supply capacity and soil SOC pools.

Benbi and Khosa (2014) reported that at field capacity moisture there was almost double C mineralization rate at 35°C compared with at 15 °C temperature. Moreover, throughout the incubation period, cumulative amount of C mineralized from different organic sources at 15°C was lower by 36 to 61% compared to that at 35 °C. Initially, C mineralization was greater followed by gradual declined in later stage of 117 days incubation study, observed that substrate quality was one of the most important factors influencing decomposition of OM and microbial activities and the decomposition of organic substrates of leguminous green manure, rice straw, wheat straw and FYM was related to their chemical composition such as C/N, Lignin/N ratio cellulose and hemicelluloses and temperature and moisture conditions, Green manure (GM) contained more labile components, had the greatest rate and extent of decomposition, however, due to the presence of recalcitrant components in FYM showed resistance to decomposition than GM. Initially faster C mineralization continued about 4 weeks represented mineralization of easily decomposable constituents such as water-soluble components.

Benbi *et al* (2014) investigated the effect of different temperature on C mineralization in differentially fertilized soils and they observed that regardless of the treatment, the C mineralization was rapid during initial days of incubation then decreased gradually with increase the incubation period and levelled off at the end of incubation (54 days). They also observed that C mineralization increased with increase the temperature in whole soil but the magnitude of increase was greater between 15-35°C than 35-45°C. After 54 days 4-12 % C was mineralized of whole soil. They used different models and showed

that one degree Celsius increase in temperature increased decomposition SOM in whole soil to a greater magnitude at low temperatures and the effect decreased with increase in temperature, predicted that the C mineralization of whole soil will increase by 4-9 per cent at 10-15°C temperature and the effect will diminish to about 2-3 percent at 35°C.

Kaur *et al* (2008) reported greater amounts of C mineralization in NPK+FYM treatment as compared to N, NP and NPK treatments. The cumulative amount of mineralized CO₂-C varied between 0.58-6.5 g CO₂-C kg⁻¹ soil C in CK plots, respectively. In the plots receiving N fertilizer alone, it varied between 1.1 and 7.7 g CO₂-C kg⁻¹ soil C. The amount of mineralized CO₂-C increased further with an application of P along with N fertilizer (1.5-9.1 g CO₂-C kg⁻¹ soil C). In 100% NPK and 100% NPK + FYM plots, cumulative amount of mineralized CO₂-C ranged between 2-10.8 and 2.2-12.7 g CO₂-C kg⁻¹ soil C, respectively. They concluded that regular application of manure-enhanced water-soluble fraction of C acted as an important source of energy for microbial growth as compared to inorganic alone.

According research findings of Dash *et al* (2014), kinetics of C mineralization data described the first-order kinetic equation well. The GM treatment tended to decompose at higher rate as the power of the equation was found highest compared to that of the other treatments due to higher quality of C and also increased by higher amount of SOM.

2.2 Effect of cropping systems/ land-use on soil P and carbon dynamics

In general, different land use system and plant species play an important role in the effectiveness of residual and currently applied P fertilizers. The soil P exists in inorganic and organic compounds that range from ions in solution to highly stable compounds. The distribution of P in these different forms reflects the history and actual structure and function of an ecosystem (Sardi and Csatho 2002). Gill and Meelu (1983) concluded omission of fertilizer P for *kharif* crops in wheat based cropping systems in Punjab, where a recommended dose of phosphate to the wheat has been regularly applied for the past several years.

Rong *et al* (2014) evaluated the effect of land use on soil P sorption-desorption, observed that changes in land use affected soil pH, EC, available N, P and SOC content soil thereby influence the soil P sorption, sorption maxima (S_{max}) was in the order of Rice (1380 mg kg⁻¹) > plastic-film greenhouse vegetable and flower production (VFCL) for more than 10 years (1154 mg kg⁻¹) > Vegetable (747 mg kg⁻¹), suggested that soil P sorption capacity decreased when rice-legume production converted to more intensive vegetation and flower production. Pal and Mandal (2009) recorded the highest amount of desorption of added P in cultivated land (52.2%), while tea garden recorded the least (32.2%), indicated, the higher Olsen-P concentration in cultivated land which received continuous fertilizers for crop production, may led to lesser P sorption of applied P. Pandian (2009) observed that CK plots showed

greater amount and rate of P adsorption than fertilizer treated plots possibly due to the exhaustion of native soil P resulting from continuous cropping.

Pypers *et al* (2007) suggested that under low P status soil, legumes supplied with phosphate rock (RP) increase P acquisition by a subsequent maize crop compared to direct application of RP to maize. They assessed positive rotational effect in terms of soil P availability through the mechanism of P solubilization due to the released organic acids by legume crop. Kabengi *et al* (2003) assessed the effect on soil P dynamics of common cereal-based long-term rotations, soil was uniformly treated with the same P rate, observed that only total P was significantly affected by the rotation sequence in the topsoil (0–20 cm) of the wheat/medic rotation than others, could be attributed to the extensive root system of the medic which increased P mineralization, They have also observed that with increasing the incubation period raised available P levels from 17 to 21.25 mg kg⁻¹.

Gnankambary *et al* (2008) demonstrated the effect of tree canopies and fertilization on P availability for microbes and CO₂ evolution. Initially, respiration was higher in soil from under the canopy which received C plus N or C plus P, showing that both nutrients were more readily available under the canopy, than soil outside of canopy because less availability of P. Moreover, higher microbial biomass and the presence of more soil enzymes in the dead cells indicated that more P is available in forms that are immediately accessible to microorganisms under tree canopies, than outside the cover of their canopies may be due to the P fixation in soil. Tchienkoua and Zech (2004) reported significant increase in soil organic P under tea plantation than soils under mixed food crop field (CF), whereas it was significantly lower in tree planted soils ($P=0.05$). Inorganic P (NaHCO₃-Pi) was significantly greater in CF soils than tea planted and tree planted soils (0-10 cm soil depth), lower inorganic P and higher organic P in tree planted soils was due to strong phosphorus immobilization in standing biomass and litter. Higher values of labile NaHCO₃-Pi in cultivated fields attributed to fertilization but also annual burning that converts a fraction of soil organic P to mineral form (Andriesse and Koopmans 1984).

Lin *et al* (2015) reported that total P concentrations was lowest in the soils under tea plantation, while total P values of the paddy and dry soils was similar to the forest land soils. Olsen-P concentration was highest in paddy and dry soils followed by tea plantation and forest land soils, SOM was highest in forest land soils and lowest in tea plantation soils. The highest concentration of total P and SOM may be due to the addition of leaves and root litters. But Olsen-P was lower, could possibly due to the restricted P fertilization. Aguiar *et al* (2013) observed that intensive and continuous use of annual crops in the soils of the humid tropics may increase of the active and potential acidity thus decrease of the labile organic matter and organic P which was ~5% of total P than grass and secondary forest. Beauchemin *et al* (1996) estimated that available P sorption capacities were 50% lower in A horizons of agricultural soils under high animal density than in the forest soil. The poor sorption capacity of former soils may be attributed to

its low Al-oxides content and higher addition of manure P that accumulated in inorganic P forms. Darilek *et al* (2010) studied the effect of land use conversion from rice paddies to vegetable fields on soil phosphorus fractions, observed significant increases of 33, 281, 293, and 438 mg kg⁻¹ in soluble- Al-, Ca-, and Fe-inorganic P, respectively, most increased of Fe-P ranged from 8% of total P under paddy soil to 31% of total P in soils with >20-year vegetable cultivation, possibly could be due to the lower pH under vegetable soils.

Manlay *et al* (2002) studied the effect of different land management practice on nutrients status under continuous cultivation, observed that carbon stored in the plant–soil system was 25.0, 27.4, 34.9 and 71.9 t ha⁻¹, respectively, in groundnut, millet, maize and rice plots, High C and nutrient amounts found in rice plots were attributed to the clayey texture and seasonal flooding, respectively. Higher values for C, N and available P in soils under millet and maize than groundnut cultivation may be due to addition of higher organic and nutrient inputs.

Castillo and Wright (2008) reported that the distribution of P fractions in soil (0-15 cm) in relation to long-term land management. Soils under pasture (100 yrs) and planted to sugarcane (*Saccharum sp.*) for 50 yrs were amended with P (0, 10, 50, 150 kg P ha⁻¹). Labile P increased with increasing P doses, ranging from 1.3 to 7.2 mg kg⁻¹ for cultivated soil and 1.4 to 10.7 mg kg⁻¹ for pasture soils. The Ca-bound P fraction represented the greatest proportion of total P for sugarcane (41%) due to higher pH (6.8), but only 12% for pasture, indicated that most of the applied fertilizer P converted to Ca-P under cultivated soils, suggested more availability of P under pasture soils.

Hedley *et al* (1982) compared soil P fractions in a permanent pasture and the adjacent wheat-fallow rotation. They reported that a cultivated site contained lower total, medium available, and available-P than those of the permanent pasture.

Kolawole *et al* (2003) studied the dynamics of phosphorus fractions during fallow with natural vegetation and planted *Pueraria phaseoloides*, after one year, regardless of the management practice Olsen-P increased as fallow length increased. NaOH and conc. HCl extractable-organic P increased by 43% under natural fallow and by 24% under *Pueraria* fallow, increase in Olsen extractable P with fallow age could be due to sustained demand, uptake of P and litter production, which would increase its mobilization from non-readily extractable sources and magnitude of organic P increased was lower under *Pueraria* could be possibly due to litter decomposes very fast gets converted into inorganic P forms.

Xavier *et al* (2011) compared the P dynamics in the soils under natural forest (NF) and coffee cultivation. They have observed that cultivated soils had lower H₂O-inorganicP and NaHCO₃-inorganic P (~ 4% of total P) than NF (~6% of total P) but lower inorganic P, however, organic and total P were also higher under NF than cultivated soils, Although P fertilizers were applied to cultivated soils, larger

organic P pools under NF, indicated that organic P has an important role on the distribution and availability of P.

Kim *et al* (2006) studied the P dynamics in relation to land use and soil properties and observed that farmland soils contained greater amount of total P, water-soluble reactive P, organic and adsorbed inorganic PP content of the farmland soils was twofold to fivefold higher than that of the forest soils in the following order: upland fields>orchards>paddy fields>forest. Organic and adsorbed inorganic P were the dominant P forms in the soils, The higher P content of the farmland soils compared with the forest soils might be because of the addition of P the chemical and organic fertilizers.

Long *et al* (2011) concluded that total P and SOM were higher in the soils under tropical montane evergreen forest which were 1.1 (g kg⁻¹) and 8.16%, respectively, compared to tropical dwarf forest because tropical dwarf forest characterized by lower air temperature and high frequency of fog condensation.

Chen *et al* (2004) suggested that greater root exudation might have occurred under radiata pine. This played an important role in increase of soil microbial activities and labile C, solubility of organic P and mineralization of organic P in soils under radiata pine than ryegrass.

Grerup *et al* (2006) studied the long term effects of forestation on soil N, P, C and pH in the soils which were under continuous forest and cultivation and observed that the total P and available P tended to be lower in the continuously forested land than in the formerly cultivated fields. Soil C was higher and pH was lower in the continuously forested land than in the formerly cultivated fields. Due to less acidic soil under continuous cultivation increased P availability result in higher biomass production, thereby restricting the concentration of potentially toxic Al and promoting several acid-restricted microbial processes.

Sigua *et al* (2009) studied the significant impact of beef cattle pasture to wetland reversion on C and P dynamics, observed that draining natural wetlands to pastures reduced TOC. Total P ranged from 1134 mg kg⁻¹ to 2752 mg kg⁻¹ under drained and flooded conditions, respectively. They also found declining trend ($r=0.82^{**}$; $p\leq 0.01$) in total P from natural wetland (763 mg kg⁻¹) to pastures (340 mg kg⁻¹). It may be due to drying or wetland conversion to agricultural use, would lead to OM mineralization and immobilization of stored nutrients because of the changed in soil redox status. Haynes (2000) observed MBC increased linearly with increasing soil organic C content. Long-term pasture samples have a considerable higher TOC, P, WSC and MBC than arable soils due to the build-up of SOM under pasture and its greater breakdown under arable conditions (Shi *et al* 2015) and higher addition of SOM under pasture raised from senescing plant roots and tops, exudation of organic compounds from pasture roots, turnover of the large microbial biomass in the pasture rhizosphere (Kuzyakov *et al* 2001) and return of ingested material by grazing animals mainly in the form of dung. Under arable cropping, the amount of

organic material returned to the soil is much less than under pasture and, in addition, the soil is often tilled several times per year which favours decomposition of native SOM.

Al-Kaisi *et al* (2005) reported that regardless of soil depths, smooth brome-grass and switch-grass cropping systems resulted in substantially greater SOC than corn–soybean–alfalfa rotation after 10 years of cropping system, indicated that perennial grass cropping systems maintain a more stable soil environment due to less soil disturbance and the extensive root system of the perennial grasses than row cropping systems..

Benbi *et al* (2012) investigated the effect different land-use systems on SOC pools, observed greater SOC, HWSC and MBC in soils under poplar-based agroforestry than maize-wheat and rice-wheat cropping systems. However, SOC, HWSC and MBC were significantly lower in the soils under rice-wheat cropping system (3.88 g kg^{-1} , 173 and $104 \text{ } \mu\text{g g}^{-1}$, respectively) compared with agroforestry (6.56 g kg^{-1} , $335 \text{ } \mu\text{g g}^{-1}$ and $203 \text{ } \mu\text{g g}^{-1}$) and maize-wheat (6.52 g kg^{-1} , $300 \text{ } \mu\text{g g}^{-1}$ and $185 \text{ } \mu\text{g g}^{-1}$) cropping system. They have also observed that at end of 32 days incubation study, mean value of cumulative amount of CO_2 evolved was significantly lower from soils under rice-wheat ($459 \text{ } \mu\text{g g}^{-1}$) and maize-wheat ($461 \text{ } \mu\text{g g}^{-1}$) cropping system than to the agroforestry ($526 \text{ } \mu\text{g g}^{-1}$). Ultimately, they have concluded that higher C pools in agroforestry soils, could be possibly due to the greater addition of root biomass and leaf-litters than others, but in case of maize-wheat system greater SOC might be due to the application of FYM than rice-wheat system and less labile and recalcitrant C fractions contained 63% of the organic carbon which led to lower HWSC and MBC in rice-wheat soils.

Benbi *et al* (2015a) assessed the effect of different land-use on soil C dynamics, observed that HWSC ranged between 3.0 and 3.8% of TOC and the uncultivated (undisturbed > 40 yrs) soils were significantly ($P < 0.05$) higher in HWSC pool compared to soils under maize–wheat and rice–wheat cropping systems. The agroforestry and sugarcane systems had HWSC pool similar, but in between uncultivated and above both cultivated soils. KMnO_4 -oxidizable C comprised between 12.3 and 23.7% of TOC and was highest in uncultivated (3.44 Mg ha^{-1}) soils, however it was at par with sugarcane and agroforestry systems ($P < 0.05$) where values were 2.83 Mg ha^{-1} and 3.04 Mg ha^{-1} , respectively, followed by maize-wheat (2.52 Mg ha^{-1}) and rice–wheat (2.28 Mg ha^{-1}). Uncultivated soils contained greater concentration of MBC followed by soils under agroforestry and sugarcane compared to the soils under maize–wheat and rice–wheat cropping, moreover, they have also observed higher ($P < 0.05$) dehydrogenase activity in uncultivated than other soils, higher ($P < 0.05$) TOC pool was observed in uncultivated soils than the cultivated soils, might be due to the lack of soil disturbance such as tillage. In case of soils under agroforestry the greater HWSC could be attributed due to the inclusion of legume crop than cultivated soils and in soils under sugarcane could be related to higher aboveground biomass

addition. Arshad *et al* (2011) also reported that decrease in SOC from the initial level was typically associated with cultivation of soil previously under native vegetation.

Bene *et al* (2011) reported that SOM was closely related to the amount of above and below ground organic matter inputs, indicated that the amounts of both SOM and OM input increased linearly ($r^2 = 0.908$). SOM increased significantly, from 13.4 g kg^{-1} to 25.3 g kg^{-1} as a consequence of a 13- year period of perennial herbaceous species ramie [*Boehmerianivea* (L.) Gaud.] cultivation. The increase in SOM mainly attributed to the senescent leaves which naturally returned to the soil, and the turnover of below-ground biomass which contributed to the build-up of the SOM pool.

Introduction of perennials in crop rotations has been proposed as a viable opportunity to improve the long-term sustainability and productivity of systems due to the reduction in tillage and the protection of the soil surface (Johnson *et al* 2006). Boyer and Groffman (1996) reported that SOC, microbial activities and WSC were highest in surface soil which decreased with soil depth and highest WSC was in cornfields compared to forest land, due to increased humic acids and fulvic acids and higher litter quality (lower C/N ratio) under cornfield because they observed significant correlation between SOC and WSC in cornfield soils but not in forest soils.

Kukal *et al* (2009) observed that SOC in rice-wheat system was 54 and 30% greater under FYM and NPK plots than in similar treatments in maize-wheat soils except CK under both cropping system, high SOC concentration under rice-wheat as compared to maize-wheat could be due to greater aboveground biomass production and favourable water regime (flooding) during rice season, FYM increased nutrient concentration and simultaneously, improved soil physical environment for better plant growth, which resulted in higher above-ground and below-ground plant biomass and balanced fertilization proved to increase SOC because of greater C input associated with enhanced crop production and crop residues returned to the soil.

Begum *et al* (2007) advocated that SOM content increase by including legumes crop under integrated nutrient management (INM), which is in turn influenced by soil P dynamics and its availability.

Sharma *et al* (2009) studied the soil fertility and quality assessment under tree, crop and pasture-based land-use systems in a rain-fed environment, observed that among the land-use systems, agroforestry system resulted in the highest SOC content (9.6 g kg^{-1}) compared to arable land (3.66 g kg^{-1}). This enrichment in SOC content under tree-based systems could be due to several factors such as contribution by litter fall, root biomass, and root exudates. Also reported that total P content varied from 473.5 mg kg^{-1} in arable land to 787.3 mg kg^{-1} in the agroforestry system. Significantly greater total P content could be due to recycling of P through mining by the tree species and subsequently recycling by way of surface litter fall.

Tchienkoua and Zech (2004) observed that SOC significantly ($P=0.05$) higher in soils under *Eucalyptus grandis* plantations (73.3 g kg^{-1}) followed by *Camellia sinensis* plantations (69.1 g kg^{-1}) compared with semi-permanent, maize (*Zea mays* L.)-based, mixed food crop fields (39.4 g kg^{-1}). Under *Eucalyptus* treatment, greater litters with high C: N ratio (64) was a major factor of high SOC build up, lower OC in *Camellia sinensis* system was associated with reduced litter input due to harvest of young shoots as well as its rapid turnover rate as indicated by the low C:N ratio (26) for tea leaves. Microbial activity plays a major role in nutrient turnover in general and in P transformation and redistribution into different inorganic and organic forms in particular (Stewart and Tiessen 1987). Cardoso *et al* (2003) observed that organic P/total P was lower in the conventional systems than in the agroforestry systems, suggested that agroforestry systems influence the dynamics of P through the conversion of part of the inorganic P into organic P. Agroforestry systems are expected to have more microbial activity than the conventional systems. Availability of soil P increased by intercropping with potential of some non-crop plants in agroforestry systems to release P from recalcitrant pools, thus making it available to crops (Palm 1995).

2.3 Effect of soil properties on P availability

2.3.1 Soil texture

In general, the differences in soil nutrients concentration depend on the variation in soil texture, and total P is inversely related to soil particle size (Johnston *et al* 1997). A positive correlation between P adsorption and clay content (Zhang *et al* 2002) led to high P adsorption capacity of the soils (Pinto *et al* 2013). Shaheen *et al* (2007) observed that total P was negatively correlated with sand ($r=-0.73$) and positively correlated with silt ($r=0.48$) and clay ($r=0.75$) contents. Therefore, P was probably associated with the finer particles. Higher amount of clay resulted in fixation of applied-P (Doddamani and Seshagiri-Rao 1989, Hadgu *et al* 2014), because of greater adsorption capacity of the soils with higher clay content (Bahl *et al* 1986). Zhang *et al* (2012) observed that the P sorption capacity was closely related to the content of fine particles, and P sorption increased with increase in fine clay particle. Generally, the P content in soil followed the order clayey>peaty>sandy (Pizzeghello *et al* 2011).

Singh and Gilkes (1991) reported that clay content was the major soil property that influenced P adsorption in soils. The positive relationship of P adsorption with clay content and negative correlation with sand content may be related with larger surface area of clay as compared to sand. It could also be related to the relatively large number of positively charged functional groups that interact and strongly bind the negatively charged PO_4^- in soil.

Huffman *et al* (1996) reported that soil texture had a greater effect on P transformation than did residue placement. Abdu (2013) observed that soils that contain higher amounts of clay sorbed more P

than others. Phosphorus sorption index in these soils is 2-3 times higher compared to soils with lower clay contents, which may be attributed to the high surface area of clay particles. Due to presence of higher concentration of Fe-oxides in the soils, initial rapid release of P referred to the dissolution of metastable poorly crystalline or amorphous P in the soil. Diaz *et al* (2006) reported that sandy soils have a very small sorption capacity for P because of low clay content. Ca-bound P fraction was significantly correlated with the clay, silt and total P (Jalali and Matin 2013). Muralidhar *et al* (2005) demonstrated that clay had a major influence on P fixation ($r = 0.960$) in the soil. Fe and Al hydrous oxide clays react rapidly forming a series of difficultly soluble hydroxy phosphates. High clay content increases the adsorption of P, and clay soils have a higher total P than the soils with lower clay content (Lookman *et al* 1995). P retention tends to be more pronounced in fine than in coarse-textured soils because most of the compounds with which P reacts are in finer soil fractions (Olsen *et al* 1977). Fine textured and highly organic soils had more amorphous Fe and Al compounds which sorb P (Sah *et al* 1989, Lockaby and Walbridge 1998). On the contrary, coarse-textured soils often release more P than the fine-textured soils (Bahl 1990).

Phosphate sorption-desorption curves for silt and clay fractions from black Chernozem and Solodized soils showed that the clay fractions adsorbed ~1 to 1.5 and 2 to 10-times more phosphate than silt fractions, respectively at same equilibrium concentration (Goh *et al* 1986).

Chaudhary (1990) evaluated P sorption characteristics of ten soils from different locations of Punjab. Phosphorus sorption data were described well by Langmuir adsorption isotherm. The highest adsorption maxima was observed in Sadhugarh clay and the minimum in Fatehpur sand. Phosphate was adsorbed with greatest affinity in Sadhugarh clay while it was the least in Bathinda sand. Significant relationships were observed between the amount of P adsorbed and clay.

About 90% variability in organic and inorganic P is reportedly related to soil texture (O' Halloran *et al* 1985). Highly significant positive correlation between P fixation capacity and clay content has also been reported (Douli and Gangopadhyay 1984). Soil clay content is reported to be significantly related to the soil P sorption indices, P buffering, Freundlich coefficient and Langmuir adsorption maxima (Samadi 2006).

Toor *et al* (1997) reported that the soils having higher clay content, calcium carbonate, extractable Fe and Al exhibited higher P adsorption. Vig *et al* (2000) reported that addition of calcium carbonate enhanced P sorption, the effect being greater in coarse-textured soils than in fine textured soils. P sorption maxima, affinity coefficient for P and differential buffering capacity were higher in the soil samples equilibrated with calcium carbonate. Xiao *et al* (2012) indicated that the P distribution was dependent on the properties of the soil. Wani and Bhat (2010) studied the effect of soil properties on P sorption and maximum P buffering capacity (MPBC) and observed that soils with higher clay contents showed maximum P sorption ($353.5 \mu\text{g g}^{-1}$) along with highest MPBC (26.3 mL g^{-1}) compared to soils

with lower clay content. Wisawapipat *et al* (2009) reported that slightly greater portion of sorbed P was more readily available in the soil solution where soils were low in clay content

Zheng and MacLeod (2005) studied the effect of soil texture on P availability and indicated that labile and moderately-labile inorganic P pools were much higher in clayey soils than coarser textured soil.

Mashal *et al* (2014) observed that sand% and clay% were the most significant variables influencing P sorption-desorption process in calcareous soil.

2.3.2 Calcium carbonate

Availability of P in soil, to a large extent, depends upon the presence of CaCO_3 both in amorphous and crystalline forms. CaCO_3 exerts a dominant effect on the nature and properties of P in calcareous soils. High amounts of CaCO_3 and the large surface area of this mineral lead to rapid precipitation of P which reduces P availability for plant growth (Tisdale *et al* 2002). Water-extractable phosphate gets converted to relatively less soluble compounds within a very short time due to rapid reactions and high sorbing capacities of the soils (Jalali and Ranjbar 2010). Trivedi *et al* (2010) observed greater Ca-P content in soils due to the presence of CaCO_3 content. Shaheen *et al* (2007) reported that Ca-P was the dominant P fraction in different soils and represented 68, 66, 58, 52, and 30% of the total P in fluvial, marine, lacustrine, calcareous, and sandy and fluvio-sandy soils, respectively. In calcareous soils, the accumulation of CaCO_3 is believed to govern soil P reactions (Lindsay 1979) because of adsorption and precipitation of P on the CaCO_3 surface (Freeman and Rowell 1981, Amer *et al* 1985, Dunne *et al* 2011). Pizzeghello *et al* (2011) observed the overall positive relationship of total P with CaCO_3 and total P with Ca-P. Hadgu *et al* (2014) observed that Langmuir adsorption maxima was positively correlated ($r=0.912$) with CaCO_3 content. Diaz *et al* (2006) reported that P adsorption and precipitation with Ca represents a more stable fraction than exch-P and Fe-Al-P fractions. Castro and Torrent (1998) showed that in calcareous soils, reaction between Ca and P led to precipitation as Ca-phosphates which decreased fertilizers use efficiency. Wani and Bhat (2010) also reported that increase in CaCO_3 in the soils resulted in increase in P sorption and P buffering capacity of soil. This suggested that the large amount of P should be dressed for maintaining a desired P concentration in soil solution.

Muralidhar *et al* (2005) reported that alkaline soils which contained high amounts of soluble and exchangeable Ca^{++} and frequently CaCO_3 , decreased the availability of P due to rapid reactions with both the ionic and carbonate form of Ca by forming apatites of low solubility. Dominguez *et al* (2001) reported that Ca-saturation as a result of the amendment in calcareous soils raised the short-term sorption capacity of sorbent surfaces and resulted in a major contribution of Ca-phosphate precipitation to long-term P sorption. Jalali and Matin (2013) reported that the variations in the soil P forms in selected paddy soils. They showed that the total P concentrations ranged from 288 to 850 mg kg^{-1} and were enriched in site 1.

The trend of P fractions followed the order as HCl-P (Ca-P)>residual-P (Res-P)>NaOH-P (Fe-Al-P)>KCl-P (Exch-P) in all sites, which indicated that Ca compounds are main soil components for retaining P in calcareous paddy soils. The exch-P represented on an average <1 % of total P which was lower as compared to Fe-Al-P, ranging between 3.3–18 %. The Ca-P showed considerable contribution from 63.6–85.6 % to total P (represented on average 75.3 % of total P), observed a high proportion of P was in stable inorganic form and strong correlation of Olsen-P with Fe-Al-P and Ca-P fractions. Dunne *et al* (2011) reported that wetland soils in dairy had greater P sorption capacity due to greater concentrations of Ca and Mg. Trivedi *et al* (2010) observed that Ca-P content was dominant P form in the soils varied from 109.4 to 333.6 mg kg⁻¹. Its contribution was higher in deeper layers, which was evident as the CaCO₃ content also increased with depth. They have also indicated that Al-P content of the soils decreased with depth which contributed to 3.2 to 10.0% of the total P. The Fe-P content in the profiles followed the same trend as of Al-P.

Tunesi *et al* (1999) reported that the calcium ion activity in the liquid phase was mainly responsible for formation of insoluble Ca-phosphate mineral in calcareous soil. However, the greater contribution of exchangeable Ca ions to P precipitation than that of CaCO₃ has been reported by Akinremi and Cho (1991). Therefore Ca-P compounds had an important role in the control of P release in soils (McDowell and Sharpley 2003). The adsorption process has been seen to be predominant at lower P (<10⁻⁴M) concentrations in solution (Halford and Mattingly 1975, Freeman and Rowell 1981, Solis and Torrent 1989), while the precipitation reaction dominates at higher P concentration (Matar *et al* 1992). Olsen-P in soils showed a positive correlation with active CaCO₃ as reported by Halajnia *et al* (2009).

Soper and El-Bagouri (1964) reported that the availability of added phosphate was not related to carbonate content of soil, but CaCO₃ had very large effect on movement of applied-P. Further movement of P from fertilizer decreased with increase in CaCO₃ contents in soil (Bell and Black 1970). Similarly, Sharpley *et al* (1989) reported decreased fertilizer-P availability and fertilizer-P availability index with increase in CaCO₃ contents in soil. Borrero *et al* (1988) reported that in calcareous soil both the total apparent surface area of CaCO₃ and P-sorption by CaCO₃ are relatively lower than clay but plays a dominant role in P-sorption. Vig *et al* (2000) reported that the calcium carbonate enhanced P sorption effect being greater in coarse textured than in fine-textured soil, P sorption maxima, affinity coefficient for P and differential buffering capacity were higher in soil samples equilibrated with calcium carbonate.

Mashal *et al* (2014) observed that little P was released from the adsorbed phase where CaCO₃ was higher. The small amount of P released from soils which could be attributable to the conversion of poorly crystalline indigenous Ca phosphates into hydroxyl-apatite. In the floodplain calcareous soils of Indian-Punjab, Singh and Singh (2007) reported that for soils with comparatively higher CaCO₃ content,

isotherm inflection point that indicates the P precipitation in soil was distinct at high equilibrium solution P concentration.

2.3.3 Soil organic carbon

Fox and Kamprath (1970) proposed that 0.2 ppm P in the supernatant solution in soils as critical value for optimum plant growth, however, Halford and Mattingly (1975) suggested that in calcareous soils, organic matter and phosphate compete for the same sites for adsorption on CaCO_3 surfaces and the adsorption of decomposed organic materials on sorption sites decreases the bonding energy of the adsorbed phosphate may replenish the required P in soil solution for plant growth.

Application of organics (Benbi and Senapati 2010) and lesser disturbance (Benbi *et al* 2015a) of soil leads to increase the soil macro-aggregate and organic matter (OM) levels also influence P availability and related dynamics (Messiga *et al* 2012). An improvement in soil organic carbon (SOC) with organic manure application enhances soil microbial biomass and thereby alters P availability through mineralization-immobilization reactions (Chen *et al* 2003, Sigua *et al* 2009). Organic manure application along with inorganic-P fertilizers caused a significant improvement in organic and inorganic P fractions (Ranatunga *et al* 2013), reduction in sorption (Prasad and Mathur 1997, Varinderpal-Singh *et al* 2006, Song *et al* 2007). The soil management practices that involved higher addition of organic matter (Jalali and Ranjbar 2010) to the soil thorough crop biomass like in agroforestry systems, as relatively higher MBC in the soils under poplar based agroforestry compared to rice-wheat and maize-wheat cropping system in the northern Punjab (India), has been reported by Benbi *et al* (2012), affects the soil P availability by mineralization of organic P. Inter-cropping as in agroforestry system had an added advantage of using the potential of some non-crop plants to release some of the P from recalcitrant P pools, and thus making it available to the crop. The higher proportion of organic P relative to total P in the agroforestry systems compared to the conventional systems has been attributed to the effect of agroforestry land-use on the dynamics of P in the soils through the conversion of inorganic into organic P (Cardoso *et al* 2001). Increased microbial biomass plays a major role in P turnover by affecting its transformation and redistribution into different inorganic and organic P forms in particular (Stewart and Tiessen 1987, Oberson *et al* 2011). A linear relationship between organic P content and SOC in calcareous soils has been reported by Sharpley *et al* (1989). Shaheen *et al* (2007) observed that the Olsen-P was relatively higher in soils with greater SOM. This was supported by the significant correlation between Olsen-P and SOM content (Trivedi *et al* 2010). SOC controls the short and long term P availability in the soils (Runyan and Dodorico 2012).

Jiang *et al* (2006) evaluated the SOC and soil P interactions under seeded alfalfa fields in China, observed that number of growing years results increase in SOC, total and available P. SOC was

significantly positively correlated with total P, available P, TOC and soil total N (0.627**, 0.691**, 0.497*, and 0.546*, respectively), indicating beneficial effect of SOC on P. Pinto *et al* (2013) observed positive correlation between available P and SOM. Mashal *et al* (2014) also reported that soils with lower SOM% showed H-type P sorption isotherm, concluded that SOM play an important role in P sorption. Zhang *et al* (2012) observed that the amounts of P released from the soils were strongly in positive correlations with the organic P content, indicated that organic P can release P easily thereby enhanced P availability. Hadgu *et al* (2014) observed that phosphorus adsorption at low concentrations of added P negatively correlated with SOC suggesting that organic matter may compete with P for adsorption sites.

2.3.4 Available P

Hadgu *et al* (2014) observed a negative non-significant correlation between the soil Olsen-P and P adsorption maxima. At low initial P addition (60 mg P kg⁻¹ soil), percent of P adsorption was maximum while at high initial P addition (540 mg P kg⁻¹), percent P adsorption was minimum. As increment of P addition, percent adsorption decreased which concluded that soil P saturation can decrease adsorption, *i.e.* when the soil is saturated with P, rate of adsorption decreased with increased soil P concentration. Khorasgani *et al* (2009) observed positive and significant correlation of Olsen-P with Ca-P and Fe-P fractions and positively but not significantly with the Al-P fraction, indicating the contribution of Ca-P to available P for plant growth.

Emadi *et al* (2009) observed that highest maximum P buffering capacity (MPBC) and adsorption isotherm of P in the sandy clay soil from Jamaledinkola, which also contained high amounts of iron (Fe), aluminium (Al) and clay particles, and lowest in sandy soil from Deseleh, which contained very high initial available P and the low content of Fe, Al, silt and clay content.

Zhang *et al* (2002) reported that percentage of water soluble P of total P was the lowest among all the fractions, observed initially rapid release of P and decline thereafter, which indicated the release of loosely adsorbed P through fast reaction, whereas, less soluble P fractions were more slowly released. However, the rate of P release was slower in the low P status soils than in the soils with high P soils.

2.4 Effect of moisture and temperature on nutrient availability in soils

2.4.1 Influence of moisture and temperature regimes on phosphorus dynamics in soils

Phosphorus availability tends to differ in response to soil moisture (Runyan and Dodorico 2012) conditions. Flooding of soil leads to increase the availability of both native and applied P (Patric and Mahapatra 1968) to plants. This could be due to rapid diffusion of P to actively growing plant roots and because of enhanced concentration of soluble-P as a result of reductive dissolution of Fe-oxides (Huguenin-Elie *et al* 2003).

Xiao *et al* (2012) reported that flooding and wetting processes may enhance P release, which contribute to a significant pool of inorganic P. Soils under flooded, over wetted and alternate wetting–

drying conditions had higher soil P contents than which were soils under drying areas, might be due to dissolution of inorganic minerals. Increase in the concentration of labile-P in the equilibrium soil solution with the development of the reduced conditions has been reported by Hundal *et al* (1988). With prolonged flooding the P may become re-immobilized in less available form (Kirk *et al* 1990). Conversely, subsequent drying of the soil results in rapid re-oxidation of reduced P compounds and their precipitation on and as crystalline forms, which may become immobilized. However, if the soil remains aerobic, P slowly reverts to its pre-flooding state over a period of months (Willet 1991). Darilek *et al* (2011) observed that P solubility and availability largely affected by moisture regimes, under flooded conditions, soluble and loosely bound P significantly decreased to half of aerobic levels, only Fe or Al-P increased by 66%, organic P decreased by 64% but Ca-P and residual-P were not affected under both moisture regimes. However, wheat cultivation during dry season required P fertilization. Kabba and Aulakh (2004) reported higher P mineralization from added crop residues at nearly-saturated than under upland moisture regime. Singh *et al* (2010) reported 11-12% increase in Olsen-P concentration with press-mud application to floodplain soils incubated at nearly-saturated than in aerobic soil moisture conditions. Under saturated soil moisture conditions soil pH is decreased due to the accumulation of carbon dioxide (CO₂) in the calcareous soils (Yadvinder-Singh *et al* 1988) which enhanced the amount of labile-P and concentration of P in the soil solution.

Increased production of organic acids due to decomposition of organic matter under higher moisture regime (Wang *et al* 1967) leads to the conversion of meta-stable calcium phosphate to less soluble form (Singh *et al* 2010). The liberation of organic acids (Hundal *et al* 1988) that compete with the ortho-phosphate ions for the active adsorption sites, occurred in greater amounts in the soil under waterlogged conditions as compared to under aerobic ones (Wang *et al* 1967). Sood and Minhas (1989) conducted an incubation study for 60 days at different moistures regimes and observed that at each incubation time higher rate of organic P mineralization under flooded (Patel *et al* 1992) conditions compared at 50% of water holding capacity was reported.

Adeli *et al* (2005) observed non-significant differences in available-P between the 18°C and 25°C incubation temperatures than at 32°C where concentration of available P significantly increased. It was likely due to that the higher temperature (32°C) promoted higher biological activity than lower temperature, there by increased organic P mineralization, available P was significantly smaller at 18°C and 25°C than at 32°C. Kabengi *et al* (2003) observed not significant effect of varying the temperatures, indicated that P that might have been mineralized was rapidly immobilized by the highly calcareous matrix. Shi *et al* (2015) reported that MBP was greater after soybean than after corn suggesting overall metabolic activity reduced during this period, possibly due to lower temperature. Roger *et al* (2014) observed the significant effect of land uses on soil P status, found highest available P under croplands

than mountain pastures land, however, reverse pattern was observed for total P which was 1039 and 935 mg kg⁻¹ in mountain pastures land and croplands, respectively. Organic P was also in similar pattern as total P, in mountain pastures (737 mg kg⁻¹) and croplands (427 mg kg⁻¹). These variations in the distribution of different P forms among land uses could be explained by the presence of livestock and continuous addition of cattle manure in mountain pastures, often responsible for increases in total and organic P whereas tillage practices and high temperature that could increase microbial decomposition of SOM in croplands.

2.4.2 Influence of moisture regime on Fe, Mn and SOC in soils

Submergence of soils tends to increase Fe and Mn solubility, which initially increases their availability but decreases as submergence period progressed, in well drained soils Fe (Nayyar and Chhibba 2000) and Mn (Takkar and Nayyar, 1981) availability decreases for plant uptake. Gogoi *et al* (1999) conducted an study with five soils, observed a sharp increase in water soluble and exchangeable-Fe from 40 and 44 mg kg⁻¹ at 0 day to 159 and 282 mg kg⁻¹, respectively, at 14 days (attained a peak at 14 days after submergence) and decreased thereafter, as submergence period progressed, water soluble-Fe was greater (50 mg kg⁻¹) than at 0 day. Saha *et al* (1992) demonstrated the increase in DTPA-Fe and Mn after 45 days of submergence by -3 and -1.8 times, respectively, over their initial their contents. Bandyopadhyay and Sen (1992) assessed the effect of 14 days of super saturated soil water condition on exchangeable Fe and Mn in silty clay (inceptisol) soils and observed significant (P=0.05) decrease in redox potential and oxygen diffusion rate which led to significant (P=0.05) increase in exchangeable Fe and Mn by 402.8% and 703.28%, respectively, over 0 day.

Suthar *et al* (1992) conducted an incubation study for 16 weeks to investigate the effect of varying moisture regimes which included saturation, 80% of available water and 20% of available water on Fe availability, observed that Fe availability significantly affected by each moisture level, available Fe increased (285% over its initial value) upto 4 weeks and thereafter decreased, however, magnitude of increase was much greater at saturation followed by 80% of available water and 20% of available water regimes. Waterlogged condition tended to 213.6 % increase in Fe content over field capacity moisture level where Fe content was 44 mg kg⁻¹ (Tiwari *et al* 1976). Decrease in available Fe content in soil due to submergence than air dried condition has also been observed by Mishra and Pande (1976).

Maji and Bandyopadhyay (1992) also recorded the increase 201.8 to 2022.3% DTPA-Fe and 2.1 to 101% in DTPA-Mn, from their initial contents in submerged soils. Furthermore, observed positive correlation (r=0.59) of DTPA-Fe with SOC. Mandal (1961) also reported the a sharp increase in insoluble ferrous Fe in waterlogging of soils and thereafter, with an increase in CO₂ concentration, Fe ⁺⁺ entered into the exchangeable complex but slowly than Mn where the trend was same as for Fe, concluded that

transformation of Fe and Mn were due to direct reduction of their oxidised forms. Mandal and Mitra (1982) observed a sharp increase in water soluble and exchangeable Mn after 10 days of waterlogged soil moisture condition followed by significant decline thereafter upto 85 days in alluvial and saline soils, and similar trend was in case of Fe but with small magnitude, increase in Mn and Fe were always greater under continuous waterlogged moisture regime than continuous saturated and alternate waterlogged moisture regime.

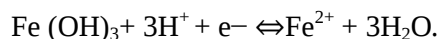
Sadana and Bajwa (1985) reported the increase in Mn concentration of sodic soils after 6 weeks of submergence followed by a decline upto 12 weeks, however gypsum + green manure application followed same trend as above, but magnitude of Mn concentration was greater, could be possibly due to the precipitation of MnCO_3 and possible formation of organic complexes.

Phillips (1998) reported that waterlogged soils contain remarkable amount of SOC, reduced form of Fe and Mn, which may increase P availability, due to solubilization of Fe^{3+} oxides and Mn^{3+} hydroxides and mineralization of organic P under reducing conditions, and the subsequent release of sorbed P. It was suggested that this Fe was then reprecipitated as amorphous Fe^{2+} hydrous oxides which removed soluble P via sorption mechanism. Willett (1989) observed that mineralization of organic matter was a major contributor to increases in P under reduced soil

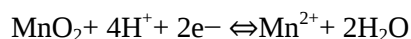
Under submerged condition, the main electron acceptors were organic substances degraded by organic matters and other substances, such as Fe^{3+} , Mn^{4+} , NO_3^- , SO_4^{2-} etc and the energy released by the redox reaction was low (Xu *et al* 2009), therefore, less energy is provided for the synthesis of microbial cells per unit of SOC mineralization. Patrick and Mikkelsen (1971) showed that soils under submerged rice cultivation subjected to various changes which resulted decrease in oxidation–reduction, which tended to increase in iron (Fe^{2+}) and manganese (Mn^{2+}) concentrations resulted from reductions of Fe^{3+} to Fe^{2+} and Mn^{4+} to Mn^{2+} .

Ultimately, oxidation-reduction is a chemical reaction in which electrons are transferred from a donor to an acceptor. The electron donor loses electrons and increases its oxidation number or is oxidized, the acceptor gains electron and decreases its oxidation number or is reduced. SOM acts as a source for microbial activities (Ponnamperuma 1972).

The reduction of Fe^{3+} to Fe^{2+} is expressed by following equation (Ponnamperuma 1977):



Principal reduction processes in flooded soils



According to Sahrawat (2004) the principal mechanisms involved in organic matter accumulation in the soils under submerged for longer period included slower, incomplete and inefficient decomposition SOM in the absence of oxygen, stabilization of organic matter, accumulation of antimicrobial toxicants.

SOC was 7 fold greater in wetland soils compared with aerobic pastures (Sigua *et al* 2009). Sahrawat (2007) reported that reduced soil conditions led to increase Fe concentration and the rapid decomposition of SOM in aerobic soils due to the presence of oxygen, however under flooded conditions SOM decomposition governed by the availability of alternate electron acceptors such as oxidised forms of Fe and Mn. Zhou (2002) reported that the main organisms under submerged condition such as anaerobic microorganisms, did not completely oxidized organic substrates to CO₂ through Tri Carboxylic acid cycle (TCA), but forms small molecules organic acids, alcohols, etc. through other biochemical pathways there by reduced C mineralization. Marinari *et al* (2010) reported that mild temperature of the Mediterranean sites seems to favour microbial metabolism for C mineralization. Decomposition of SOM tended to increase with increase with temperature which has also been reported by Katterer *et al* (1998) who found that change in temperature favoured microbial activities there by enhanced C mineralization in the soils.

Therefore nutrient management practices, land-use, cropping system and soil properties influence soil P dynamics.

CHAPTER III

MATERIALS AND METHODS

The present study on “Dynamics of soil phosphorus in relation to carbon under different cropping systems” comprises field and laboratory studies. Field experiment included studies at Research farms of Department of Soil Science, PAU, Ludhiana, and at farmers’ fields in different districts of Punjab. The laboratory study involved laboratory analysis of phosphorus (P) sorption-desorption and release kinetics in soils. The laboratory incubation experiments involved study of carbon mineralization kinetics in soils and changes in available P in relation to temperature and moisture.

3.1 Description of field experimental sites and soil characteristics

The field experiments were established during *kharif* 2006 on rice (*Oryza sativa* L.)-wheat (*Triticum aestivum* L.) and during *rabi* 2006-2007 on basmati (*Oryza sativa* L.)-wheat (*Triticum aestivum* L.) cropping systems at Research farm of Punjab Agricultural University (PAU), Ludhiana, India (Latitude: 30° 56’N, Longitude: 75° 52’E and mean sea level=247.5m). The study location is at the center of Punjab state which forms the northwestern part of the country. The climate of the place is sub-tropical, semi-arid. During 1970-2005, the experimental area received ~750 mm rainfall annually, of which ~80% was received during the *kharif* season extending from 1 May to 31 October (Kaur and Hundal, 2008). Important physical and chemical properties of the surface (0-15 cm) soils of two field experimental sites are detailed in table 3.1.

Table 3.1 Important physical and chemical properties of the surface (0-15 cm depth) soil at the start of the field experiments in 2006

Soil property	Rice-wheat cropping system	Basmati-wheat cropping system
pH	7.22	7.34
EC (dS m ⁻¹)	0.21	0.30
Soil organic carbon (g kg ⁻¹)	5.72	3.22
Available N (kg N ha ⁻¹)	141.0	175.0
Available P (kg P ha ⁻¹)	21.8	16.4
Available K (kg K ha ⁻¹)	89.6	158
Soil texture	Sandy loam	Sandy loam

3.1.1 Effect of P rates and source of application on soil phosphorus and carbon pools under rice-wheat cropping system

3.1.1.1 Details of the experiment

The treatments in experiment on rice-wheat system included i) application of nil and 30 kg P₂O₅ ha⁻¹ to rice through single super phosphate (SSP) and rock phosphate (RP) and ii) application of farmyard manure (FYM) at 10 Mg ha⁻¹ (dry weight basis) with or without fertilizer application to rice. Except in control plot wheat was fertilized with 60 kg P₂O₅ ha⁻¹ through SSP (Table 3.2). Each treatment was

replicated three times and arranged in a randomized complete block design (RBD) on a plot size of 3.0 m X 8.0 m (24 m²). Fertilizer N was applied through urea in three equal splits viz. at the time of puddling, 3 and 6 weeks after transplanting to rice. Whole of the P as single super phosphate or rock phosphate and K as potassium chloride was applied as a basal dose to rice. The field was flooded with 5-6 cm standing water and puddled under wet conditions. Immediately after field puddling, 30-35 days old rice (variety PR-118 or PR 114) seedlings were transplanted in rows 20 cm apart with plant-to-plant distance of 15 cm, ensuring 33 plants m⁻² area in second week of June. Rice crop was harvested manually in the fourth week of October each year. After rice, wheat (variety PBW-550) crop was sown at 100 kg ha⁻¹ in second week of November in rows 22.5 cm apart (*rabi* season). Half dose of fertilizer N was applied as urea at the time of sowing and remaining one week after first irrigation. Whole of the P as single super phosphate and K as potassium chloride was applied as a basal dose to wheat each year. Wheat was irrigated with canal or ground water and an irrigation of about 7.5 cm was applied when required depending on the visual inspection of the field. Wheat crop was harvested manually in the third week of April each year.

Table 3.2 Details of treatments applied to rice and wheat crops

Treatment reference	Treatment acronym		Nutrient applied (kg ha ⁻¹ yr ⁻¹)	
	Rice	Wheat	Rice	Wheat
CK	P ₀	P ₀	120 N + 30 K ₂ O	120N + 30 K ₂ O
F ₀ P ₀	P ₀	P ₆₀ SSP	120 N + 30 K ₂ O	120N + 60 P ₂ O ₅ + 30 K ₂ O
F ₀ P ₃₀ RP	P ₃₀ RP	P ₆₀ SSP	120 N + 30 P ₂ O ₅ (RP) + 30 K ₂ O	120N + 60 P ₂ O ₅ + 30 K ₂ O
F ₀ P ₃₀ SSP	P ₃₀ SSP	P ₆₀ SSP	120 N + 30 P ₂ O ₅ (SSP) + 30 K ₂ O	120N + 60 P ₂ O ₅ + 30 K ₂ O
F ₁ P ₀	FYM	P ₆₀ SSP	120 N + 30 K ₂ O + 10 t FYM	120N + 60 P ₂ O ₅ + 30 K ₂ O
F ₁ P ₃₀ RP	FYM+P ₃₀ RP	P ₆₀ SSP	120 N + 30 P ₂ O ₅ (RP) + 30 K ₂ O + 10 t FYM	120 N + 60 P ₂ O ₅ + 30 K ₂ O

CK=Control, RP=Rock phosphate, SSP=Single super phosphate, FYM=Farmyard manure

3.1.1.2 Collection and preparation of soil samples

Soil samples from field experiment were collected from 0-7.5, 7.5-15, 15-30 and 30-60 cm soil depths. The soil samples were collected from three replicates of each treatment plot and then composited. Soil samples from field experiments at PAU, Ludhiana were collected with a metallic soil core sampler (inner diameter 7 cm and 7.50 cm length) from each depth. Soil samples were air dried in shade, ground to pass through 2 mm sieve for different analysis.

3.1.1.3 Soil Analyses

3.1.1.3.1 Basic Soil Analyses

Soil samples collected from field experiment were analyzed for pH (1: 2 soil: water), electrical conductivity (E.C., 1: 2 soil: water suspension), calcium carbonate (CaCO₃), available P, available K and mineral-N. The details of the methods used for these analyses are given in table 3.3.

Table 3.3 Brief description of the standard methods used for soil sample analysis

Property	Description of the method	Reference (s)
pH	1: 2 Soil: water suspension using glass calomel electrode	Jackson (1967)
EC	1: 2 soil: water supernatant using a conductivity meter	Jackson (1967)
CaCO ₃	Calcium Carbonate was determined by titrating soil suspension (soil, water, calcium sulphate powdered and aluminium chloride) with 0.5N H ₂ SO ₄ in presence of bromothymol blue and bromocresol green indicators	Puri (1950)
Available P	0.5M sodium bicarbonate (pH 8.5; 1:20 soil: extractant), P concentration determined using ascorbic acid method	Olsen <i>et al</i> (1954), (Murphy and Riley 1962)
Available K	1N ammonium acetate (pH 7.0) as extractant and measuring K on flame photometer	Jackson (1967)
Mineral-N	Mineral N (NO ₃ ⁻ -N and NH ₄ ⁺ -N) was determined by extracting the soil samples with 2M KCl followed by by mineral N estimation by steam distillation of extract using Mgo and Devarda's alloy	Mulvaney (1996)

3.1.1.3.2 Soil physical properties

3.1.1.3.2.1 Bulk density: Soil bulk density (D_b) at surface (0-7.5 cm), sub-surface (7.5-15 cm), 15-30 cm and 30-60 cm soil depth was determined by core method using metallic cores (inner diameter=7.0 cm and 7.5 cm length). Soil cores collected from each sampling were oven dried at 105°C for 24 h, and dry soil weight was recorded (Blake and Hartge 1986). The D_b (Mg m⁻³) was calculated as:

$$D_b = \frac{Ws}{Vt}$$

Where, ' Ws ' is weight of soil (Mg) and Vt is the volume of soil sample (m³)

3.1.1.3.2.2 Soil porosity: Soil porosity was determined as ratio of bulk density to particle density using the following equation

$$\text{Soil porosity (\%)} = \left(1 - \frac{D_b}{D_p}\right) \times 100$$

Where, D_b and D_p are bulk density and particle density, respectively. The D_p of the mineral soil was taken as 2.65 Mg m⁻³.

3.1.1.3.3 Phosphorus fractionation

The chemical speciation of P in soil samples was achieved by using a sequential extraction scheme proposed by Golterman (1996) and Golterman *et al* (1998) (Figure 3.1). Briefly, 0.5 g soil was sequentially extracted by shaking with 30 ml deionized water for 2 hours. This was followed by 2 hours shaking with 0.05M Ca-EDTA (+1% Na-dithionite, pH=7.8). Then same soil was shaken for 16 hours with 0.1M Na-EDTA (pH=4.5). After this same soil was shaken for 2 hours with 0.5M H₂SO₄, and 2 hours with cold 0.5M tri-chloroacetic acid (TCA; 0 °C,) followed by the shaking of same soil with hot 0.5M TCA (95°C) for 30 minutes. Then, in the same soil 2M NaOH (90°C) was added and shaken for 1 hour. Finally, the same soil was shaken for 2 hours with persulphate (K₂S₂O₈)+H₂SO₄ which is believed to remove the residual Pi. These fractions represent in sequential order: water soluble or soil solution P (H₂O-P), Fe associated P, Ca associated P, acid soluble organic P (ASOP), sugar bound P after digestion with K₂S₂O₈ (cold TCA), nucleic acid and polyphosphate organic P after digestion with K₂S₂O₈ (hot TCA; Golterman 1960), humic bound P and phytate (NaOH inorganic and NaOH organic P), and residual P. Following extraction, each soil-suspension was centrifuged at 3500 rpm for 15 min, decanted, and an aliquot was taken for P determination. For H₂O-P, Fe-P, Ca-P, and NaOH fractions, the organic P fraction was defined as the difference between P detectable before and after digestion with K₂S₂O₈. Phosphorus in extracts was determined colorimetrically with the molybdate-ascorbic acid method (Murphy and Riley 1962).

3.1.1.3.4 Soil organic, inorganic and total P stocks, and P enrichment

Phosphorus stock (kg P ha⁻¹) in surface (0-7.5 cm) and subsurface (7.5-15 cm) soil was computed by multiplying the respective P concentration (mg P kg⁻¹) with measured soil bulk density (Mg m⁻³) and depth (m) of sampling using the following formula:

$$P (kg P ha^{-1}) = P (mg P ha^{-1}) \times Soil\ depth (cm) \times Bulk\ density (Mg\ m^{-3}) / 10$$

Phosphorus enrichment was calculated as the difference in the concentration of a P pool in the treated and the control plots.

3.1.1.3.5 Kinetics of P release

Phosphorus release kinetics were studied by equilibrating each soil (0-15 cm soil) with 0.5M NaHCO₃ (pH 8.5) in 1:5 soil: solution ratio for 0.5, 1, 2, 3, 6, 12, 24, 48, 72 and 96 h. The supernatant solution was analyzed for P concentration using ascorbic acid method (Murphy and Riley 1962). Amount of P released (C_A) was determined for different equilibration periods (t) and P release data were fitted to six different models (Table 3.4).

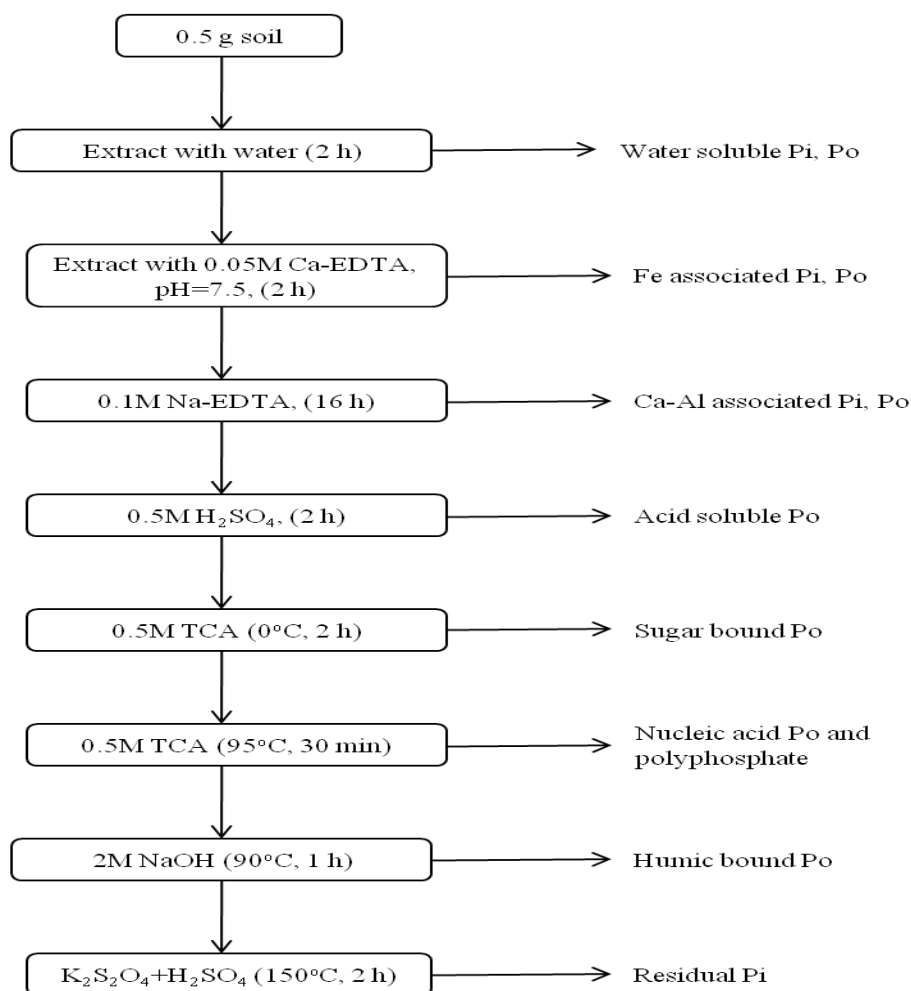


Fig 3.1 Flow chart of the sequential P fractionation scheme proposed by Golterman (1996) and Golterman *et al* (1998)

Table 3.4 Kinetics models fitted to P release versus time data

Model	Equation	Parameter
Zero-order	$C_A = C_{A0} + k_A t$	k_A is rate coefficient
First-order	$\ln C_A = \ln C_{A0} + k_A t$	k_A is first-order rate coefficient
Second-order	$1/C_A = 1/C_{A0} + k_A t$	k_A is second-order rate coefficient
Power function	$\ln C_A = \ln k_A + b \ln t$	k_A is rate coefficient and b is empirical constant
Elovich	$C_A = (1/\beta) \ln(\alpha\beta) + (1/\beta) \ln t$	α is initial P release rate coefficient and β is release constant
Parabolic diffusion	$C_A = R t^{1/2} + C$	R is diffusion rate constant

3.1.1.3.6 Soil organic carbon and its fraction

Total organic carbon (TOC) concentration and its labile pools from the soils under different field experiments and land-use systems were determined using standard procedures are outlined in table 3.5.

3.1.1.3.7 Carbon management Index

Carbon management index (CMI) was worked out in surface (0-7.5cm) and subsurface (7.5-15 cm) soil. The mean value for control treatment was used as a reference. The CMI was calculated using mathematical procedure of Blair *et al* (1995) as described below:

$$\text{CMI} = \text{CPI} \times \text{LI} \times 100$$

Where, CPI is the C pool index and LI is the lability index.

The CPI and the LI were calculated as:

$$\text{CPI} = \frac{\text{TOC}_{\text{treated}} (\text{g kg}^{-1} \text{ soil})}{\text{TOC}_{\text{control (reference)}} (\text{g kg}^{-1} \text{ soil})}$$

$$\text{LI} = \frac{L_{\text{treated}}}{L_{\text{control (reference)}}$$

Where, *L* refers to the C lability, calculated as

$$L = \frac{\text{Content of labile C (KMnO}_4\text{-C)} (\text{g kg}^{-1} \text{ soil})}{\text{Content of non-labile C (g kg}^{-1} \text{ soil)}}$$

Table 3.5 Brief description of procedures used for determining total and labile pools of carbon

Soil carbon pool	Description of the method	Reference (s)
Total organic carbon (TOC)	Digestion of soil sample in 1N potassium dichromate and concentrated H ₂ SO ₄ , followed by heating at 150 °C for 1 hour and titration with ammonium ferrous sulphate using diphenylamine indicator	Snyder and Trofymow (1984)
Soil organic carbon (SOC)	Digestion of soil sample in 1N potassium dichromate and concentrated H ₂ SO ₄ , followed by titration with N/2 ammonium ferrous sulphate using diphenylamine indicator	Walkley and Black (1934)
Water extractable organic carbon (WEOC)	WEOC was determined by shaking 10 g of soil with 20 ml (1:2; soil: solution ratio) deionized water for 1 h	McGill <i>et al</i> (1986)
Hot water soluble carbon (HWSC)	HWSC was determined by moderately boiling 20 g soil with 100 ml distilled water for 1 hour under reflux condenser. The amount of C in the extract was determined by chromo-sulfuric acid method	Schulz <i>et al</i> (2003)
Potassium permanganate oxidizable carbon (KMnO ₄ -C)	KMnO ₄ -C was determined by shaking 3 g soil with 33 mM (25 ml) KMnO ₄ solution for 24 hours on a reciprocal shaker. After centrifuging at 3500 rpm for 15 minutes, 2 ml of aliquot was diluted to 50 ml to read absorbance at 565 nm on a double beam spectrophotometer	Blair <i>et al</i> (1995)
Microbial biomass carbon (MBC)	MBC was determined by Chloroform Fumigation Extraction (CFE) method (Vance <i>et al</i> 1987) using a recovery factor (KEC) of 0.41 (Voroney and Paul 1984).	Vance <i>et al</i> (1987)

3.1.1.3.8 Mineralizable carbon

Carbon mineralization was studied in the laboratory by conducting aerobic incubation under controlled conditions. Fifty grams of each air-dried surface soil (0-15 cm) was wetted to field capacity moisture and placed in a 500 ml conical flask along with vials containing 10 ml of 1 M L⁻¹ NaOH to trap CO₂ and water to maintain humidity. The soils were incubated for 36 d at 25 and 35°C in a BOD incubator. Alkali traps were replaced daily during the first week and every 2 or 3 d thereafter. Evolved CO₂ was determined by titrating alkali in the traps with 0.1 M L⁻¹ HCl. The cumulative amount of CO₂-C evolved in the 36 d incubation was referred to as C mineralization.

3.1.1.4 Statistical analysis

Statistical and correlation analyses were performed with SPSS for Windows 16.0 (SPSS Inc., Chicago, U.S.A.). Data were subjected to analysis of variance (ANOVA) in a completely randomized block design. Mean separation for different treatments was evaluated at 95% confidence interval using the Duncan's multiple range test (DMRT). Phosphorus release data were fitted to six different kinetic models with SPSS 16.0 for Windows (SPSS Inc., Chicago, U.S.A.).

3.1.2 Effect of nutrient management practices on soil phosphorus and carbon pools under basmati-wheat cropping system

3.1.2.1 Details of the experiment

The treatments in experiment on basmati-wheat sequence included different organic sources of nutrients viz. FYM, rice straw compost (RSC) and vermicompost (VC) and integrated use of FYM and inorganic fertilizers, and recommended rates of fertilizers (NPK) (Table 3.6). Prior to seeding basmati, a green manure crop of Sunhemp was raised *in situ* for 45-50 days, except NPK and control plots. The green manure was incorporated in the soil one day before transplanting of basmati every year. A total of six treatments were replicated three times and arranged in a randomized complete block design (RBD) on a plot size of 4 m X 10 m (40 m²). Basal application of 30 kg P₂O₅ was made to basmati in recommended fertilizer (NPK) plots. Immediately after the field puddling 30 days old seedlings of basmati (variety Super Basmati) was transplanted on third week of July. Nitrogen was applied in two splits viz. 3 and 6 weeks after transplanting. The crop was kept weed free manually. Basmati harvesting was done manually in the third week of November each year.

After basmati, farmyard manure (FYM), vermicompost (VC) and rice straw compost (RSC) were applied in their respective plots to supply 400 kg N ha⁻¹. In INM treatments, farmyard manure was applied to supply 200 kg N ha⁻¹ with recommended fertilizers (NPK). In each treatment farmyard manure

(FYM), RSC and VC, containing on average 7.2 g kg⁻¹ N, 6.3 g kg⁻¹ N and 5.1 g kg⁻¹ N, respectively. The organic sources were incorporated to their respective treatments before seeding wheat. In recommended fertilizer treatments whole of P and K and half of recommended N were applied at the time of sowing. Remaining N was applied one week after first irrigation. Wheat variety (PDW 277 or PBW 550) was sown at 100 kg ha⁻¹ in the fourth week of November and harvested in third week of April each year. An irrigation of about 7.5 cm with canal or groundwater was applied to wheat when required depending on the visual inspection of the field.

Table 3.6 Treatment details of field experiment under basmati-wheat cropping system at Research Farm, Punjab Agricultural University, Ludhiana

Treatment reference	Nutrient applied (kg ha ⁻¹ yr ⁻¹)	
	Basmati	Wheat
CK	Nil	Nil
NPK	40 N + 30 P ₂ O ₅	120 N + 60 P ₂ O ₅ + 30 K ₂ O
INM	GM	RF+200 kg N ha ⁻¹ through FYM
FYM	GM	400 kg N ha ⁻¹ through FYM
RSC	GM	400 kg N ha ⁻¹ through RSC
VC	GM	400 kg N ha ⁻¹ through VC

CK=Control, NPK=Recommended fertilizer GM=Green manure (*Sunhemp*), INM=Integrated nutrient management, FYM=Farm yard manure, RSC=Rice straw compost, VC=Vermicompost

3.1.2.2 Collection and characterization of organic manures

At the time of field preparation for rice transplanting, well decomposed FYM was obtained from the dairy farm of Punjab Agricultural University, Ludhiana. Well decomposed RSC and VC were obtained from composting heaps at Research farms of Department of Soil Science, PAU, Ludhiana. Before, their field application, sub-samples were brought to the laboratory for analysis. The samples were collected in polythene bags, then oven dried at 50°C to a constant weight, ground and passed through 2 mm stainless steel for determining the nutrient concentration. Total N in FYM, RSC and VC was determined by adopting the procedure of Jackson (1967). Briefly, 0.5 g of manure was wet-digested in concentrated H₂SO₄ with Hibbard's digestion mixture consisting of K₂SO₄, CuSO₄, Se and HgO. The extract obtained was analysed for total N using a Micro-Kjeldahl assembly.

3.1.2.3 Collection and preparation of soil samples

Same as described under sub-section 3.1.1.2.

3.1.2.4 Soil analyses

Same as described under sub-section 3.1.1.3.1-3.1.1.3.8.

3.1.2.5 Statistical analysis

Same as described under sub-section 3.1.1.4.

3.2 Phosphorus and carbon fractions in soils under different land-uses at farmers' fields

3.2.1 Soil sampling sites and sample collection

Punjab state is located in North-Western India and lies between latitudes 29.30° N to 32.32° N and longitudes 73.55° E to 76.50° E. Punjab climate comprises of three seasons viz. summer from mid-April to the end of June, the rainy season from early July to end of September and the winter season from early December to end of February. The region falls in the agro-ecological sub-region 4.1 of India and is characterized as semiarid subtropical with monsoonal climate. Annual rainfall ranges between 700 and 800 mm and more than 70% of it occurs during the monsoon months of July–September. The temperature ranges from minimum of 4 °C in winter to 45 °C in summer. The mean monthly minimum and maximum air temperature respectively average 18 and 35 °C during rice/maize growth season (June–October) and 7 and 23°C during wheat season (November–April).

Surface soil samples (0-15 cm) were collected from 96 sites representing four different land-uses viz. rice-wheat, maize-wheat, cotton-wheat and under agroforestry systems for 15 years or more. Soil samples were collected from different districts of Punjab (India) (Figure 3.2). For every land-use, 24 samples, each composite of three spots within a field were taken with a core sampler, after the harvest of wheat crop in April/May 2013. Samples were air-dried and ground to pass 2 mm sieve before analysis. In the agroforestry systems, samples were collected between tree rows. Between the trees row, farmers were growing intercrops viz. moong (*Vigna radiata*), black gram (*Vigna mungo*) in summer and wheat (*Triticum aestivum*) during winter for 3-4 yr of each succession. In agroforestry, fertilizers are applied to wheat only. Wheat under agroforestry and sole cropping system is fertilized at 120-135 kg N, 50-60 kg P₂O₅, 20-30 kg K₂O. Rice, maize and cotton are fertilized at 115-125 kg N, 15-25 kg P₂O₅, 15-20 kg K₂O. Farmyard manure (FYM) at 8-9 Mg ha⁻¹ is applied to rice, 5-6 Mg ha⁻¹ to both maize and cotton. All the land-use systems were irrigated with the canal or groundwater. Rice fields were kept submerged during first month after transplanting and thereafter flood-irrigated and all the other crops received an irrigation of 7.5 cm as and when required.

3.2.1.1 Sample analyses

Soil reaction, EC, CaCO₃, available P and K, particle size distribution, phosphorus fractions, SOC, HWSC and KMnO₄-C was determined as described under sub-section 3.1.1.3.1, 3.1.1.3.3 and 3.1.1.3.6. Particle size distribution was estimated by an International pipette method (USDA, 1930).

3.2.2 Statistical analyses

Results were subjected to analysis of variance (ANOVA) using a completely randomized block design. Mean separation for different treatments was evaluated at 95% confidence interval using the Duncan's multiple range test (DMRT). To identify P pools and other soil properties that may contribute towards group separation of various land-use systems, Discriminant Function Analysis (DFA) was performed. The statistical analyses were performed with SPSS 16.0 for Windows (SPSS Inc., Chicago, U.S.A.).

3.3 Phosphorus release and sorption-desorption kinetics in soils of differing clay, available P, organic C and CaCO₃

3.2.1 Soil sampling sites, sample collection, sample analyses and selection criteria for P release and sorption-desorption kinetics studies

Sixteen surface soil samples (0-15 cm) were collected from farmers' field in different districts of Punjab, India (Figure 3.3). Each sample was a composite of 3 sites within a field. Soil samples were collected with a core sampler, after the harvest of wheat crop in April/May 2013. Samples were air dried in shade, ground to pass 2 mm sieve for laboratory analysis. Soil reaction, EC, SOC, available P and CaCO₃ was determined as described under sub-section 3.1.1.3.1 and 3.1.1.3.6. Particle size distribution was estimated by an International pipette method (USDA, 1930). The samples were selected on the basis of variation in clay (8-20%), available P (5-25 mg P kg⁻¹), soil organic carbon (2.2-7.2 g kg⁻¹), and calcium carbonate (0-2%) content (Table 3.7). The samples were grouped into four classes depending on variation in one of the selected soil property and similar values for other properties.

3.2.2 Kinetics of P release

Same as described under sub-section 3.1.1.3.5.

3.2.3 Phosphorus sorption and desorption studies

3.2.3.1 Phosphorus sorption

Three gram of each soil sample was equilibrated with 15 ml KH₂PO₄ (1:5) in 0.01M CaCl₂ solution containing 0, 2, 3, 5, 10, 20, 40, 60, 80 and 100 µg P ml⁻¹. Two drops of toluene were added to each sample to check microbial activity. The centrifuge tubes containing soil suspension were intermittently shaken on an end to end shaker for 24 hours and thereafter centrifuged at 3500 rpm for 15 minutes. Phosphorus in the equilibrium solution was determined colorimetrically using ascorbic acid method (Murphy and Riley 1962). Sorbed P was calculated from the difference between P added and that remained in equilibrium solution (Ipinmidun 1973) as follows:

$$x/m = \frac{V}{G} (C_0 - C)$$

Where, x/m = amount of P sorbed ($\mu\text{g P g}^{-1}$ soil), V = volume of equilibrium solution (ml), G = weight of soil taken (g), C_0 = P concentration in added solution ($\mu\text{g ml}^{-1}$), C = P concentration in equilibrium solution ($\mu\text{g ml}^{-1}$)

Phosphorus sorption data were fitted to Langmuir and Freundlich sorption isotherms.

3.2.3.1.1 Langmuir sorption equation

$$\frac{C}{x/m} = \frac{1}{k \cdot b} + \frac{C}{b}$$

Where, x/m = Amount of P sorbed ($\mu\text{g g}^{-1}$ soil), C = Concentration of P in equilibrium solution ($\mu\text{g ml}^{-1}$), b = Langmuir adsorption maxima ($\mu\text{g g}^{-1}$ soil), k = Langmuir bonding energy constant (ml g^{-1}). A plot of ' $C/x/m$ ' versus ' C ' gives a straight line. The slope and intercept were used to obtain the constant k (slope/intercept) and b (1/slope), respectively.

3.2.3.1.2 Freundlich sorption equation

$$x/m = aC^{1/b}$$

Where, x/m = Amount of P sorbed ($\mu\text{g g}^{-1}$ soil), C = Concentration of P in the equilibrium solution ($\mu\text{g ml}^{-1}$), A plot of ' $\log x/m$ ' versus ' $\log C$ ' gives a straight-line. The intercept and slope were used to obtain constants ' a ' ($\mu\text{g g}^{-1}$) and ' b ', (g ml^{-1} , 1/slope), respectively. Antilog of ' a ' and ' b ' of Freundlich adsorption isotherm were taken as measures of the extent and rate of sorption, respectively.

3.2.3.2 Phosphorus desorption

Phosphorus desorption was carried out on the residual soils previously used for P sorption as described above. The residual soils were equilibrated with 15 ml of 0.01M CaCl_2 for 6 hours (Singh and Jones 1976) and P was measured in equilibrium solution by ascorbic acid method (Murphy and Riley 1962). The data on P desorption were fitted to the following equation:

$$De/x/m = 1/Kd \cdot Dm + De/Dm$$

where x/m is the amount of pre-sorbed P ($\mu\text{g g}^{-1}$), De is the amount of P desorbed ($\mu\text{g ml}^{-1}$), Dm is desorption maxima ($\mu\text{g g}^{-1}$ soil), and Kd is desorption constant related to P mobility in soils (ml g^{-1}). The desorption maxima (Dm) and constant (Kd) were calculated from the slope and intercept of the linear plot of $De/x/m$ versus De respectively.

3.2.4 Statistical analysis

Phosphorus release data were fitted to six different kinetic models with SPSS 16.0 for Windows (SPSS Inc., Chicago, U.S.A.). A stepwise regression analysis for predicting release constants was performed by adding linear term for different soil properties. All the statistical and regression analysis were performed using SPSS 16.0 for Windows (SPSS Inc., Chicago, U.S.A.).

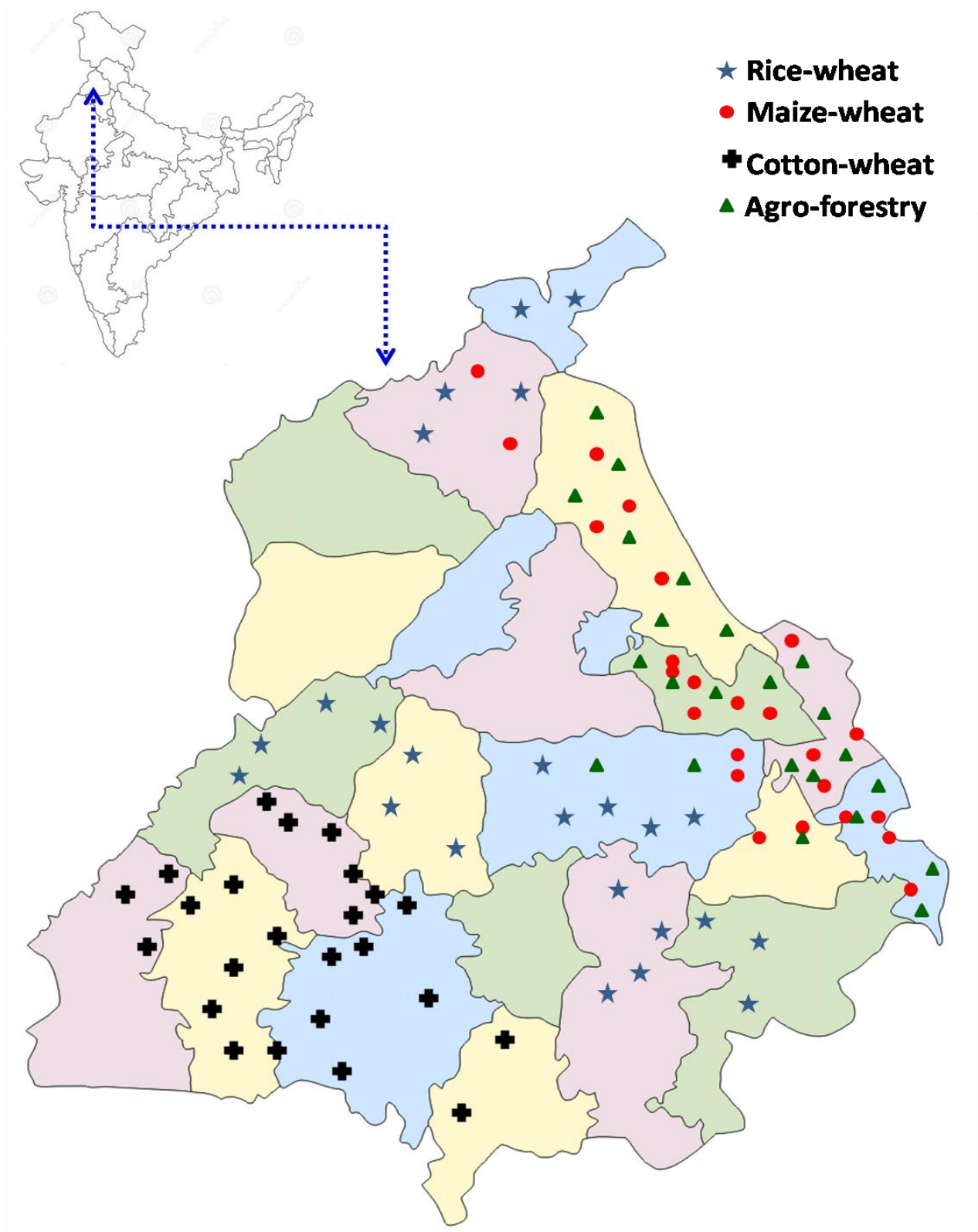


Fig 3.2 Soil sampling sites in different districts of Punjab (India)

3.4 Effect of moisture and temperature regimes on changes in soil organic C, available Fe, Mn and P in texturally different soils

3.4.1 Soil sample collection and sample analyses

Three bulk soil samples (0-15 cm soil depth) were collected from farmers' fields under rice-wheat cropping system. Soil samples were collected from Hoshiarpur (loamy sand soil), Rupnagar (clay loam soil) and Patiala (silty clay soil) districts of Indian Punjab. Samples were air dried in shade, ground to pass 2 mm sieve for laboratory analysis. Soil reaction, EC, SOC, $\text{KMnO}_4\text{-C}$ and available P was determined as described under sub-section 3.1.1.3.1 and 3.1.1.3.6. Particle size distribution was estimated by an International pipette method (USDA, 1930). Diethylene triamine penta acetic acid extractable micro-nutrients (DTPA-Fe and Mn) were assessed by extracting 10 g portion of soil sample with 20 ml of Diethylene triamine penta acetic acid (DTPA) extractant (0.005M DTPA + 0.01M CaCl_2 + 0.1M TEA buffer (pH=7.3), followed by determination of their concentration on atomic absorption spectrophotometer (Varian Model AAS-FS) (Lindsay and Norvell 1978). Important physical and chemical properties of three surface (0-15 cm) soils are detailed in table 3.8.

3.4.1.1 Determination of soil moisture retention

For determining of soil volumetric moisture content (θ) at field capacity, samples were saturated over-night in the rings, weighed and then kept in pressure plate assembly. Pressure of 0.33 bars (field capacity) was maintained. After applying 0.33 bars pressure, the samples were taken out of the assembly and weighed. The volumetric moisture content at field capacity (FC) of three soils is given in table 3.8.

3.4.2 Laboratory incubation study

A laboratory incubation study was conducted for 120 days to study changes in SOC, Fe, Mn and P in soils under different moisture and thermal regimes (Table 3.9). At the time of start of the incubation, fifty g of each soil (oven dry basis) was taken in plastic vial. Then soil in each bottle was hand compacted to representative of natural reconsolidation for soils. Thereafter, distilled water was added drop wise using fine jet pipette to obtain requisite moisture at field capacity. One set of different treatments was kept at air dry conditions and one set of different treatments was flooded with 1 cm standing water. In flooded soils, water head was marked at plastic vial and was maintained by adding distilled water throughout the incubation period. Each vial was covered with a perforated polythene sheet using a rubber band to allow diffusion of gases in and out and to restrict the evaporation of moisture. The soils at field capacity were weighed and moisture was maintained by adding distilled water during incubation study. A total of 567 repacked vials were prepared for incubation. After termination of each incubation period, soil samples were analyzed for SOC, $\text{KMnO}_4\text{-C}$ and available P as described under sub-section 3.1.1.3.1 and 3.1.1.3.6.

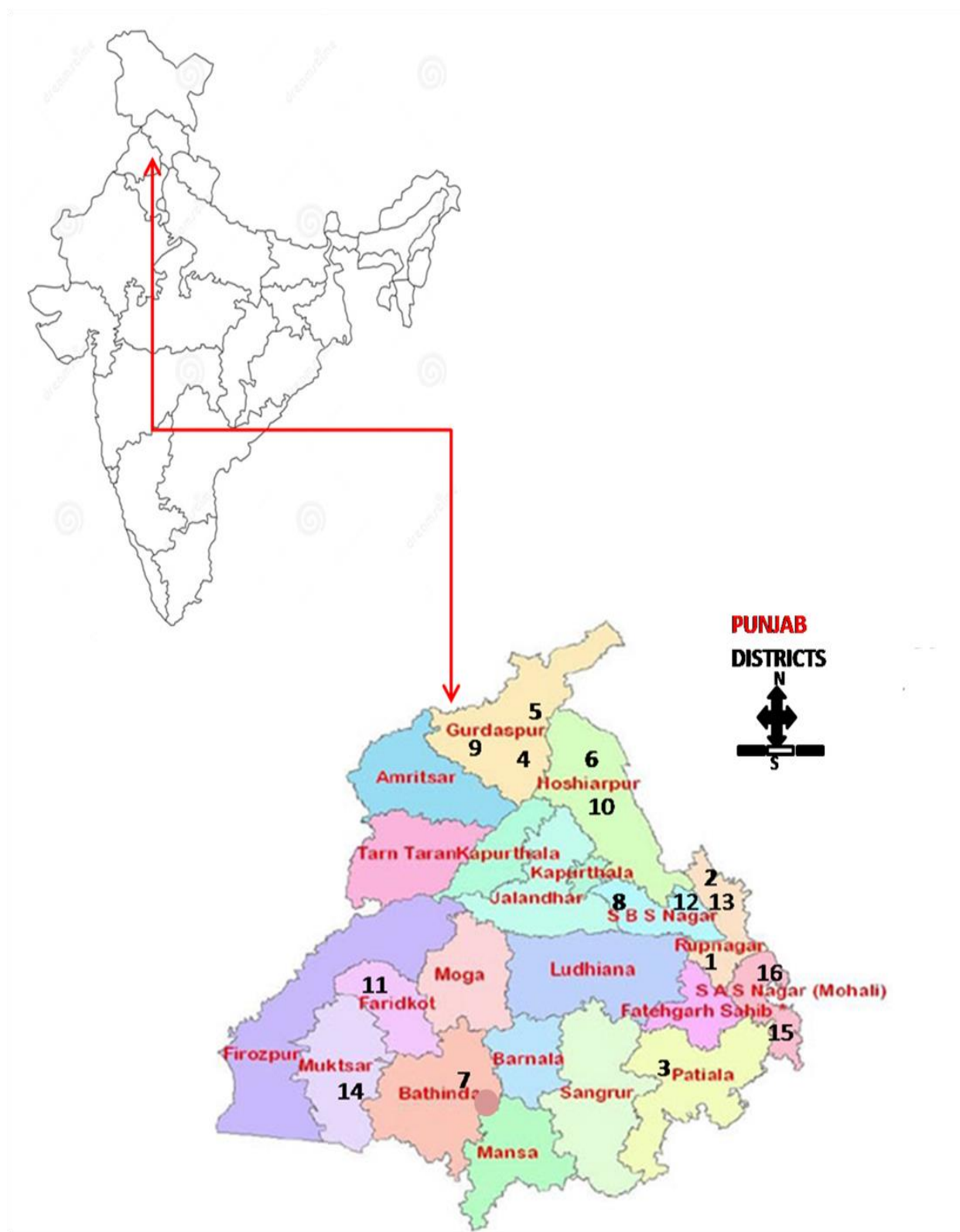


Fig 3.3 Location of soil sampling sites in north Indian state of Punjab

Table 3.7 Important physical and chemical properties of the surface (0-15 cm) soil samples selected for phosphorus release and sorption-desorption kinetics studies

Soil /Group	pH	EC (dS m ⁻¹)	SOC (g kg ⁻¹)	Available P (mg P kg ⁻¹)	Calcium carbonate (%)	Soil texture		
						Sand (%)	Silt (%)	Clay (%)
Group-I								
Soil-1	7.6	0.30	3.05	10.4	0	71.5	20.3	8.2
Soil-2	7.4	0.36	3.13	11.0	0	58.5	29.0	12. 6
Soil-3	7.8	0.37	3.13	9.4	0	59.6	24.1	16.2
Soil-4	7.6	0.24	3.43	11.2	0	56.3	23.7	20.1
Mean	7.6	0.32	3.18	10.5	0	61.5	24.3	14.3
Group-II								
Soil-5	7.7	0.26	2.98	5.11	0	67.2	22.6	10.2
Soil-6	7.7	0.31	2.83	12.4	0.1	64.6	25.0	10.4
Soil-7	7.5	0.24	3.13	18.3	0	65.9	23.6	10.6
Soil-8	7.6	0.31	3.05	25.1	0	68.4	21.0	10.6
Mean	7.6	0.28	2.99	15.2	0	66.5	23.1	10.4
Group-III								
Soil-9	7.8	0.28	2.15	15.9	0	62.8	23.0	14.3
Soil-10	7.6	0.34	3.95	16.3	0	65.2	20.3	14.4
Soil-11	7.3	0.26	5.68	16.8	0	69.4	16.4	14.2
Soil-12	7.2	0.29	7.18	15.7	0	66.1	19.2	14.7
Mean	7.5	0.29	4.74	16.2	0	65.9	19.7	14.4
Group-IV								
Soil-13	7.3	0.33	4.93	16.8	1.5	66.8	18.0	15.3
Soil-14	7.5	0.22	4.85	14.2	0.6	68.1	16.7	15.2
Soil-15	7.2	0.37	5.00	13.4	0	64.8	20.0	15.2
Soil-16	7.3	0.25	5.08	16.6	2.0	67.2	17.7	15.1
Mean	7.3	0.29	4.96	15.2	1.0	66.7	18.1	15.2

Table 3.8 Important physical and chemical properties of surface (0-15 cm) soils at the start of the incubation experiment

Soil property	Loamy sand	Clay loam	Silty clay
pH	7.43	7.36	7.25
EC (dSm ⁻¹)	0.26	0.29	0.24
Available P (mg kg ⁻¹)	8.2	11.1	13.4
SOC (g kg ⁻¹)	3.6	5.0	6.6
KMnO ₄ -C (mg kg ⁻¹)	259	425	742
DTPA-Fe (mg kg ⁻¹)	3.84	7.62	10.5
DTPA-Mn (mg kg ⁻¹)	3.12	4.46	5.62
Sand (%)	85.7	63.0	29.0
Silt (%)	4.7	11.0	30.5
Clay (%)	9.6	26.0	40.5
θ ^v (%)	20.4	29.3	32.2

θ^v = Volumetric moisture content

Diethylene triamine penta acetic acid extractable micro-nutrients (DTPA-Fe and Mn) were determined by method detailed under sub-section 3.4.1.

Table 3.9 Treatment details for incubation study

Parameter	Number	Description
Soils	3	Loamy sand, clay loam and silty clay
Moisture regimes	3	Air-dry, field capacity and submergence
Temperature regimes	3	20, 30 and 40°C
Incubation periods	7	0, 15, 30, 45, 60, 90 and 120 days
Replications	3	--
Total no of samples	567	

3.4.3 Statistical analysis

The data on different soil parameters from an incubation study were subjected to ANOVA in factorial completely randomized design (CRD) using CPCS-1 software, and mean separation was evaluated at 95% confidence interval using least significant difference (LSD).

CHAPTER IV

RESULTS AND DISCUSSION

The present study entitled “Dynamics of soil phosphorus in relation to carbon under different cropping systems” comprised field and laboratory studies. Field experiment included studies at Research farm Department of Soil Science, PAU, Ludhiana, and at farmers’ fields in different districts of Punjab. The laboratory study involved laboratory analysis of phosphorus (P) sorption-desorption and release kinetics in soils. The laboratory incubation experiments involved study of carbon mineralization kinetics in soils and changes in available P in relation to temperature and moisture.

4.1 Effect of P rates and source of application on soil phosphorus and carbon pools under rice-wheat cropping system

Effect of two rates of P application viz. 0 and 30 kg P_2O_5 ha⁻¹ to rice in rice-wheat sequence was studied on soil properties, soil P fractions and labile pools of soil organic carbon (SOC). Phosphorus was applied either through single super phosphate (SSP) or rock phosphate (RP) with and without FYM.

4.1.1 General soil properties

4.1.1.1 Soil reaction and electrical conductivity

Soil pH ranged between 6.90 and 7.05 in the surface (0-7.5 cm) and 7.04 to 7.09 in the subsurface (7.5 to 15 cm) soil. Irrespective of the treatment, soil pH increased with soil depth, and ranged between 7.23 and 7.47 at the lower depths (Table 4.1). Soil electrical conductivity (EC) ranged between 0.11 and 0.15 dS m⁻¹ in the surface and subsurface layers. Under all the treatments soil EC decreased with depth and ranged between 0.07 and 0.10 dS m⁻¹. Application of P through single super phosphate or rock phosphate (RP) either alone or in combination with FYM did not influence soil pH significantly. Several studies (Bhat 2013 and Yadav 2014) have reported increase in soil pH and decrease in EC with depth. The increase in pH with depth may be attributed to i) leaching of bases from the surface to lower layers, ii) decrease in SOC concentration with depth (Singh *et al* 2008, Kumar and Singh 2010) and iii) decrease in ammonium oxidation to nitrate (Schoenau 2006). The decrease in EC with depth shows decrease in salt content of the soil. The results on pH and EC show that the experimental soil was free from acidity/alkalinity and salinity problems

4.1.1.2 Ammonical and nitrate-N distribution

The data on the effect of amount and source of P application on NH_4^+ -N and NO_3^- -N content in soil are given in table 4.2 and figure 4.1. The NH_4^+ -N concentration ranged between 47 to 125 and 43 to 108 mg N kg⁻¹ soil in 0-7.5 and 7.5-15 cm soil depth, respectively. The concentration of NH_4^+ -N at both the soil depths was significantly lower in the CK compared with F_0P_0 treatment where 60 kg P_2O_5 ha⁻¹ was applied only to wheat. Application of P through single super phosphate (F_0P_{30SSP}) to rice significantly

increased the NH_4^+ -N concentration in soil than the soils that received same amount of P through rock phosphate ($\text{F}_0\text{P}_{30\text{RP}}$). The highest NH_4^+ -N concentration (125 mg kg^{-1} soil) was observed in $\text{F}_1\text{P}_{30\text{RP}}$ treated plots and it was significantly higher than FYM alone treated plots(F_1P_0). At 15-30 and 30-60 cm soil depth, NH_4^+ -N concentration ranged between 40 to 65 and 38 to 51 mg N kg^{-1} , respectively. The NH_4^+ -N concentration was also significantly lower in the CK compared to all other treatments, however, the treatment $\text{F}_0\text{P}_{30\text{RP}}$ and $\text{F}_0\text{P}_{30\text{SSP}}$ did not differ significantly. Similarly, concentration of NH_4^+ -N in plots amended with $\text{F}_1\text{P}_{30\text{RP}}$ and F_1P_0 was statistically at par.

Table 4.1 Effect of amount and source of P application on soil pH and EC (dS m^{-1}) at different depths after 7 cycles of rice-wheat cropping

Treatment	Depth (cm)							
	0-7.5	7.5-15	15-30	30-60	0-7.5	7.5-15	15-30	30-60
	pH				EC			
CK	7.05 ^a	7.08 ^a	7.23 ^a	7.47 ^a	0.15 ^a	0.14 ^a	0.10 ^a	0.08 ^a
F_0P_0	7.01 ^a	7.09 ^a	7.23 ^a	7.46 ^a	0.15 ^a	0.14 ^a	0.09 ^a	0.08 ^a
$\text{F}_0\text{P}_{30\text{RP}}$	6.94 ^a	7.06 ^a	7.24 ^a	7.44 ^a	0.13 ^a	0.11 ^a	0.08 ^a	0.07 ^a
$\text{F}_0\text{P}_{30\text{SSP}}$	6.96 ^a	7.09 ^a	7.23 ^a	7.41 ^a	0.14 ^a	0.12 ^a	0.09 ^a	0.07 ^a
F_1P_0	6.92 ^a	7.06 ^a	7.22 ^a	7.46 ^a	0.15 ^a	0.13 ^a	0.10 ^a	0.09 ^a
$\text{F}_1\text{P}_{30\text{RP}}$	6.90 ^a	7.04 ^a	7.24 ^a	7.44 ^a	0.14 ^a	0.12 ^a	0.07 ^a	0.08 ^a

*Mean values in a column followed by same letter are not significantly different ($p < 0.05$) by Duncan's multiple range test (DMRT)

The NO_3^- -N concentration ranged between 22.5 to 69.6 and 18.3 to 56.4 mg N kg^{-1} soil in 0-7.5 and 7.5-15 cm soil depth, respectively. Application of P (F_0P_0) to wheat did not influence NO_3^- -N concentration significantly (Table 4.2). At 0-7.5 and 7.5-15 cm soil depths, $\text{F}_1\text{P}_{30\text{RP}}$ and $\text{F}_0\text{P}_{30\text{SSP}}$ treatments significantly increased the concentration of NO_3^- -N compared with F_1P_0 and $\text{F}_0\text{P}_{30\text{RP}}$, respectively. At 15-30 and 30-60 cm depth, NO_3^- -N concentration ranged between 16.7 to 39.3 and 15.9 to 32.7 mg N kg^{-1} , respectively. $\text{F}_0\text{P}_{30\text{SSP}}$ significantly increased NO_3^- -N concentration than CK, but, did not differ significantly from $\text{F}_0\text{P}_{30\text{RP}}$ where 30 kg P_2O_5 ha^{-1} was supplied through rock phosphate to rice. The treatment $\text{F}_1\text{P}_{30\text{RP}}$ and F_1P_0 showed similar effect on soil NO_3^- -N. The increase in the concentration of NH_4^+ -N and NO_3^- -N with FYM application was probably because of mineralization of organic N contained in manure. The slow mineralization of organic N could have also resulted in lower losses of N (Yadav *et al* 2000). These results are similar to those reported by Begum *et al* (2007), Beri *et al* (1989), Kumar and Wagenet (1984). Integrated nutrient management is reported to enhance the ammonification and nitrification process (Jagtap *et al* 2007) leading to greater NH_4^+ -N and NO_3^- -N in soil. The profile distribution of NH_4^+ -N and NO_3^- -N concentration is shown in figure 4.1. Evidently, the concentration of NH_4^+ -N and NO_3^- -N was higher in the surface 0-7.5 cm soil, and it decreased with depth, under all the treatments.

4.1.1.3 Available phosphorus and potassium

Available P concentration in soil ranged between 11.2 to 19.3 and 10.5 to 17.8 mg P kg⁻¹ soil in 0-7.5 and 7.5-15 cm soil depth, respectively (Table 4.3). At 0-7.5 cm depth, the concentration of available P in plots treated with F₀P₀ and F₀P_{30RP} did not differ significantly, though it was significantly higher than unfertilized plots (CK). The FYM application resulted in significant increase in available P concentration. The effect of FYM application in improving available P concentration was more pronounced in soils amended with both fertilizer P and FYM in rice (F₁P_{30RP}) compared with FYM alone in rice (F₁P₀). Garg and Aulakh (2010) also reported increase in available P in plots amended with FYM plus fertilizer P than unamended control. Significant improvement in available P concentration with FYM application may be attributed to P supplementation through FYM and solubilization of mineral P and decreased rate of P sorption in the presence of FYM (Saroa and Vig 1992, Sui and Thompson 2000, Gaston *et al* 2003). The effect of different P sources (F₀P_{30RP} and F₀P_{30SSP}) on the concentration of available P in soil was statistically non-significant (Table 4.3). At 7.5-15 cm soil depth, available P concentration did not differ significantly in treatments F₀P₀ and CK. However, other treatments significantly increased the concentration of available P in soils compared with CK. Treatments F₀P_{30RP} and F₀P_{30SSP} exhibited similar effect. Plots amended with FYM either alone (F₁P₀) or in conjunction with rock phosphate (F₁P_{30RP}) showed similar effect on available P concentration.

The profile distribution of available P in soil is shown in figure 4.2. Available P concentration was higher in surface (0-7.5 cm) compared with subsurface soil (7.5-15 cm) and it decreased further with depth. Available P concentration did not differ significantly among different treatments at soil depth below 15 cm and ranged between 7.5-10.3 mg P kg⁻¹ (Figure 4.2). Higher concentration of available P in the plough layer (0-15 cm) was due to the application of fertilizer P in the seed zone, greater biomass addition in upper soil and formation of stable and meta-stable compounds of low P solubility in the soil (Toor and Bahl 1997, Alleoni *et al* 2012), which do not allow movement of P to lower layers. Similar results were earlier reported by Galvani *et al* (2008) Trivedi *et al* (2010), Pizzeghello *et al* (2011). The available K concentration ranged between 91 to 119 and 85 to 108 mg K kg⁻¹ soil in 0-7.5 and 7.5 to 15 cm soil depth, respectively (Table 4.3). In 0-7.5 and 7.5-15 cm soil depth, available K was significantly higher in plots treated with FYM either alone (F₁P₀) or in combination with fertilizer P in rice (F₁P_{30RP}) compared to other treatments.

The concentration of available K did not differ significantly among treatments involving FYM application. Application of P either through single super phosphate or rock phosphate did not influence available K concentration significantly compare to control (CK) (Table 4.3). Below 15 cm soil depth, concentration of available K ranged between 58 and 83 mg K kg⁻¹ soil and different treatments did not differ significantly. Significant increase in available K in FYM treated soils has also been reported by

Naidu *et al* (2009), Prasad and Mathur (1997). Desai *et al* (2009) observed that application of crop residues and FYM improved available K in organic-treated soils compared with chemical fertilizers treated soils. Singh *et al* (2008) observed increase in available K in soils dressed with FYM, vermi-compost, green manure and rice residue alone or in combination with biofertilizers. A significant change in available K content in plough layer (0-7.5 and 7.5-15 cm) for the treatments involving FYM application could be attributed to the supplementation of K through applied FYM and decrease in K fixation by soil clay. The profile distribution of available K (Figure 4.2) showed a decrease in its concentration with depth.

Table 4.2 Effect of amount and source of P application on NH_4^+ -N, NO_3^- -N and mineral N concentration (mg N kg^{-1}) in the surface (0-7.5 cm) and subsurface (7.5-15 cm) soil after 7 cycles of rice-wheat cropping

Treatment	NH_4^+ -N		NO_3^- -N		Mineral N	
	0-7.5 cm	7.5-15 cm	0-7.5 cm	7.5-15 cm	0-7.5 cm	7.5-15 cm
CK	47 ^{a†}	43 ^a	22.5 ^a	18.3 ^a	69.5 ^a	61.3 ^a
F ₀ P ₀	68 ^b	61 ^b	28.4 ^a	23.7 ^a	96.4 ^b	84.7 ^b
F ₀ P _{30RP}	82 ^c	74 ^c	38.1 ^b	31.1 ^b	120.1 ^c	105.1 ^c
F ₀ P _{30SSP}	98 ^d	88 ^d	46.3 ^c	38.5 ^c	144.3 ^d	126.5 ^d
F ₁ P ₀	108 ^e	96 ^e	57.5 ^d	46.3 ^d	165.5 ^e	142.3 ^e
F ₁ P _{30RP}	125 ^f	108 ^f	69.6 ^e	56.4 ^e	194.6 ^f	164.4 ^f

[†]Mean values within a column followed by different letters differ significantly ($p < 0.05$) by Duncan's multiple range test (DMRT)

Table 4.3 Effect of amount and source of P application on available P and available K concentration in the surface (0-7.5 cm) and subsurface (7.5-15 cm) soil after 7 cycles of rice-wheat cropping

Treatment	Available P (mg kg^{-1})		Available K (mg kg^{-1})	
	0-7.5 cm	7.5-15 cm	0-7.5 cm	7.5-15 cm
CK	11.2 ^{a†}	10.5 ^a	91 ^a	85 ^a
F ₀ P ₀	13.5 ^b	12.1 ^{ab}	93 ^a	86 ^a
F ₀ P _{30RP}	14.2 ^b	13.1 ^{bc}	95 ^a	88 ^a
F ₀ P _{30SSP}	14.8 ^{bc}	13.5 ^{bc}	97 ^a	90 ^a
F ₁ P ₀	16.6 ^c	14.8 ^{cd}	114 ^b	103 ^b
F ₁ P _{30RP}	19.3 ^d	17.8 ^d	119 ^b	108 ^b

[†]Mean values within a column followed by different letters differ significantly ($p < 0.05$) by Duncan's multiple range test (DMRT)

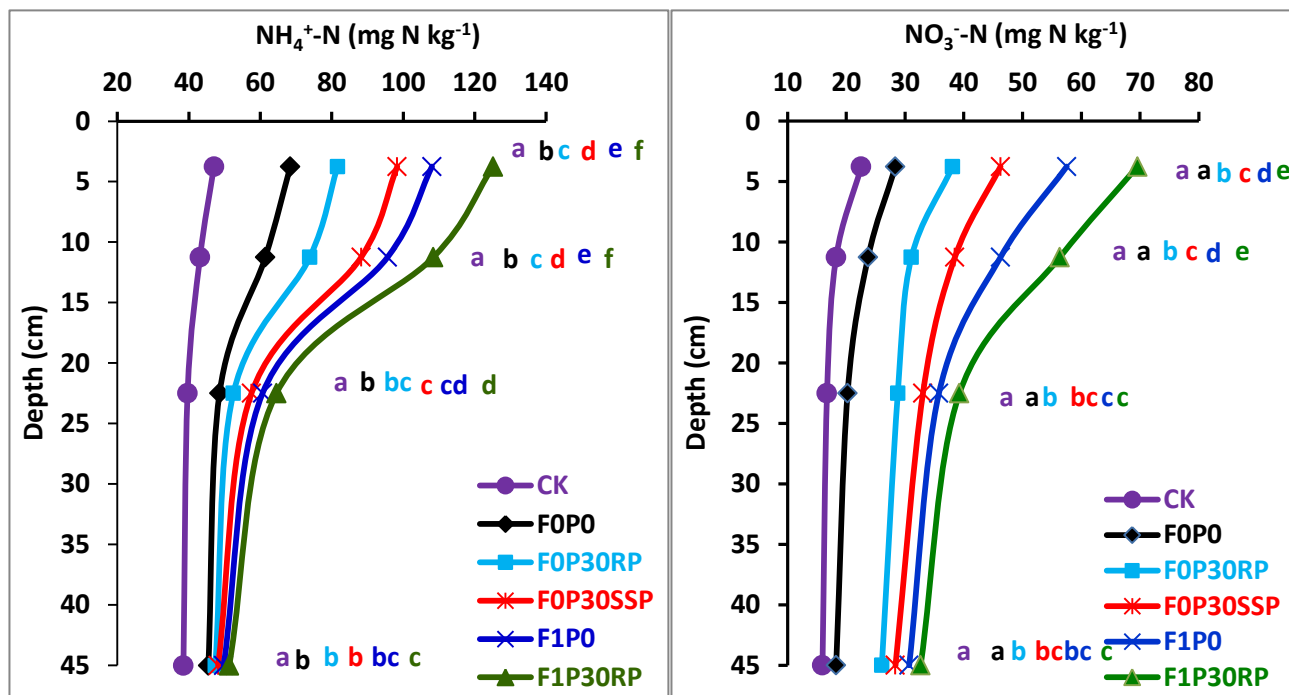


Fig 4.1 Effect of amount and source of P application on profile distribution of NH₄⁺-N and NO₃⁻-N in soils after 7 cycles of rice-wheat cropping [Mean values for a soil property at a given depth followed by different letters differ significantly ($p < 0.05$) by Duncan's multiple range test (DMRT)]

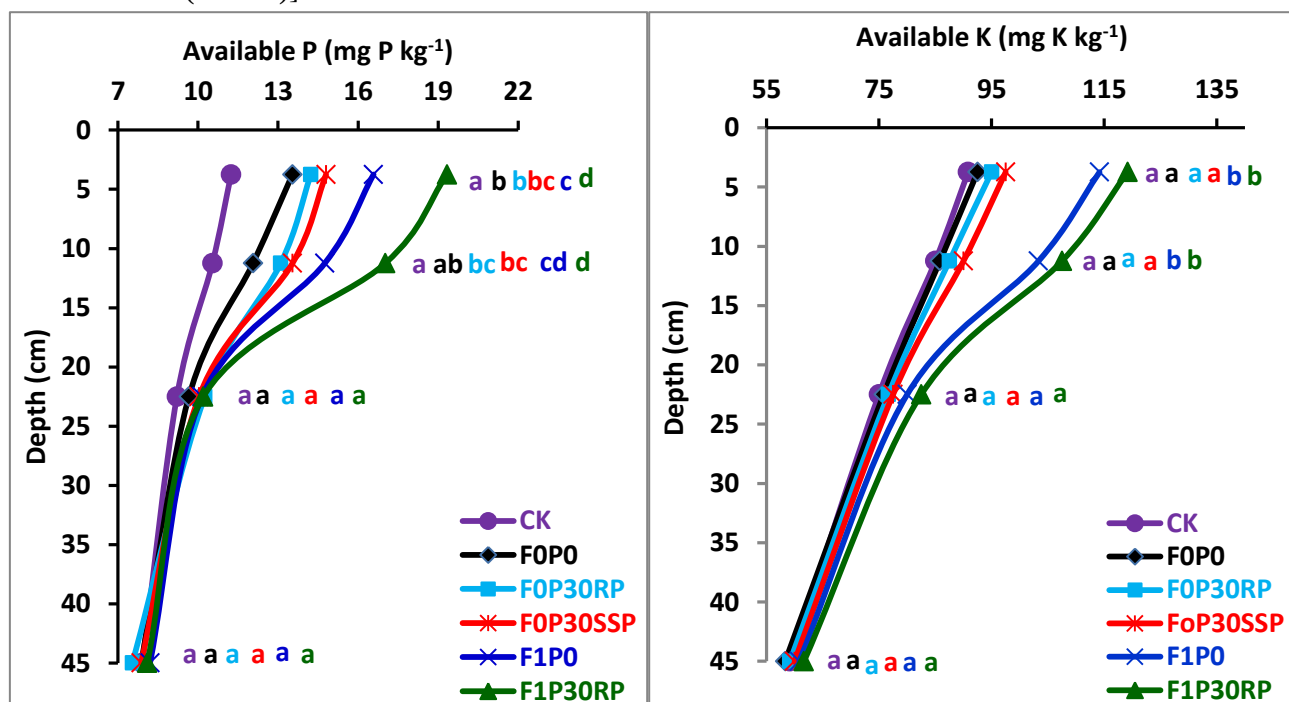


Fig 4.2 Effect of amount and source of P application on profile distribution of available P and available K in soils after 7 cycles of rice-wheat cropping [Mean values for a soil property at a given depth followed by different letters differ significantly ($p < 0.05$) by Duncan's multiple range test (DMRT)]

4.1.1.4 Soil bulk density

The results on effect of P rates and sources on soil bulk density (D_b) are shown in figure 4.3. In surface soil (0-7.5 cm), the lowest D_b (1.42 Mg m^{-3}) was observed in plots receiving FYM in conjunction with P through rock phosphate (F_1P_{30RP}) and the highest (1.55 Mg m^{-3}) in unamended control. The soil D_b in plots receiving P through SSP (F_0P_{30SSP}) did not differ significantly from plots receiving P through RP (F_0P_{30RP}). Similar effect of treatments was observed at 7.5-15 cm depth where it ranged between 1.45 and 1.61 Mg m^{-3} under different treatments. The soil D_b followed the order $CK > F_0P_0 > F_0P_{30RP} > F_0P_{30SSP} > F_1P_0 > F_1P_{30RP}$ to 15 cm soil depth. Several researchers have reported decrease in soil D_b with NPK, FYM and NPK+FYM application (Bi *et al* 2009, Nayak *et al* 2012). The application of organic matter besides leading to dilution because of low D_b of added organic matter improves soil aggregation, resulting in decreased soil D_b (Halvorson *et al* 1999, Benbi and Senapati 2010, Aulakh *et al* 2010, Yaduvanshi *et al* 2013, Huang *et al* 2014). Soil D_b increased with depth though the effect of different treatments was non-significant. Soil D_b ranged between 1.67 and 1.73 Mg m^{-3} below 15 cm soil depth (Figure 4.3). This may be due to decrease in SOC with depth (Rasool *et al* 2008, Kukal *et al* 2009).

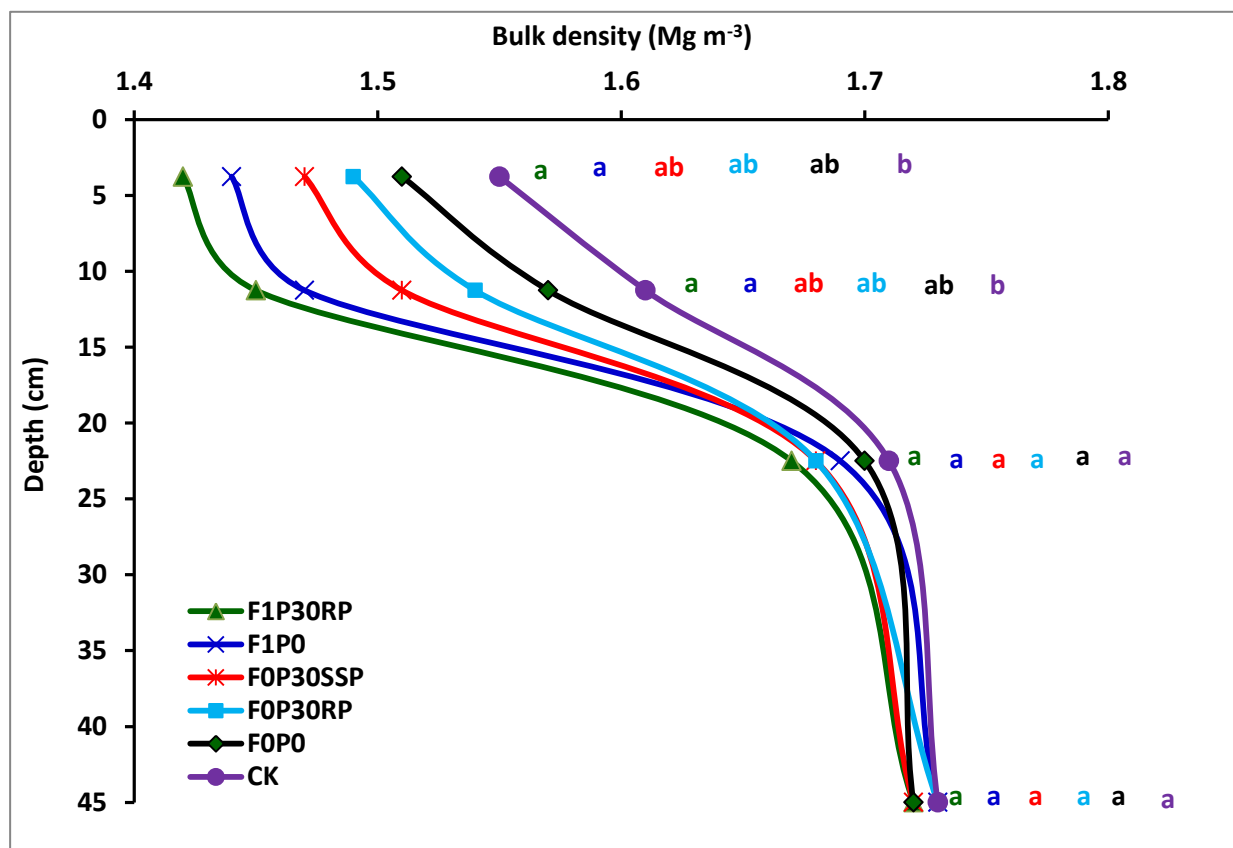


Fig 4.3 Effect of amount and source of P application on soil bulk density (D_b) at different soil depths after 7 cycles of rice-wheat cropping [Mean values for a soil property at a given depth followed by different letters differ significantly ($p < 0.05$) by Duncan's multiple range test (DMRT)]

4.1.1.5 Soil porosity

Soil porosity ranged between 41.5 and 46.4 and 39.2 and 45.3% in 0-7.5 cm 7.5-15 cm soil depth, respectively. Soil porosity was significantly higher in soils receiving FYM either alone (F_1P_0) or in combination with fertilizer P (F_1P_{30RP}) as compared to unamended soil (Figure 4.4). Application of fertilizer P did not influence soil porosity significantly. Soil porosity decreased with depth and the effect of different treatments was similar to that observed in 0-7.5 cm soil. Soil porosity ranged between 34.7 and 37.0 % in lower soil layers. Different treatments had non-significant effect on soil porosity at 15-30 and 30-60 cm soil depth (Figure 4.4). Bhagat and Verma (1991) observed significant increase in soil porosity with FYM applicatio in 0-15 cm soil layer under rice-wheat cropping system. Increase in soil porosity with FYM application is because of better aggregation and consequently lower soil bulk density (D_b).

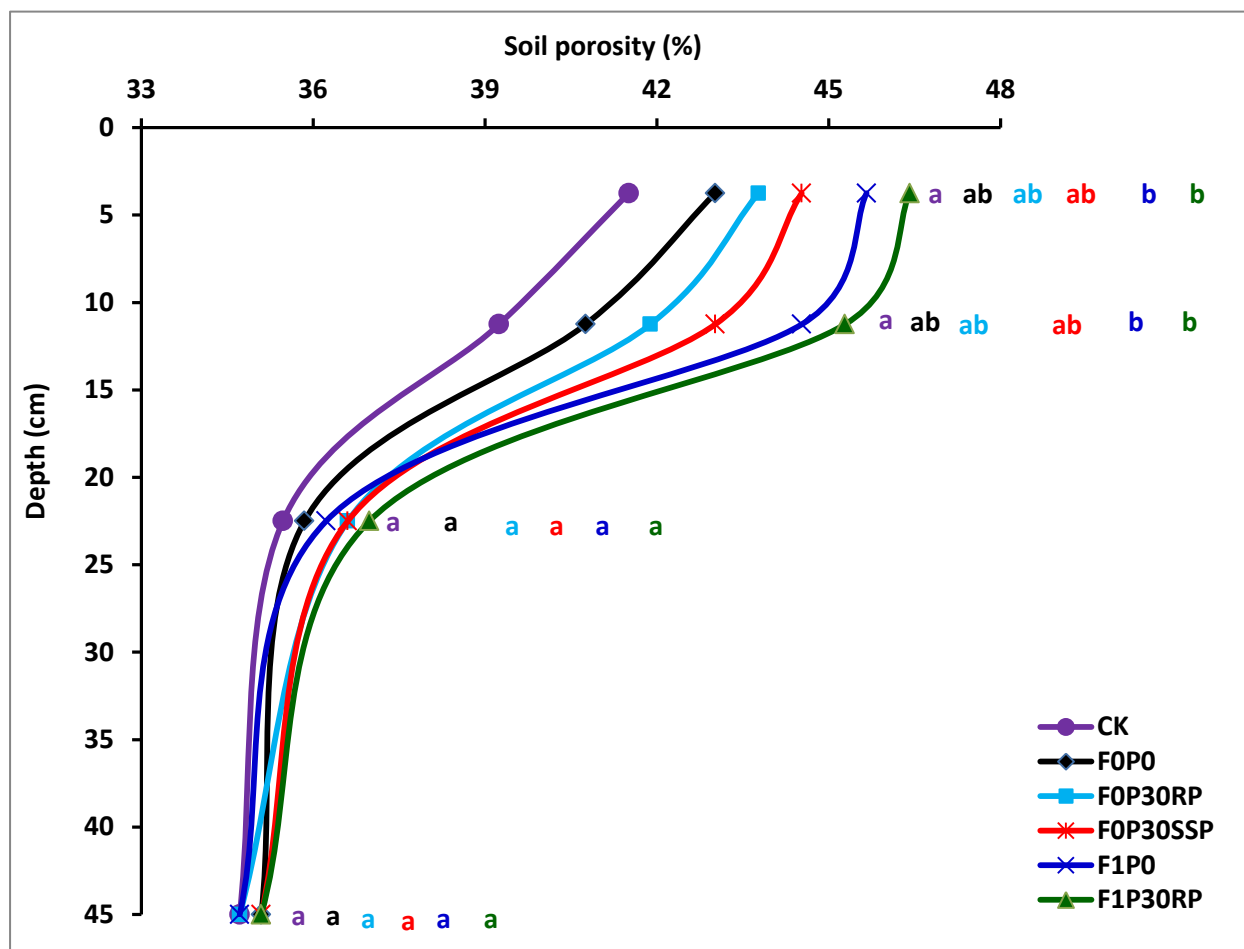


Fig 4.4 Effect of amount and source of P application on soil porosity at different soil depths after 7 cycles of rice-wheat cropping [Mean values for a soil property at a given depth followed by different letters differ significantly ($p < 0.05$) by Duncan's multiple range test (DMRT)]

4.1.2 Soil phosphorus fractions

Total P was differentiated into inorganic and organic P fractions using a sequential extraction technique (Golterman 1996, Golterman *et al* 1998). Total P ranged between 381 and 712 mg P kg⁻¹ in 0-7.5 cm depth, 307 to 543 mg P kg⁻¹ in 7.5-15 cm depth and 272 to 347 mg P kg⁻¹ in 15-30 cm depth under different treatments (Table 4.4). Inorganic P ranged between 348 and 627 mg P kg⁻¹ in 0-7.5 cm depth, 282 to 481 in 7.5-15 cm depth and 250 to 307 mg P kg⁻¹ in 15-30 cm depth under different treatments, which constituted 88.1 to 92.0 percent of total P at different soil depths and organic P constituted 7.2 to 10.2 % of total P at different soil depths. Organic P ranged between 27.5 and 74.4 mg P kg⁻¹ in 0-7.5 cm depth, 21.3 to 55.2 mg P kg⁻¹ in 7.5-15 cm depth and 18.5 to 35.3 mg P kg⁻¹ in 15-30 cm depth. In 0-7.5 cm soil depth, concentration of organic and inorganic P significantly increased in plots treated with fertilizer P in wheat compared to unamended control. Application of FYM either alone or in conjunction with P (F₁P_{30RP}) to rice resulted in significant increase in the concentration of inorganic, organic and total P over CK. However, the magnitude of increase was higher in the soils receiving conjoint application of fertilizer P and FYM (F₁P_{30RP}) compared to the soils receiving FYM alone (F₁P₀). Significant increase in inorganic P, organic P and total P with FYM application has earlier been reported by Lopez-Contreras *et al* (2007) and Schmidt *et al* (1996). Application of fertilizer P to rice through single super phosphate (F₀P_{30SSP}) significantly increased organic P concentration compared to the same amount applied through rock phosphate (F₀P_{30RP}). However, F₀P_{30SSP} and F₀P_{30RP} exhibited similar effect on total P and inorganic P concentration (Table 4.4). In subsurface soil (7.5-15 cm), effect of different treatment was similar to that observed in 0-7.5 cm depth. At 15-30 cm soil depth, organic P, inorganic P and total P concentrations in plots receiving P during wheat (F₀P₀) did not differ significantly from CK. Application of P through single super phosphate (F₀P_{30SSP}) in rice significantly increased organic P concentration in 15-30 cm soil depth by 11.9% compared to F₀P_{30RP}. Plots amended with FYM and P fertilizer (F₁P_{30RP}) showed significant increase in organic P concentration compared to plots amended with FYM alone (F₁P₀). Similar to surface layers (0-7.5 and 7.5-15 cm), inorganic P and total P concentration did not differ significantly between F₀P_{30SSP} and F₀P_{30RP}. Effect of F₁P_{30RP} and F₁P₀ on inorganic P and total P concentration was also non-significant (Table 4.4). Averaged across 0-7.5 and 7.5-15 cm soil depths, organic P, inorganic P and total P concentration in the plough layer (0-15 cm) was the highest under F₁P_{30RP} and the lowest in CK treatment (Figure 4.5). Irrespective of the treatment, organic P, inorganic P and total P concentration decreased with depth (Table 4.4).

In surface soil (0-7.5 cm), the highest water soluble organic P concentration (1.95 mg P kg⁻¹) was observed in plots receiving fertilizer P in conjunction with FYM (F₁P_{30RP}) and the lowest (0.86 mg P kg⁻¹) in absolute control. However, F₀P₀ showed significant increase in water soluble organic P concentration compared to CK. Application of FYM and rock phosphate to rice (F₁P_{30RP}) significantly increased its

concentration by 21.9% compared to F_1P_0 . However, application of P fertilizer either through rock phosphate or single super phosphate to rice exhibited similar water soluble organic P concentration. Iron associated organic P concentration ranged between 2.09 and 7.68 mg P kg⁻¹ under different treatments. Application of fertilizer P to wheat (F_0P_0) significantly increased iron associated organic P concentration in soil compared to CK. Plots treated with single super phosphate (F_0P_{30SSP}) showed significant increase in iron associated organic P concentration than plots receiving fertilizer P through rock phosphate (F_0P_{30RP}). Plots amended with FYM and P fertilizer (F_1P_{30RP}) showed significant increase in iron associated organic P concentration compared to plots amended with FYM alone (F_1P_0). Effects of different treatment on calcium-aluminium associated organic P, acid soluble organic P, sugar bound organic P, nucleic acid-organic P and polyphosphate, and humic bound organic P concentration was similar to that observed for iron associated organic P concentration.

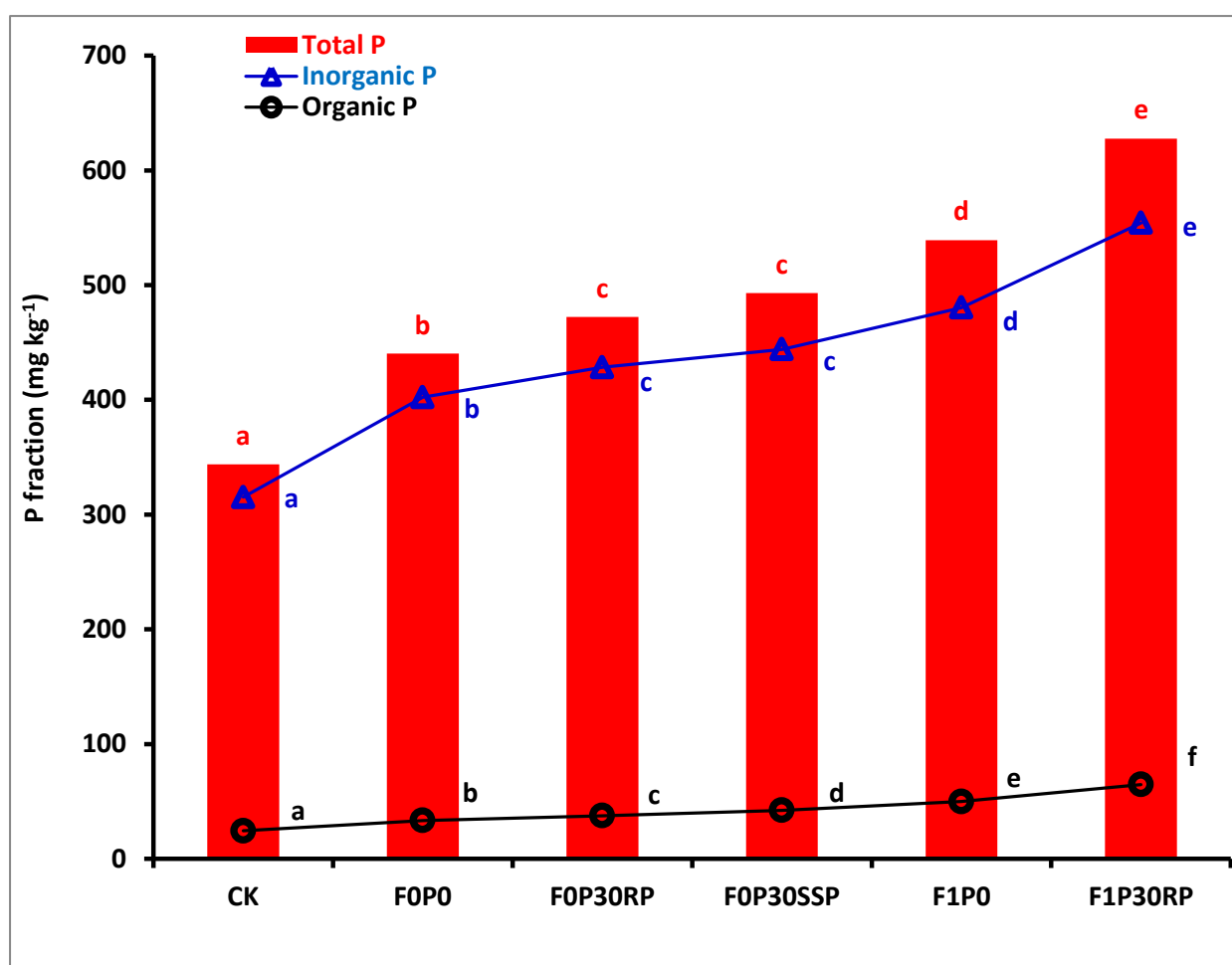


Fig 4.5 Effect of amount and source of P application on total P, inorganic P and organic P pools in plough layer (0-15 cm) after 7 cycles of rice-wheat cropping [Mean values for a soil property followed by different letters differ significantly ($p < 0.05$) by Duncan's multiple range test (DMRT)]

Table 4.4 Effect of amount and source of P application on inorganic and organic P fractions (mg P kg⁻¹) in different layers of soil profile after 7 cycles of rice-wheat cropping

Treatment	Inorganic P					Organic P									
	H ₂ O-Pi*	Ca-EDTA-Pi [†]	Na-EDTA-Pi [‡]	NaOH-Pi [►]	▼TPi	H ₂ O-Po*	Ca-EDTA-Po [†]	Na-EDTA-Po [‡]	H ₂ SO ₄ -Po [‡]	cTCA-Po [▲]	hTCA-Po [▼]	NaOH-Po [►]	▲TPo	Res-P [◄]	Total P
0-7.5 cm soil depth															
CK	0.85 ^a	50.7 ^a	259 ^a	38.0 ^a	348 ^a	0.86 ^a	2.09 ^a	4.98 ^a	3.08 ^a	3.07 ^a	1.91 ^a	11.5 ^a	27.5 ^a	4.95 ^a	381 ^a
F ₀ P ₀	1.23 ^b	73.5 ^b	337 ^b	46.5 ^{cd}	458 ^b	1.25 ^b	2.82 ^b	6.92 ^b	4.28 ^b	4.48 ^b	2.82 ^b	15.8 ^b	38.3 ^b	5.35 ^b	502 ^b
F ₀ P _{30RP}	1.37 ^c	79.3 ^c	358 ^c	46.7 ^d	486 ^c	1.32 ^b	3.38 ^c	7.19 ^b	4.24 ^b	7.52 ^c	2.74 ^b	16.5 ^b	42.8 ^c	6.95 ^c	535 ^c
F ₀ P _{30SSP}	1.57 ^d	83.3 ^c	371 ^c	43.2 ^b	499 ^c	1.39 ^b	3.71 ^d	8.08 ^c	5.16 ^c	8.53 ^d	3.83 ^d	17.8 ^c	48.5 ^d	7.48 ^d	555 ^c
F ₁ P ₀	1.82 ^e	97.5 ^d	400 ^d	44.4 ^{bc}	544 ^d	1.60 ^c	6.09 ^e	7.26 ^b	6.49 ^d	8.55 ^d	3.59 ^c	23.3 ^d	56.8 ^e	10.1 ^e	611 ^d
F ₁ P _{30RP}	2.49 ^f	112.9 ^e	462 ^e	50.4 ^e	627 ^e	1.95 ^d	7.68 ^f	9.63 ^d	8.35 ^e	11.72 ^e	4.49 ^e	30.6 ^e	74.4 ^f	10.1 ^e	712 ^e
7.5-15 cm soil depth															
CK	0.65 ^a	41.9 ^a	209 ^a	30.3 ^a	282 ^a	0.55 ^a	1.59 ^a	3.75 ^a	2.20 ^a	2.49 ^a	1.61 ^a	9.09 ^a	21.3 ^a	3.38 ^a	307 ^a
F ₀ P ₀	0.99 ^b	55.9 ^b	255 ^b	34.8 ^b	346 ^b	0.79 ^b	2.09 ^b	4.76 ^a	2.94 ^b	2.88 ^a	1.98 ^b	12.9 ^b	28.4 ^b	3.98 ^b	379 ^b
F ₀ P _{30RP}	1.02 ^b	61.8 ^c	272 ^c	36.2 ^b	371 ^{bc}	0.93 ^{cd}	2.57 ^c	5.31 ^b	3.19 ^b	5.55 ^b	2.44 ^c	12.3 ^b	32.3 ^c	5.76 ^c	409 ^c
F ₀ P _{30SSP}	1.14 ^c	64.6 ^c	290 ^d	34.0 ^b	389 ^c	0.90 ^c	2.86 ^d	6.16 ^d	4.09 ^c	6.50 ^c	2.82 ^d	12.8 ^b	36.2 ^d	5.94 ^c	431 ^c
F ₁ P ₀	1.50 ^d	74.6 ^d	307 ^e	33.8 ^b	417 ^d	1.00 ^d	4.85 ^e	5.31 ^c	4.62 ^d	6.40 ^c	2.63 ^{cd}	18.3 ^c	43.1 ^e	7.60 ^d	468 ^d
F ₁ P _{30RP}	1.75 ^e	85.2 ^e	355 ^f	38.8 ^c	481 ^e	1.32 ^e	5.62 ^f	7.42 ^e	6.61 ^e	8.55 ^d	3.55 ^e	22.1 ^d	55.2 ^f	7.48 ^d	543 ^e
15-30 cm soil depth															
CK	0.54 ^a	37.2 ^a	185 ^a	27.1 ^b	250 ^a	0.45 ^a	1.41 ^a	3.42 ^a	1.88 ^a	2.18 ^a	1.38 ^b	7.79 ^a	18.5 ^a	3.14 ^a	272 ^a
F ₀ P ₀	0.61 ^{ab}	42.9 ^b	194 ^a	26.9 ^b	264 ^{ab}	0.55 ^b	1.52 ^a	3.53 ^{ab}	2.06 ^a	2.04 ^a	1.20 ^a	9.89 ^b	20.8 ^a	3.31 ^a	288 ^a
F ₀ P _{30RP}	0.71 ^{bc}	45.6 ^b	213 ^b	27.1 ^b	287 ^{bc}	0.65 ^c	1.84 ^b	3.85 ^b	2.31 ^b	4.00 ^b	1.76 ^c	9.09 ^b	23.5 ^b	4.13 ^b	314 ^b
F ₀ P _{30SSP}	0.78 ^c	47.6 ^{bc}	212 ^b	25.2 ^{ab}	285 ^{bc}	0.72 ^{cd}	1.91 ^b	4.54 ^c	2.94 ^c	4.73 ^c	1.98 ^d	9.45 ^b	26.3 ^c	4.41 ^b	316 ^{bc}
F ₁ P ₀	0.95 ^d	52.1 ^{cd}	213 ^b	24.0 ^a	290 ^c	0.65 ^c	3.34 ^c	3.85 ^b	3.27 ^d	4.18 ^b	1.76 ^c	12.3 ^c	29.4 ^d	4.34 ^b	324 ^{bc}
F ₁ P _{30RP}	1.06 ^d	54.1 ^d	226 ^b	25.9 ^{ab}	307 ^c	0.79 ^d	3.82 ^d	4.65 ^c	3.31 ^d	5.88 ^d	1.98 ^d	14.9 ^d	35.3 ^e	4.34 ^b	347 ^c

*H₂O-Pi/Po=Water soluble inorganic and organic P, [†]Ca-EDTA-Pi/Po=Iron associated inorganic and organic P, [‡]Na-EDTA-Pi/Po=Calcium-aluminium associated inorganic and organic P, [§]H₂SO₄-Po=Acid soluble organic P, [▲]cTCA-Po=Sugar bound organic P, [▼]hTCA-Po=Nucleic acid organic P and polyphosphate, [►]NaOH-Pi/Po=Humic bound inorganic and organic P, [◄]Res-P=Residual P, [▲]TPo= organic P, [▼]TPi= inorganic P [[†]Mean values within a column followed by different letters differ significantly ($p < 0.05$) by Duncan's multiple range test (DMRT)]

Calcium-aluminium associated organic P concentration ranged between 4.98 and 9.63 mg P kg⁻¹. Acid soluble organic P concentration ranged between 3.08 to 8.35 mg P kg⁻¹. Sugar bound organic P concentration ranged between 3.07 to 11.72 mg P kg⁻¹. Nucleic acid organic P and polyphosphate concentration ranged between 1.91 to 4.49 mg P kg⁻¹. Humic bound organic P concentration ranged between 11.5 to 30.6 mg P kg⁻¹. Averaged across treatments, organic P concentration followed the order humic bound organic P > calcium-aluminium associated organic P > sugar bound organic P > acid soluble organic P > iron associated organic P > nucleic acid organic P and polyphosphate > water soluble organic P. Humic bound organic P and calcium-aluminium associated organic P fractions constituted major proportion (55.3%) of organic P (Table 4.4).

In subsurface soil (7.5-15 cm), water soluble organic P concentration ranged between 0.55 to 1.32 mg P kg⁻¹, but effects of different treatment were similar to that observed in 0-7.5 cm soil. Iron associated organic P, acid soluble organic P and nucleic acid organic P and polyphosphate concentration ranged between 1.59 to 5.62, 2.20 to 6.61 and 1.61 to 3.55 mg P kg⁻¹, respectively. Effect of different treatment on iron associated organic P, acid soluble organic P and nucleic acid organic P and polyphosphate concentration was similar to that observed in surface soil (0-7.5 cm). Highest concentration (7.42 mg P kg⁻¹) of calcium-aluminium associated organic P was observed in plots receiving fertilizer P and FYM and the lowest (3.75 mg P kg⁻¹) in CK plots. Sugar bound organic P concentration ranged between 2.49 and 8.55 mg P kg⁻¹. Humic-bound organic P concentration ranged between 9.09 and 22.1 mg P kg⁻¹ and the effect of different treatment was similar to that observed for water soluble organic P concentration in surface layers (0-7.5 and 7.5-15 cm).

In 15-30 cm soil, water soluble organic P and humic bound organic P concentration ranged between 0.45 and 0.79 and 7.79 and 14.9 mg P kg⁻¹, respectively. The effect of different treatment was similar to those observed for 7.5-15 cm soil. Iron associated organic P concentration ranged between 1.41 and 3.82 mg P kg⁻¹ and application of fertilizer P through rock phosphate in conjunction with FYM (F₁P_{30RP}) significantly increased its concentration by 14.4% over FYM alone application (F₁P₀). Calcium-aluminium associated organic P and sugar-bound organic P concentration ranged between 3.42 and 4.65 and 2.18 and 5.88 mg P kg⁻¹, respectively. Application of single super phosphate significantly increased calcium-aluminium associated organic P and sugar-bound organic P concentration compared to rock phosphate application. Plots amended with fertilizer P in conjunction with FYM (F₁P_{30RP}) significantly increased calcium-aluminium associated organic P and sugar bound organic P concentration over plots amended with FYM alone (F₁P₀). Acid soluble organic P and, nucleic acid organic P and polyphosphate concentration ranged between 1.88 and 3.31 and 1.38 and 1.98 mg P kg⁻¹, respectively. Significantly higher acid soluble organic P concentration was observed in single super phosphate treated plots compared to rock phosphate application. Effect of F₁P_{30RP}, F₁P₀, F₀P_{30RP} and F₁P_{30RP} treatments on nucleic acid organic P and polyphosphate concentration was similar to that observed in subsurface (7.5-15 cm) soil.

In surface soil (0-7.5 cm), the highest water soluble inorganic P concentration ($2.49 \text{ mg P kg}^{-1}$) was observed in plots receiving fertilizer P in conjunction with FYM (F_1P_{30RP}) and the lowest ($0.85 \text{ mg P kg}^{-1}$) in CK plots. Application of P in wheat (F_0P_0) resulted in significant increase in water soluble inorganic P concentration compared to unfertilized plots. Farmyard manure and rock phosphate (F_1P_{30RP}) applications significantly increase water soluble inorganic P concentration by 36.8% compared to F_1P_0 . Application of P fertilizer through single super phosphate (F_0P_{30SSP}) to rice and wheat exhibited significant increase in water soluble inorganic P concentration compared to rock phosphate (F_0P_{30RP}) application. Iron associated inorganic P concentration ranged between 50.7 and $112.9 \text{ mg P kg}^{-1}$ under different treatments. Application of fertilizer P to wheat (F_0P_0) significantly increased iron associated inorganic P concentration in soil compared to CK. Plots treated with single super phosphate (F_0P_{30SSP}) showed non-significant difference in iron associated inorganic P concentration compared to plots receiving fertilizer P through rock phosphate (F_0P_{30RP}). Plots amended with FYM and P fertilizer (F_1P_{30RP}) showed significant increase in iron associated inorganic P concentration compared to plots amended with FYM alone (F_1P_0). Calcium-aluminium associated inorganic P concentration ranged between 259 and 462 mg P kg^{-1} . Effects of different treatment on calcium-aluminium associated inorganic P concentration were similar to those observed for iron associated inorganic P concentration. Humic-bound inorganic P concentration ranged between 38.0 and $50.4 \text{ mg P kg}^{-1}$. Application of P in wheat (F_0P_0) showed significant increase in humic-bound inorganic P concentration compared to unfertilized plots. Farmyard manure and P fertilizer (F_1P_{30RP}) significantly increased humic-bound inorganic P concentration by 13.5% compared to F_1P_0 . Application of P fertilizer through rock phosphate (F_0P_{30RP}) to rice and wheat crop exhibited significant increase in humic-bound inorganic P concentration compared to single super phosphate (F_0P_{30SSP}) application (Table 4.4).

In subsurface soil (7.5-15 cm), water soluble inorganic P concentration ranged between 0.65 and $1.75 \text{ mg P kg}^{-1}$. Effects of different treatment were similar to those observed in 0-7.5 cm soil. Iron associated inorganic P concentration ranged between 41.9 and $85.2 \text{ mg P kg}^{-1}$ under different treatments. Effects of amount and source of P application on iron associated inorganic P concentration were similar to those observed in 0-7.5 cm soil. Calcium-aluminium associated inorganic P concentration ranged between 209 and 355 mg P kg^{-1} . Effect of different treatments on calcium-aluminium associated inorganic P concentration were similar to those was observed for water soluble inorganic P concentration. Humic-bound inorganic P concentration ranged between 30.3 and $38.8 \text{ mg P kg}^{-1}$. Application of P in wheat (F_0P_0) showed significant increase in humic-bound inorganic P concentration compared to unfertilized plots. Farmyard manure and P fertilizer (F_1P_{30RP}) significantly increase it concentration compared to F_1P_0 . The treatment F_0P_{30SSP} and F_0P_{30RP} did not differ significantly (Table 4.4). At 15-30 cm depth, water soluble inorganic P concentration ranged between 0.54 and $1.06 \text{ mg P kg}^{-1}$. Iron associated inorganic P concentration ranged between 37.2 to $54.1 \text{ mg P kg}^{-1}$ under different treatments. Application of P in wheat (F_0P_0) showed significant increase in

iron associated inorganic P concentration compared to unfertilized plots. Calcium-aluminium associated inorganic P concentration ranged between 185 and 226 mg P kg⁻¹. Humic bound inorganic P concentration ranged between 24 and 27.1 mg P kg⁻¹. All inorganic P fractions decreased with depth, indicating P accumulation in surface soil resulting from fertilizers and manure application (Wright 2009).

Irrespective of treatment and soil depth, relative abundance of different inorganic P fractions in soils followed the order calcium-aluminium associated inorganic P > iron associated inorganic P > humic-bound inorganic P > water soluble inorganic P. The data revealed that calcium-aluminium associated inorganic P fraction alone represented 66.5% of total P. Calcium-aluminium associated inorganic P and iron associated inorganic P constituted major fraction of total P in soils. This may be due to the fact that unutilized P is transformed mainly into calcium-P, aluminium-P and iron-P in these soils. These results are similar to those reported by Takahashi and Anwar (2006), Emadi *et al* (2009), Zhang *et al* (2012), Meena and Biswas (2015). Several studies (Aulakh and Pasricha 1991, Guo *et al* 2000) have reported that in less weathered and subtropical soils, the excess P from fertilizer tends to accumulate as calcium-associated inorganic P with fertilizer P. Whereas, Alleoni *et al* (2012) reported that predominant fraction of P was iron associated inorganic P, followed by aluminium associated inorganic P and calcium-associated inorganic P. The lower values of calcium-associated inorganic P were due to advanced weathering processes. Application of manure leads to the general shift from iron associated inorganic P and aluminium associated inorganic P to Calcium-associated inorganic P forms (Graetz and Nair 1995). Motavalli and Miles (2002) also observed marked increase in these soil inorganic P fractions with continuous fertilizer P application for 9 or more years. Marked increase in calcium-aluminium associated inorganic P and iron associated inorganic P may serve as a primary sink for FYM and fertilizer P added to soils (Bhattacharyya *et al* 2015). Organic P comprised 8.6% of total P in the 15 cm plough layer (Figure 4.5). This shows that inorganic P is the major P fraction constituting 91.4% of total P concentration in soils. These values are within the range reported earlier for the soils in this region (Aulakh *et al* 2003, Singh and Singh 2007). Significant improvement in the concentration of different organic P fractions with application of FYM either alone or in conjunction with P fertilizer is because of the existence of organic P compounds with rapidly to slowly decomposable organic molecules, such as nucleic acids, phospholipids, sugar phosphates, inositol phosphates, and recalcitrant humic substances (Hedley *et al* 1982). Chelation of applied inorganic P with organic anions of decomposed soil organic matter leads to increase in organic P fractions in soil (Majumdar *et al* 2007). The release of organic acids during the decomposition of organic matter solubilize native as well as applied P that governs the dynamics of P in the soils (Wang *et al* 1967, Song *et al* 2007, Singh *et al* 2010). Application of organic manure along with inorganic-P fertilizers causes significant improvement in organic and inorganic P fractions (Ranatunga *et al* 2013). Organic P is mainly confined to the surface layer, mineralized into inorganic forms but plants mainly depend on inorganic P forms for their P requirements. Thus inorganic P

fractions are the main source of P supply to the plants (Tiessen *et al* 1984, Devra *et al* 2014). Favourable effect of fertilizer and manure application on different P fractions in lower soil layer may be due to (i) less minning of P from lower layers because of greater application at the surface layer, (ii) mixing of P during cultivation, and (iii) movement of P from organic sources during crop growth period.

4.1.3 Phosphorus stocks in soils

Phosphorus stocks in surface soil (0-7.5cm) and subsurface soil (7.5-15 cm) under different treatments are shown in figure 4.6. In surface soil (0-7.5 cm) highest inorganic P and organic P stocks (668 and 79 kg ha⁻¹) were observed in plots amended with FYM and RP and the lowest (405 and 32 kg ha⁻¹) in CK plots. Total P stocks ranged between 443 and 758 kg ha⁻¹ under different treatments. Total P and inorganic P stocks were significantly higher in plots receiving fertilizer P in combination with FYM (F₁P_{30RP}) than those receiving FYM alone (F₁P₀). However, the effect of fertilizer P sources viz. single super phosphate and rock phosphate on soil P stocks was not significant. Plots treated with P in wheat (F₀P₀) showed significant increase in total P and inorganic P stocks compared to absolute control. Application of fertilizer P to wheat (F₀P₀) significantly increased organic P stocks by 34.3% compared to CK. Application of FYM and rock phosphate (F₁P_{30RP}) significantly increased organic P stocks compared to FYM alone application (F₁P₀). Irrespective of the treatment, soil P stocks decreased with depth (Figure 4.6). Jiao *et al* (2010) has reported the decline in soil P stock with depth. In subsurface (7.5-15 cm) soil, effects of different treatment on soil P stocks were similar to those observed in subsurface soil (0-7.5 cm). Under different treatments, inorganic P, organic P and total P stocks ranged between 340 to 523, 26 to 60 and 370 to 591 kg P ha⁻¹, respectively. Increase in soil P stocks in treated plots may be due to fertilizer P and manure application. Because, application of FYM and fertilizer P increases organic and inorganic P fractions in soil (Kolawole *et al* 2003, Ranatunga *et al* 2013, Costa *et al* 2014, Wright, 2009).

4.1.4 Phosphorus enrichment in soils

Phosphorus enrichment was calculated as the difference in the concentration of a phosphorus fraction in the treated and the control plots. Phosphorus enrichment in water soluble inorganic and organic P in surface soil ranged between 0.38 and 1.64 mg P kg⁻¹ (44-192%) under different treatments (Table 4.5). In the subsurface soil, it ranged between 0.34 and 1.10 mg P kg⁻¹ (44-171%). Phosphorus enrichment in iron associated inorganic P ranged between 22.8 and 62.8 mg P kg⁻¹ (45-123%) in surface soil, and between 14.0-43.3 mg P kg⁻¹(33-103%) in subsurface soil. Iron associated organic P fraction showed enrichment between 0.73-5.59 mg kg⁻¹ (35-267%) in surface soil, and between 0.50-4.02 mg kg⁻¹ (32-253%) in subsurface soil. In surface soil, P enrichment in calcium-aluminium associated inorganic P ranged between 78-203 mg kg⁻¹ (30-78%), compared to 46-146 mg kg⁻¹ (22-70%) in subsurface soil. Calcium-aluminium associated organic P

fraction showed an enrichment of 39-93% in surface soil, and 27-98% in subsurface soil. In 0-7.5 cm and 7.5-15 cm soil depth, % enrichment in acid soluble organic P, sugar bound organic P, nucleic acid organic P and polyphosphate, humic-bound organic P ranged between 37-282% and 16-243% under different treatment (Table 4.5).

Maximum enrichment of P among different inorganic and organic P fractions occurred in plots receiving fertilizer P along with FYM (F_1P_{30RP}) followed by F_1P_0 , F_0P_{30SSP} , F_0P_{30RP} and F_0P_0 . Higher P enrichment in different fractions occurred in the surface soil (0-7.5 cm) than the subsurface soil (7.5-15 cm). Apparently it was because of P application through FYM and fertilizers. Evidently, inorganic P was major sink for fertilizer and manure P. Phosphorus enrichment in soil plough depth (0-15 cm) as inorganic, organic and total P shown in figure 4.7. Inorganic P enrichment ranged between 87 and 239 mg kg⁻¹ (27-75%). Organic P enrichment ranged between 9 and 40 mg kg⁻¹ (36-165%). Total P enrichment ranged between 97 and 284 mg kg⁻¹ (28-82%). In 0-15 cm soil % P enrichment followed the order: organic P > total P > inorganic P. Increase in inorganic, organic and total P concentration might be ascribed continuous P application through fertilizer and FYM. FYM application tends to enrich the soil organic P, which may contribute to inorganic pool of P that upon mineralization tends to increase available P concentration in soil. Similar results have earlier been reported by Garg and Aulakh (2010) who observed greater enrichment in inorganic and organic P in soil amended with fertilizer P and FYM for 34 yrs of maize–wheat and 22 yrs of rice–wheat cropping. They observed that a major portion of residual fertilizer P was converted to stable inorganic and organic P forms and accumulated in the surface 0-30-cm depth where inorganic P constituted 74 to 89% of total residual fertilizer P present in the soil. The change with time in applied P in soil is governed by organic matter content, application of organics and nature of fertilizer (Biswas and Narayanasamy 2006, Devra *et al* 2014). Among different agricultural management practices, nutrient management had a profound influence on soil P dynamics (Song *et al* 2007). The management practices that increase soil organic matter levels also influence P availability and related dynamics (Messiga *et al* 2012). Improvement in SOC with organic manure application enhances soil microbial biomass, and thereby alters P availability through mineralization-immobilization (Chen *et al* 2003, Sigua *et al* 2009). Application of organic manure with fertilizer P to soil causes significant enrichment in organic P and inorganic P fractions (Ranatunga *et al* 2013, Devra *et al* 2014).

4.1.5 Phosphorus release kinetics

Kinetics of P release were studied in surface soils (0-15 cm) collected from different treatments. Phosphorus release increased rapidly with increase in shaking time and the amount of cumulative P released was the highest at 96 hours of equilibration (Figure 4.8).

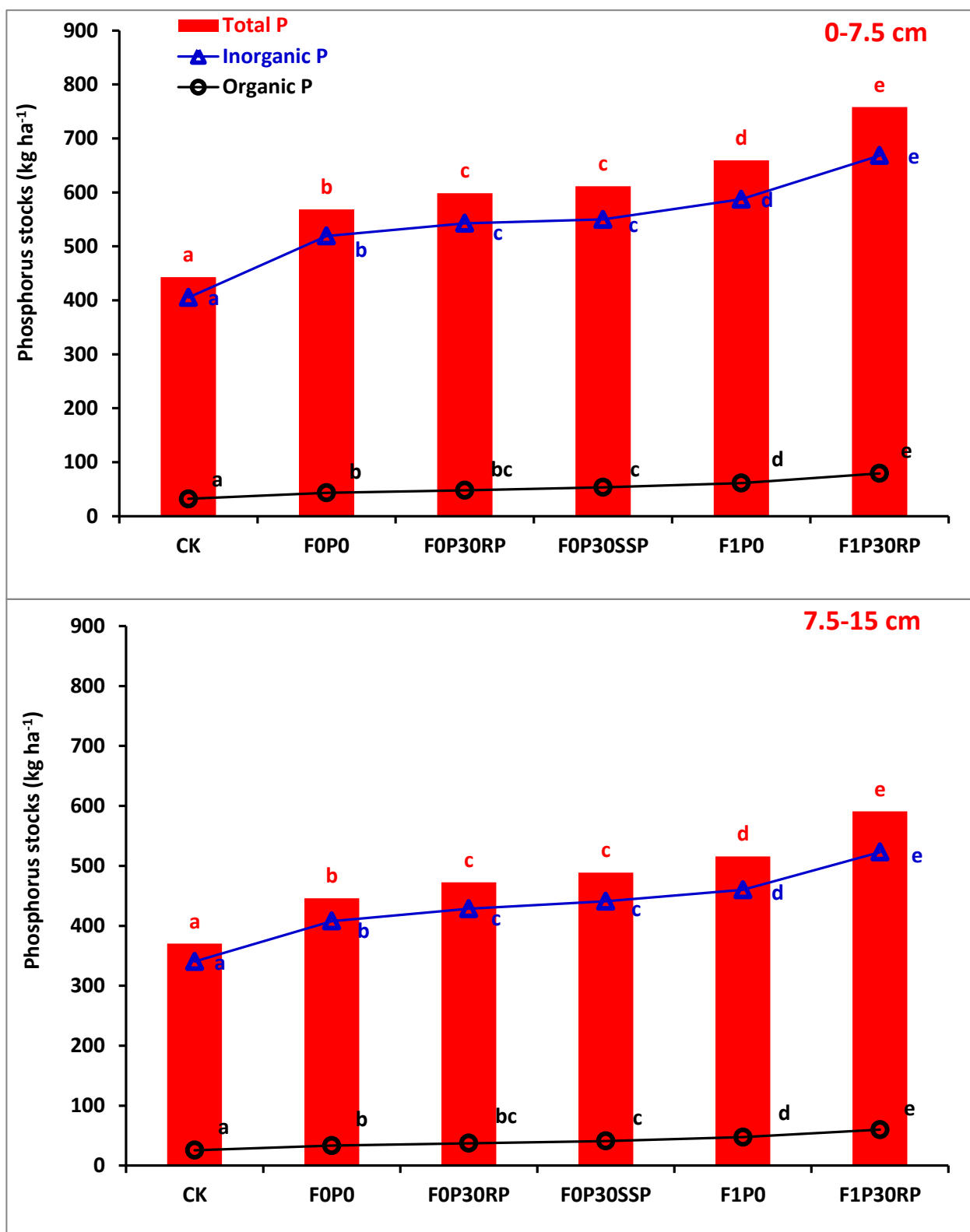


Fig 4.6 Effect of amount and source of P application on total P, inorganic P and organic P stocks in 0-7.5 cm and 7.5-15 cm soil depth after 7 cycles of rice-wheat cropping [Mean values for a soil property at a given depth followed by different letters differ significantly ($p < 0.05$) by Duncan's multiple range test (DMRT)]

Table 4.5 Phosphorus enrichment in 0-7.5 and 7.5-15 cm soil depths as influenced by amount and source of P application after 7 cycles of rice-wheat cropping

Treatment	Inorganic P					Organic P									
	H ₂ O-Pi [*]	Ca-EDTA-Pi [†]	Na-EDTA-Pi [‡]	NaOH-Pi [►]	▼TPi	H ₂ O-Po [*]	Ca-EDTA-Po [†]	Na-EDTA-Po [‡]	H ₂ SO ₄ -Po [‡]	cTCA-Po [▲]	hTCA-Po [▼]	NaOH-Po [►]	▲TPo	Res-P [◄]	Total P
P enrichment (mg kg ⁻¹) in 0-7.5 cm soil depth															
F ₀ P ₀	0.38	22.8	78	8.49	110	0.38	0.73	1.94	1.20	1.41	0.91	4.25	10.8	0.40	121
F ₀ P _{30RP}	0.52	28.6	99	8.70	137	0.45	1.28	2.21	1.16	4.45	0.83	4.95	15.3	2.00	155
F ₀ P _{30SSP}	0.72	32.6	112	5.22	150	0.53	1.62	3.10	2.08	5.46	1.92	6.29	21.0	2.53	174
F ₁ P ₀	0.97	46.8	141	6.44	195	0.74	3.99	2.29	3.41	5.49	1.68	11.8	29.3	5.16	230
F ₁ P _{30RP}	1.64	62.2	203	12.43	279	1.09	5.59	4.65	5.27	8.65	2.59	19.1	46.9	5.12	331
P enrichment (%) in 0-7.5 cm soil depth															
F ₀ P ₀	44	45	30	22	32	45	35	39	39	46	48	37	39	8	32
F ₀ P _{30RP}	61	56	38	23	39	53	61	44	38	145	44	43	56	40	41
F ₀ P _{30SSP}	85	64	43	14	43	61	77	62	67	178	100	55	76	51	46
F ₁ P ₀	114	92	54	17	56	86	191	46	111	179	88	102	107	104	60
F ₁ P _{30RP}	192	123	78	33	80	127	267	93	171	282	136	166	171	103	87
P enrichment (mg kg ⁻¹) in 7.5-15 cm soil depth															
F ₀ P ₀	0.34	14.0	46	4.47	64	0.24	0.50	1.01	0.73	0.39	0.38	3.84	7.1	0.60	72
F ₀ P _{30RP}	0.38	19.9	63	5.85	89	0.38	0.97	1.56	0.99	3.06	0.83	3.25	11.0	2.37	103
F ₀ P _{30SSP}	0.50	22.7	80	3.69	107	0.35	1.27	2.42	1.89	4.01	1.21	3.77	14.9	2.56	125
F ₁ P ₀	0.86	32.7	98	3.49	135	0.45	3.25	1.56	2.42	3.91	1.02	9.20	21.8	4.21	161
F ₁ P _{30RP}	1.10	43.3	146	8.43	199	0.77	4.02	3.67	4.41	6.06	1.94	13.0	33.9	4.10	237
P enrichment (%) in 7.5-15 cm soil depth															
F ₀ P ₀	53	33	22	15	23	44	32	27	33	16	23	42	33	18	24
F ₀ P _{30RP}	58	48	30	19	32	70	61	42	45	123	52	36	52	70	33
F ₀ P _{30SSP}	77	54	39	12	38	63	80	65	86	161	75	41	70	76	41
F ₁ P ₀	133	78	47	12	48	82	204	42	110	157	63	101	103	125	53
F ₁ P _{30RP}	171	103	70	28	71	140	253	98	200	243	121	143	159	121	77

*H₂O-Pi/Po=Water soluble inorganic and organic P, †Ca-EDTA-Pi/Po=Iron associated inorganic and organic P, ‡Na-EDTA-Pi/Po=Calcium-aluminium associated inorganic and organic P, ‡H₂SO₄-Po=Acid soluble organic P, ▲cTCA-Po=Sugar bound organic P, ▼hTCA-Po=Nucleic acid organic P and polyphosphate, ►NaOH-Pi/Po=Humic bound inorganic and organic P, ◄Res-P=Residual P, ▲TPo= organic P, ▼TPi= inorganic P

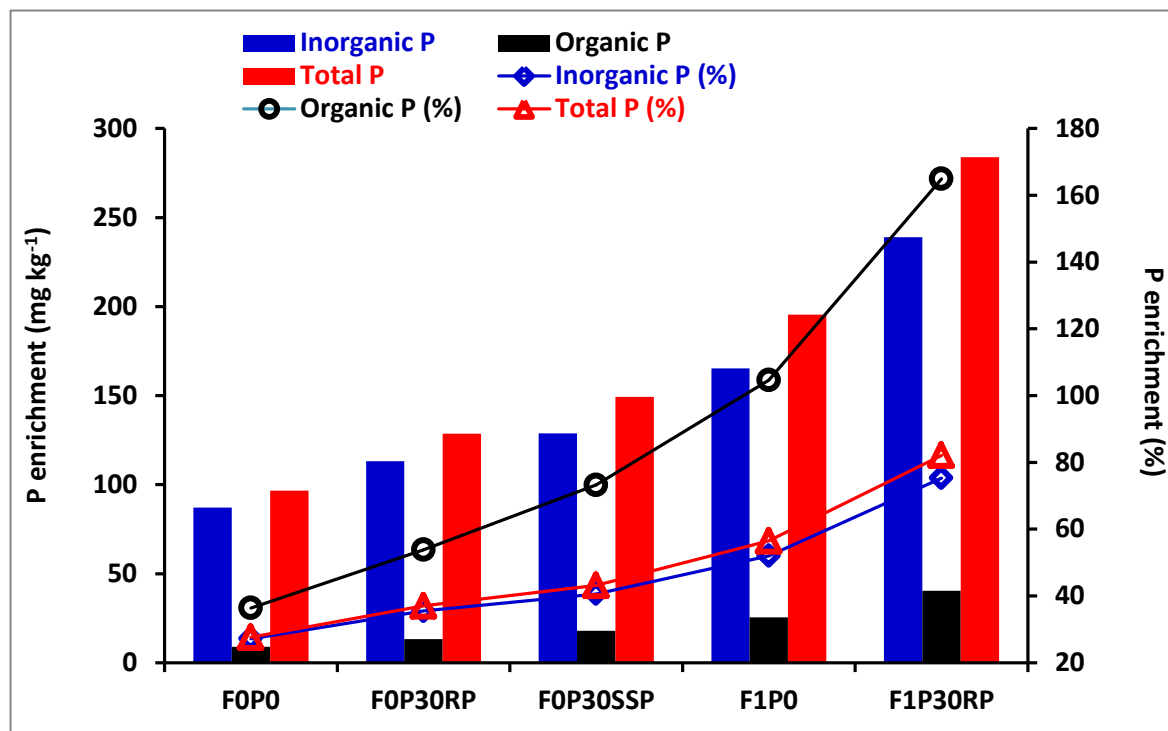


Fig 4.7 Effect of amount and source of P application on phosphorus enrichment in total P, inorganic P and organic P pools in soil plough (0-15 cm) after 7 cycles of rice-wheat cropping

The release of P in these soils proceeded in two phases: an initial rapid release phase followed by a slow release after 12-24 hours of shaking. Cumulative amount of P released from soils nearly levelled-off after 48 hours of shaking showing the existence of fast and slower reaction of P with soil matrix. Cumulative P released ranged between 18.2-29.8, 15.7-24.9, 14.3-23.6, 13.7-22.7, 12.9-22 and 10.9-20 ($\mu\text{g P g}^{-1}$) in plots treated with FYM in conjunction with RP (F_1P_{30RP}), F_1P_0 , F_0P_{30SSP} , F_0P_{30RP} , F_0P_0 and CK, respectively.

Amount of cumulative P released was the lowest in the CK plots, and increased with P application, either alone or in conjunction with fertilizer P (Figure 4.8). Regardless of the shaking time, cumulative P released was higher in soils receiving fertilizer P along with FYM (F_1P_{30RP}) than those receiving FYM alone (F_1P_0). Application of P fertilizer to wheat (F_0P_0) caused considerably higher P release than CK plots. It was interesting to observe, that regardless of application of P on equivalent basis, the amount of cumulative P released was considerably higher from the soils receiving P through single super phosphate (F_0P_{30SSP}), compared to the soils receiving P through rock phosphate (F_0P_{30RP}). This showed that single super phosphate was superior to rock phosphate in these soils as far as time dependent P availability to the growing plants was concerned. Increase in P release with manure application has been reported by Shafquat and Pierzynski (2010). Initially fast P release from the soil is due to the release of P from the labile P pools (Gorgin *et al* 2011, Abdu 2009, Toor and Bahl 1999). Subsequent a slower P release indicates the conversion of non-labile or semi-labile P pools to labile P pools (Hundal *et al* 1988). Griffin and Jurinak (1974) reported that initial

fast reaction corresponds to rapid dissolution of poorly crystalline and amorphous phosphates in soil, which results in release of large amount of P in the equilibrium solution. Wang *et al* (2000) attributed rapid reaction to sorption at aggregate surface and subsequent slow reaction to the diffusion of P into the aggregates.

4.1.5.1 Modelling kinetics of phosphorus release

Six different kinetic models viz. zero order, first order, second order, power function, Elovich and parabolic diffusion equations were fitted by least square method to describe P release as a function of time (Figure 4.9). Phosphorus release in soil was best described by Elovich and power function as indicated by higher coefficient of determination ($R^2 \geq 0.98^{**}$) closely followed by parabolic diffusion equation (Table 4.6). Earlier, Chien and Clayton (1980), Ghosh and Singh (2000) also observed the superiority of Elovich equation in describing P release kinetics in soils. The release constants deduced from Elovich equation, parabolic diffusion and power function equations, revealed that the values of P release constants were lowest for CK plots compared with plots receiving P fertilizer only to wheat (F_0P_0) (Table 4.7). Phosphorus release constants were higher for single super phosphate (F_0P_{30SSP}) treated plots than the rock phosphate treated plots (F_0P_{30RP}). However, these values increased remarkably in the soils amended with FYM in combination with P fertilizer (F_1P_{30RP}) than plots amended with FYM alone (F_1P_0). Higher release from FYM amended soils could be ascribed to the conversion of stable and meta-stable P compounds to less and sparingly soluble compounds with additional application of P fertilizer and manure (Toor and Bahl 1999, Singh *et al* 2010).

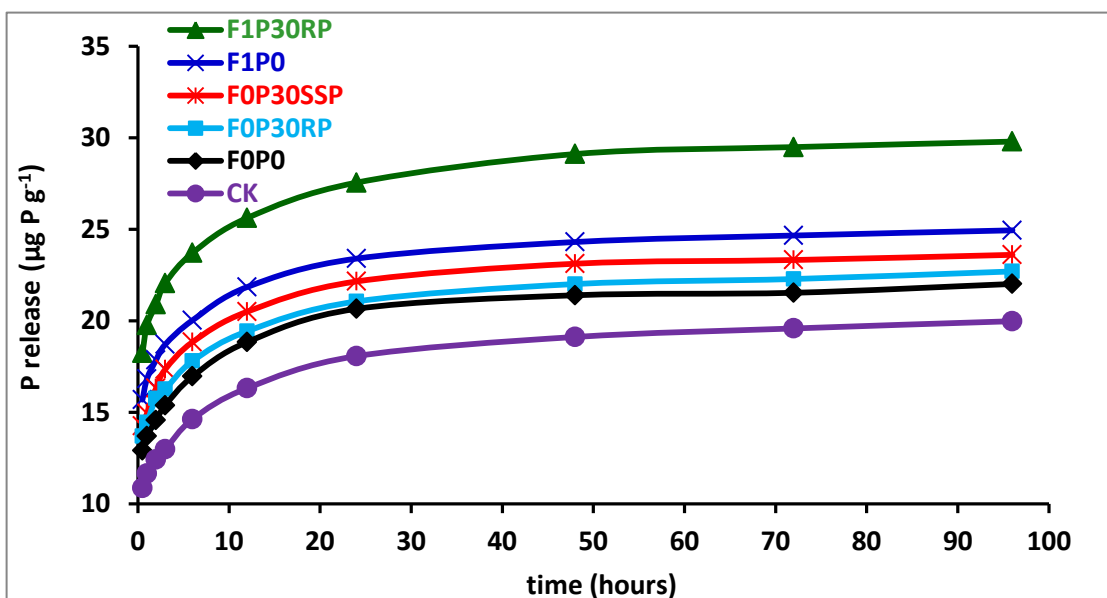


Fig 4.8 Effect of amount and source of P application on kinetics of phosphorus release in surface soils (0-15 cm) after 7 cycles of rice-wheat cropping

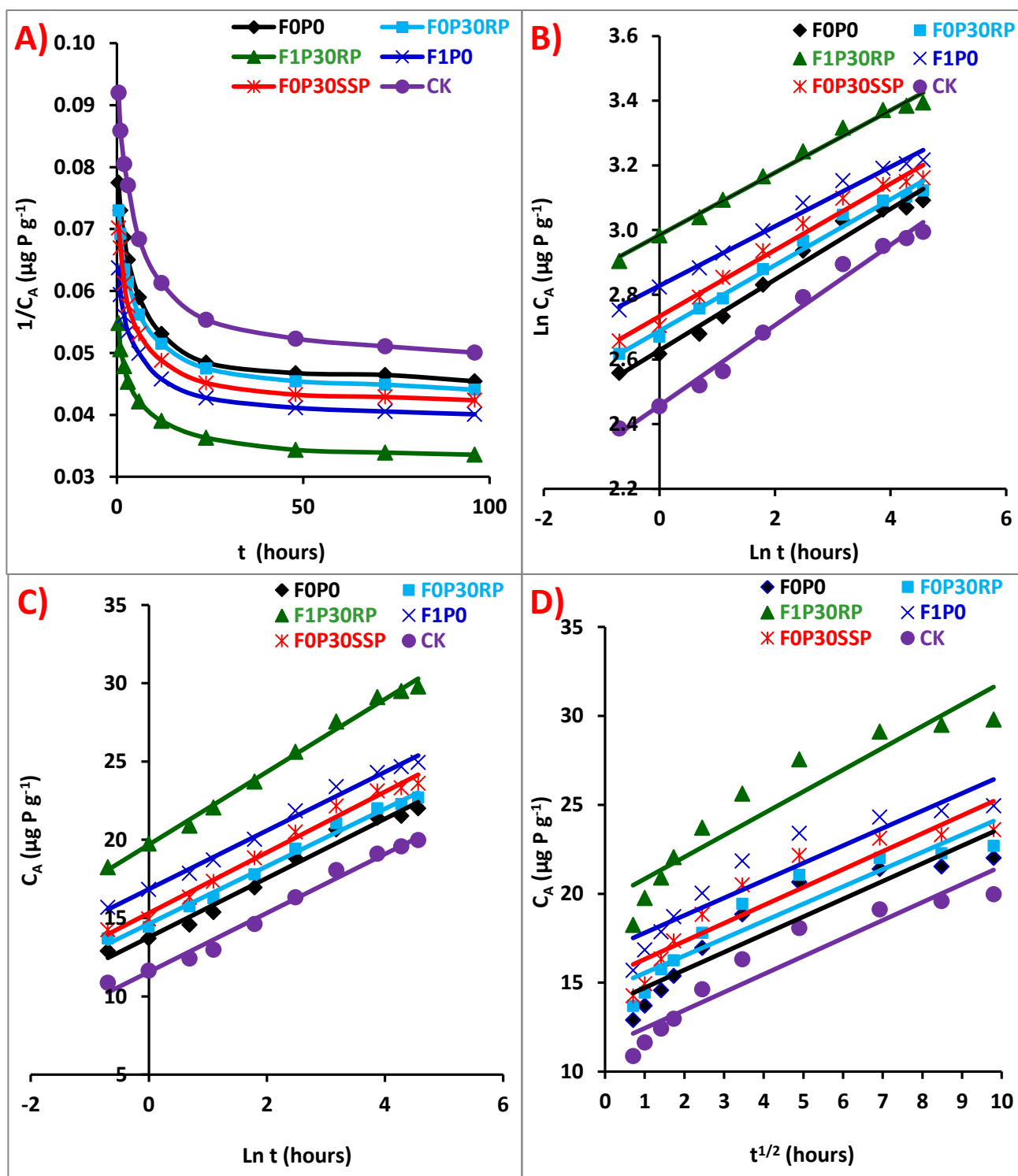


Fig 4.9 Effect of amount and source of P application on kinetics of phosphorus release in surface soils (0-15 cm) after 7 cycles of rice-wheat cropping (C_A =amount of P release, t =time, A=second order equation, B=Power function equation, C=Elovich equation, and D=Parabolic diffusion equation)

Table 4.6 Statistical criteria for judging the suitability of different kinetic models fitted to describe the kinetics of P release data for surface (0-15 cm) soils after 7 cycles of rice-wheat cropping

Treatment	Zero order equation			First order equation			Second order equation			Parabolic diffusion equation			Power function equation			Elovich equation		
	S.E. _M [†]	S.D. _M [†]	R ^{2*}	S.E. _M	S.D. _M	R ²	S.E. _M	S.D. _M	R ²	S.E. _M	S.D. _M	R ²	S.E. _M	S.D. _M	R ²	S.E. _M	S.D. _M	R ²
CK	1.11	3.49	0.75**	0.073	0.231	0.69*	0.005	0.016	0.64*	1.11	3.49	0.91**	0.073	0.230	0.99**	1.11	3.49	0.97**
F ₀ P ₀	1.11	3.52	0.70**	0.065	0.205	0.66*	0.004	0.012	0.61*	1.11	3.52	0.87**	0.064	0.204	0.98**	1.11	3.52	0.98**
F ₀ P _{30RP}	1.08	3.40	0.71**	0.060	0.189	0.66*	0.003	0.011	0.62*	1.08	3.40	0.88**	0.060	0.188	0.99**	1.08	3.40	0.99**
F ₀ P _{30SSP}	1.14	3.59	0.68*	0.060	0.191	0.63*	0.003	0.010	0.59*	1.14	3.59	0.86**	0.060	0.191	0.98**	1.14	3.59	0.99**
F ₁ P ₀	1.09	3.46	0.70**	0.054	0.172	0.66*	0.003	0.009	0.61*	1.09	3.46	0.87**	0.054	0.170	0.99*	1.09	3.46	0.99**
F ₁ P _{30RP}	1.36	4.29	0.72**	0.057	0.179	0.66*	0.002	0.008	0.62*	1.36	4.29	0.88**	0.057	0.179	0.99**	1.36	4.29	0.99**

[†]S.E._M=Standard error of mean, [†]S.D._M=Standard deviation of mean, ^{*}R²=Coefficient of determination,

*Relationship significant at $p < 0.05$

**Relationship significant at $p < 0.01$

Table 4.7 Effect of amount and source of P application on phosphorus release constants of different kinetics models for surface soils (0-15 cm) after 7 cycles of rice-wheat cropping

Treatment	Elovich Equation (EE)		Parabolic diffusion Equation (PDE)		Power function Equation (PFE)	
	α ($\mu\text{g g}^{-1} \text{h}^{-1}$)	β ($\mu\text{g g}^{-1}$)	R ($\mu\text{g g}^{-1} \text{h}^{-1/2}$)	C ($\mu\text{g g}^{-1}$)	K_A ($\mu\text{g g}^{-1} \text{h}^{-1}$)	b ($\mu\text{g g}^{-1}$)
CK	1.88	11.55	1.01	11.42	0.12	2.46
F ₀ P ₀	1.89	13.76	1.00	13.71	0.11	2.63
F ₀ P _{30RP}	1.84	14.63	0.97	14.57	0.10	2.69
F ₀ P _{30SSP}	1.94	15.32	1.01	15.30	0.10	2.73
F ₁ P ₀	1.87	16.85	0.98	16.81	0.09	2.83
F ₁ P _{30RP}	2.32	19.68	1.23	19.61	0.10	2.98

4.1.6 Soil carbon pools

4.1.6.1 Total and water extractable organic carbon

The effect of rate and source of P application on the concentration of total organic carbon (TOC) and labile C pools in soils is given in table 4.8. The concentration of TOC ranged between 2.94 to 5.82, and 2.57 to 5.29 g C kg⁻¹ in surface (0-7.5 cm) and subsurface soil (7.5-15 cm), respectively. Fertilizer P application to wheat at 60 kg P₂O₅ ha⁻¹ (F₀P₀) resulted in 14.3% increase in TOC concentration, compared to CK, in surface soil. Application of FYM in combination with P fertilizer (F₁P_{30RP}) to rice significantly increased TOC concentration by 24.6% over FYM application alone (F₁P₀). Significant increase in SOC concentration with FYM application has been reported by Aulakh *et al* (2010) and Aulakh *et al* (2012). Bhattacharaya *et al* (2010) observed ~47% higher SOC concentration in soil plough layer receiving FYM and NPK than alone NPK dressed soil.

In surface soil, application of fertilizer P to both the crops through single super phosphate (F₀P_{30SSP}) increased the TOC concentration than through rock phosphate (F₀P_{30RP}). It may be because of the higher availability of P to plant roots when P is applied through single super phosphate than rock phosphate. Increased concentration of TOC with fertilizer P application is due to the increased root growth and biomass, which adds organic matter to the soil. Beneficial effects of fertilizers and manure application was similar in the subsurface soil (7.5-15 cm) but the two treatments F₀P_{30SSP} and F₀P_{30RP} did not differ significantly. Total organic C concentration ranged between 2.17 to 2.87 and 1.89 to 2.27 g C kg⁻¹ in 15-30 and 30-60 cm soil depths, respectively. In 15-30 cm soil, application of P fertilizer to wheat (F₀P₀) led to significant increase in TOC concentration than CK. However, treatments F₀P_{30RP} and F₀P_{30SSP}, F₁P_{30RP} and F₁P₀ were at par. In 30-60 cm soil depth, these treatments did not differ significantly. Higher concentration of TOC was recorded in surface soil and decreased with soil depth (Figure 4.10). It is because of the fact that C input through all exogenous sources viz. root and leaf litter biomass as well as applied FYM is restricted to the soil plough depth (0-15 cm). A greater proportion of root biomass is also restricted to the plough depth than the lower soil layers. Brar *et al* (2013) also observed significant effect of FYM and NPK applications on SOC in a soil plough layer under rice-wheat cropping system.

Fertilizer application stimulates crop biomass production and thus increases the amount of residue retained in the soil and therefore, enhances C accumulation in the soil (Schuman *et al* 2002). A significant linear relationship between cumulative C input to the soil and amount of C sequestered in soils under rice-wheat cropping system has been reported in several studies (Srinavasarao *et al* 2012, Majumder *et al* 2007 and 2008, Mandal *et al* 2007). Thus, an improvement in TOC concentration in a soil with FYM application might be due to additional input through manure (Qian-Ru *et al* 2009, Yang *et al* 2012, Moharana *et al* 2012). Ghosh *et al* (2012) reported 2.09-times higher crop C input to soil with the NPK+FYM application over the control treatment, after 25-years long-term experiment under rice-wheat cropping system.

Similarly, Tong *et al* (2014) reported ~6.1-times higher annual crop C input to soil with NPK + pig manure application compared to the control treatment in a 17 years long-term fertilizer experiment under maize-wheat cropping system.

Water extractable organic C which represents an array of molecules in a soluble phase that remain in equilibrium with solid SOC, responded to rates and source of P application (Table 4.8, Figure 4.10). Water extractable organic C (WEOC) ranged between 16 to 29.6 mg C kg⁻¹ in surface (0-7.5 cm) soil and 14.4 to 26 mg C kg⁻¹ in the subsurface (7.5-15 cm) soil. In surface and subsurface soils, fertilizer P application to wheat at 60 kg P₂O₅ ha⁻¹ (F₀P₀) significantly increased WEOC concentration compared to CK. Application of FYM in combination with P fertilizer (F₁P_{30RP}) significantly increased WEOC concentration than FYM application (F₁P₀). Plots treated with fertilizer P during both the crops through single super phosphate (F₀P_{30SSP}) showed significant increase in WEOC concentration than F₀P_{30RP}. On an average, WEOC comprised 0.5% of TOC concentration in the soil (Table 4.7). Similarly, Benbi *et al* (2015b) reported that WEOC comprised 0.32-0.50% of TOC, after 11 years of FYM and fertilizer applications in rice-wheat system in the same region. A significant increase (2.21 times) in WEOC in the soil plough layer (0-15 cm) as a result of 9-years of rice-wheat cropping with NPK+FYM application, over the CK treatment was reported (Brar *et al* 2013). A higher increase in WEOC in FYM dressed plots compared to NPK alone indicates that added organic manure contains much soluble organic matter (Chantigny *et al* 2002). Therefore, water soluble organic C had rapid turnover rate and suggested as a sensitive indicator of management induced changes in soil organic matter under rice-wheat system (Benbi *et al* 2015b). Water extractable organic C concentration decreased with depth and ranged between 10.4 and 12.8 mg C kg⁻¹ and 9.2 and 9.6 mg C kg⁻¹ in 15-30 cm and 30-60 cm soil depth, respectively (Figure 4.10). In 15-30 cm soil, WEOC concentration did not differ significantly between treatment F₀P_{30SSP} and F₀P_{30RP}. Farmyard manure applications (F₁P_{30RP} and F₁P₀) showed similar effect on concentration of WEOC. Application of fertilizer P to wheat (F₀P₀) did not increase concentration of WEOC significantly compared to absolute control. In 30-60 cm soil depth, effect of different treatment on WEOC concentration was statistically non-significant.

Table 4.8 Effect of amount and source of P application on total organic carbon (TOC), water soluble carbon (WEOC) and hot water soluble carbon (HWSC) in the surface (0-7.5 cm) and subsurface (7.5-15 cm) soil after 7 cycles of rice-wheat cropping

Treatment	TOC (g C kg ⁻¹)		WEOC (mg C kg ⁻¹)		HWSC (mg C kg ⁻¹)	
	0-7.5 cm	7.5-15 cm	0-7.5 cm	7.5-15 cm	0-7.5 cm	7.5-15 cm
CK	2.94 ^{a†}	2.57 ^a	16.0 ^a	14.4 ^a	159 ^a	144 ^a
F ₀ P ₀	3.36 ^b	3.16 ^b	18.8 ^b	16.4 ^b	177 ^a	166 ^b
F ₀ P _{30RP}	3.88 ^c	3.63 ^c	19.6 ^b	17.6 ^b	196 ^b	182 ^c
F ₀ P _{30SSP}	4.38 ^d	3.86 ^c	22.4 ^c	19.2 ^c	221 ^c	195 ^c
F ₁ P ₀	4.67 ^d	4.34 ^d	24.0 ^d	21.2 ^d	240 ^c	219 ^d
F ₁ P _{30RP}	5.82 ^e	5.29 ^e	29.6 ^e	26.0 ^e	292 ^d	265 ^e

Mean values for a soil property at a given depth followed by different letters differ significantly (p<0.05) by Duncan's multiple range test (DMRT) ncan's multiple range test (DMRT)]

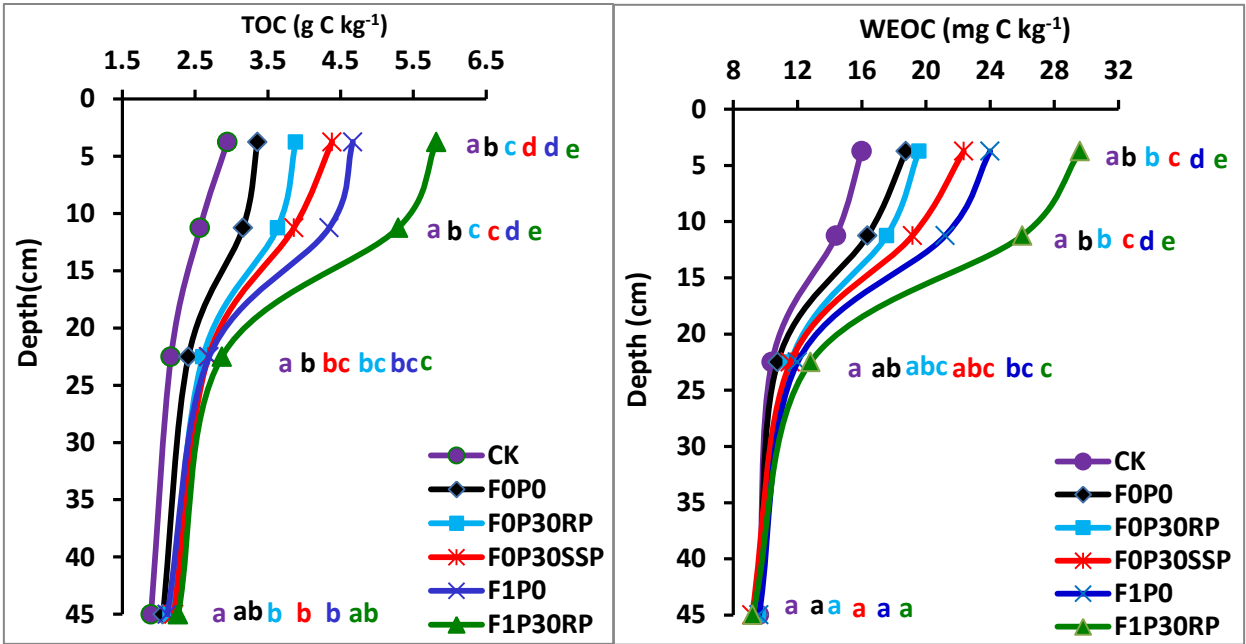


Fig 4.10 Effect of amount and source of P application on profile distribution of total organic carbon (TOC) and water extractable organic carbon (WEOC) in soil profile after 7 cycles of rice-wheat cropping [Mean values for a soil property at a given depth followed by different letters differ significantly ($p < 0.05$) by Duncan's multiple range test (DMRT)]

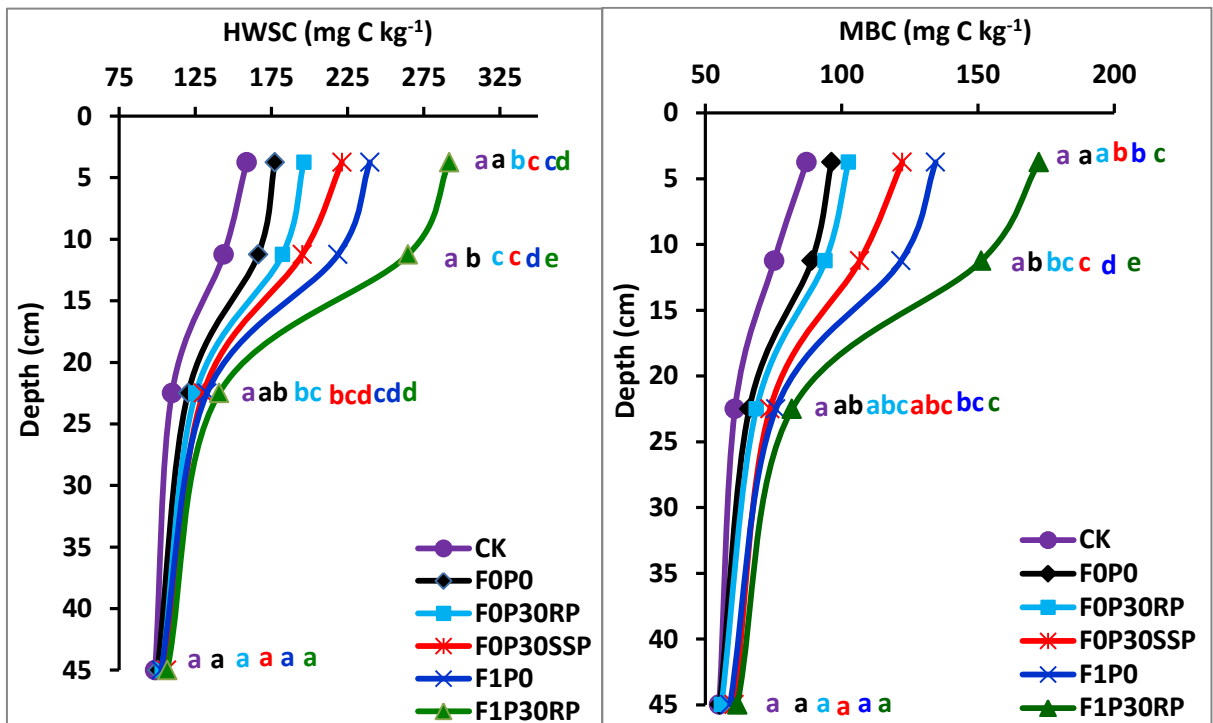


Fig 4.11 Effect of amount and source of P application on profile distribution of hot water soluble carbon (HWSC) and soil microbial biomass carbon (MBC) in soil after 7 cycles of rice-wheat cropping [Mean values for a soil property at a given depth followed by different letters differ significantly ($p < 0.05$) by Duncan's multiple range test (DMRT)]

4.1.6.2 Hot water soluble and microbial biomass carbon

Hot water soluble C ranged between 159 to 292 and 144 to 265 mg C kg⁻¹ in surface (0-7.5 cm) and subsurface soil (7.5-15 cm), respectively (Table 4.8 and Figure 4.11). In surface soil, differences between treatment F₀P₀ and CK were not significant. However, concentration of HWSC was significantly higher in the soils receiving FYM along with fertilizer P (F₁P_{30RP}), compared to soils receiving FYM alone (F₁P₀). Application of fertilizer P through single super phosphate (F₀P_{30SSP}) significantly increased concentration of HWSC by 12.8% over F₀P_{30RP} treatment. In subsurface soil (7.5-15 cm), application of fertilizer P to wheat (F₀P₀) increased HWSC concentration by 13.9% compared to unfertilized plots. The treatments F₀P_{30SSP} and F₀P_{30RP} showed similar effects on HWSC concentration. Similar to surface soil, hot water soluble C in plots treated with F₁P_{30RP} increased significantly, compared to F₁P₀ plots. Several researchers have reported the significant increase in HWSC with FYM and fertilizer applications (Simon 2008, Schulz *et al* 2011). On an average, hot water soluble C comprised 5.1% of TOC in soil and was 10 times higher than the WEOC concentration (Table 4.8). However, Benbi *et al* (2015b) reported that HWSC constituted 3-3.3% of TOC, after 11 years of FYM and fertilizer applications in rice-wheat system. Concentration of HWSC decreased with depth and ranged between 110 and 141 and 99 and 107 mg C kg⁻¹ in 15-30 and 30-60 cm soil depth, respectively (Figure 4.11). In 15-30 cm soil, hot water soluble C concentration did not differ significantly between treatment F₀P_{30SSP} and F₀P_{30RP}. Farmyard manure and manure applications (F₁P_{30RP} and F₁P₀) showed similar effects on concentration of HWSC. Application of fertilizer P to wheat (F₀P₀) and CK showed non-significant difference in HWSC concentration. In 30-60 cm soil depth, all treatments were non-significant.

Microbial biomass C plays an important role in nutrient cycling and has been recognized as component of active soil organic matter that helps in maintaining function and sustainability of terrestrial ecosystems (He *et al* 2003). In surface soil (0-7.5 cm), concentration of MBC ranged between 87.1 and 172.4 mg kg⁻¹ (Figure 4.11). Application of P through single super phosphate significantly increased MBC by 19.2% over rock phosphate treated plots. Microbial biomass C increased significantly in plots receiving FYM along with fertilizer P (F₁P_{30RP}) than those receiving only FYM (F₁P₀). Many researchers have reported the beneficial effects of FYM application on MBC (Kumar *et al* 2007, Bhattacharyya *et al* 2008, Yaduvanshi *et al* 2013, Benbi *et al* 2015b). In subsurface soil (7.5-15 cm), highest concentration (151.2 mg kg⁻¹) of soil MBC was observed under FYM and RP treated plots and the lowest (75.2 mg kg⁻¹) in CK plots. Effect of FYM and fertilizer P (F₁P_{30RP}) application on MBC was significantly higher than alone FYM (F₁P₀) application. The effects of different treatments were higher in surface soil and decreased with soil depth (Figure 4.11). Higher soil MBC in 0-7.5 cm soil layer could be attributed to higher microbial population than subsurface soils. Soil MBC ranged between 60.8 to 81.8 mg kg⁻¹ in 15-30 cm soil and 55.1 to 61.7 mg kg⁻¹ in 30-60 cm soil, respectively. Application of FYM with rock phosphate (F₁P_{30RP}) increased MBC concentration

by 7.9% over FYM (F_1P_0) application. In 30-60 cm soil, all treatments were at par. Soil MBC comprised 2.8% of TOC concentration in the plough layer. This concentration is in the range (1-5% of TOC) reported by Jenkinson and Ladd (1981). In a rice-wheat cropping system, significant increase in soil MBC with FYM application has also been reported earlier by Kaur *et al* (2008). After 16 years of rice based cropping system in semi-arid tropics, Banger *et al* (2009) also reported a significant improvement in MBC with FYM application in the plough layer. In four long-term field experiments under rice-wheat cropping system conducted in different agro-climatic conditions in India, an enhancement of 78.8 to 162.9% in soil MBC with fertilizer + FYM application has been reported (Nayak *et al* 2012).

4.1.6.3 Potassium permanganate oxidizable and non-labile C

In surface soil (0-7.5 cm), $KMnO_4$ -C ranged between 319 and 805 mg C kg⁻¹ under different treatments (Table 4.9 and Figure 4.12). Concentration of $KMnO_4$ -C did not differ significantly between plots receiving fertilizer P in wheat (F_0P_0) compared to CK plots. Effect of fertilizer sources (single super phosphate or rock phosphate) on the concentration of $KMnO_4$ -C was statistically non-significant. Potassium permanganate oxidizable carbon ($KMnO_4$ -C) concentration increased by 17.5% in soils receiving fertilizer P and FYM (F_1P_{30RP}) over plots receiving FYM alone (F_1P_0). The profile distribution of $KMnO_4$ -C under different treatments is shown in figure 4.12. Concentration of $KMnO_4$ -C was higher in surface soil (0-7.5 cm) and decreased with depth. Potassium permanganate oxidizable-C ranged between 305 and 682 mg C kg⁻¹ in subsurface soil (7.5-15 cm). Concentration of $KMnO_4$ -C did not differ significantly between treatment F_0P_{30SSP} and F_0P_{30RP} , F_1P_{30RP} and F_1P_0 , and, F_0P_0 and CK. Below subsurface soil, effect of different treatments was similar to 7.5-15 cm soil where significantly higher (386 mg kg⁻¹) concentration of $KMnO_4$ -C was recorded under treatment F_1P_{30RP} and the lowest (240 mg kg⁻¹) in CK plots. At 30-60 cm soil depth, $KMnO_4$ -C concentration ranged between 198 to 269 mg kg⁻¹, under different treatments. Effects of all treatments were non-significant at 30-60 cm soil.

Significant increase in $KMnO_4$ -C with FYM application has earlier been reported by Aulakh *et al* (2010). Moharana *et al* (2012) reported that FYM at 20 Mg ha⁻¹ yr⁻¹ application either alone or in conjunction with NPK significantly increased in $KMnO_4$ -C over absolute control. However, Blair *et al* (2006) have reported that in surface soil (0-10 cm), $KMnO_4$ -C increased by 70% after 96 years of FYM application, compared to CK. Potassium permanganate oxidizable-C comprised 10.9-13.8 % of TOC, in surface and subsurface soil. Similar range of $KMnO_4$ -C (10-13% of TOC) has earlier been reported by (Lou *et al* 2011). However, Benbi *et al* (2015b) reported $KMnO_4$ -C comprised 15-20% of TOC after 11 years of FYM and fertilizer applications in rice-wheat system in the same region.

In surface soil (0-7.5 cm), non-labile C concentration ranged between 2.62 to 5.01 (g C kg⁻¹) under different treatments. Non-labile C did not differ significantly between plots receiving fertilizer P to wheat F_0P_0 compared with CK plots. Application of fertilizer P through single super phosphate (F_0P_{30SSP})

significantly increased non-labile C concentration by 13.6% over rock phosphate treated (F_0P_{30RP}) plots. Significantly higher (25.9%) concentration of non-labile C was observed in treatment F_1P_{30RP} over F_1P_0 treatment. In subsurface soil (7.5-15 cm), it ranged between 2.26 to 4.61(g C kg⁻¹) under different treatments. Non-labile C did not differ significantly between treatment F_0P_{30SSP} and F_0P_{30RP} , F_1P_{30RP} and F_1P_0 , and, F_0P_0 and CK, respectively. Higher concentration of non-labile C in the treatments involving FYM application shows the stabilization of organic C in the soil. This could be due to the application of already stabilized material in soil. The C lability, lability index (LI), C pool index (CPI) and C management index (CMI) also improved considerably with fertilizer P application with FYM at both the soil depths (Table 4.9). Blair *et al* (2006) reported the higher CMI value under organic manure and fertilizer treated soils compared to only fertilizer treated soils. Carbon management index is a sensitive indicator depend soil organic carbon and indicates soil fertility (Whitbread *et al* 1998). Therefore, it can be concluded that the application of FYM with fertilizer P could be a possible alternate to increase the C stabilization in soil.

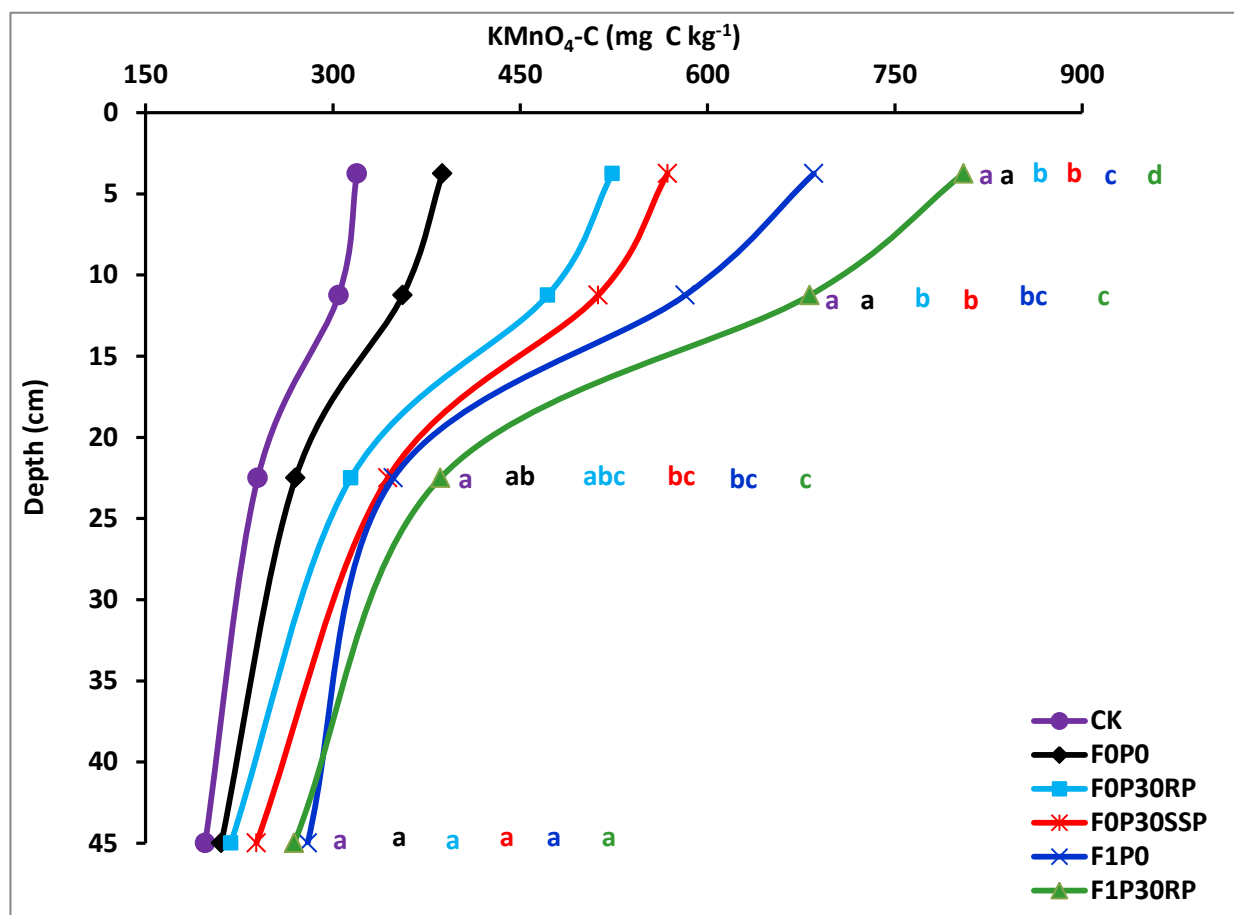


Fig 4.12 Effect of amount and source of P application on potassium permanganate oxidizable carbon ($KMnO_4$ -C) in soil profile after 7 cycles of rice-wheat cropping [Mean values for a soil property at a given depth followed by different letters differ significantly ($p < 0.05$) by Duncan's multiple range test (DMRT)]

Table 4.9 Effect of amount and source of P application on $\text{KMnO}_4\text{-C}$ (g kg^{-1}), non-labile C (g kg^{-1}), lability, lability index (LI), soil carbon pool index (CPI) and carbon management index (CMI) in the surface (0-7.5 cm) and subsurface (7.5-15 cm) soil after 7 cycles of rice-wheat cropping cropping

Treatment	KMnO ₄ -C		Non-labile C		Lability		LI		CPI		CMI	
	Depth (cm)											
	0-7.5	7.5-15	0-7.5	7.5-15	0-7.5	7.5-15	0-7.5	7.5-15	0-7.5	7.5-15	0-7.5	7.5-15
CK	0.319 ^a	0.305 ^a	2.62 ^a	2.26 ^a	0.122	0.135	--	--	--	--	--	--
F ₀ P ₀	0.388 ^a	0.356 ^a	2.97 ^a	2.80 ^a	0.131	0.127	1.07	0.94	1.14	1.23	122.4	116.1
F ₀ P _{30RP}	0.524 ^b	0.472 ^b	3.36 ^b	3.16 ^b	0.156	0.149	1.28	1.11	1.32	1.41	169.1	156.9
F ₀ P _{30SSP}	0.568 ^b	0.512 ^b	3.82 ^c	3.35 ^b	0.149	0.153	1.22	1.14	1.49	1.50	182.3	171.0
F ₁ P ₀	0.685 ^c	0.582 ^{bc}	3.98 ^c	3.76 ^{bc}	0.172	0.155	1.41	1.15	1.59	1.69	224.3	194.5
F ₁ P _{30RP}	0.805 ^d	0.682 ^c	5.01 ^d	4.61 ^c	0.161	0.148	1.32	1.10	1.98	2.06	260.9	226.5

†Mean values within a column followed by different letters differ significantly ($p < 0.05$) by Duncan's multiple range test (DMRT)

4.1.6.4 Carbon mineralization

Mineralizable-C in differentially treated field soil was estimated by conducting a laboratory study at 25 and 35°C temperature and field capacity moisture. Carbon mineralization was higher at 35°C than at 25°C, but the magnitude varied with the field treatment. Irrespective of the treatments, C mineralization was faster during initial period of incubation followed by a relatively slower rate thereafter (Figure 4.13). Similar trends of C mineralization have been reported by Benbi and Khosa (2014). The treatments differed in extent and rate of C mineralization. The amount to $\text{CO}_2\text{-C}$ evolved was highest in soils receiving fertilizer P and FYM ($\text{F}_1\text{P}_{30\text{RP}}$), followed by F_1P_0 treatment at both the temperatures. Carbon mineralization was lower in the CK plots, regardless of the temperature. The cumulative amount of $\text{CO}_2\text{-C}$ evolved in different treatments ranged between 158.2 and 528.1 mg C kg^{-1} at 25°C, and between 259 and 828.5 mg C kg^{-1} at 35°C (Figure 4.13). Regardless of the temperatures, cumulative amount of $\text{CO}_2\text{-C}$ evolved in soil followed the order FYM ($\text{F}_1\text{P}_{30\text{RP}}$) > F_1P_0 > $\text{F}_0\text{P}_{30\text{SSP}}$ > $\text{F}_0\text{P}_{30\text{RP}}$ > F_0P_0 > CK. These results corroborate the findings of Dumale *et al* (2008), who also observed that the CO_2 evolution rates were higher for the soils receiving leaf-litter, compared to the CK soils. Similarly, Jha and Ratan (2007) observed the highest $\text{CO}_2\text{-C}$ evolution in soils treated with different organics compared with CK. The process of organic matter decomposition is triggered at higher temperature (Joergensen *et al* 1990, Dalias *et al* 2001). Greater C mineralization at 35°C than at 15°C temperature has been reported by Benbi *et al* (2014), Benbi and Khosa (2014).

4.1.7 Correlation among different soil phosphorus and carbon pools and soil properties

The correlation matrix depicting relationship between soil C pools and available nutrients (Table 4.10) revealed highly significant positive correlation among different soil C pools for soil plough depth (0-15 cm). Highly significant positive correlation among TOC, $\text{KMnO}_4\text{-C}$, WEOC, HWSC revealed that there

exists a dynamic relationship governing the existence of each-other. These properties also showed highly significant linear positive correlation with available P, K and mineral-N in the soil plough depth. Several researchers have reported the positive and significant correlation among TOC, HWSC, MBC and WEOC (Ghani *et al* 2003, Benbi *et al* 2015b).

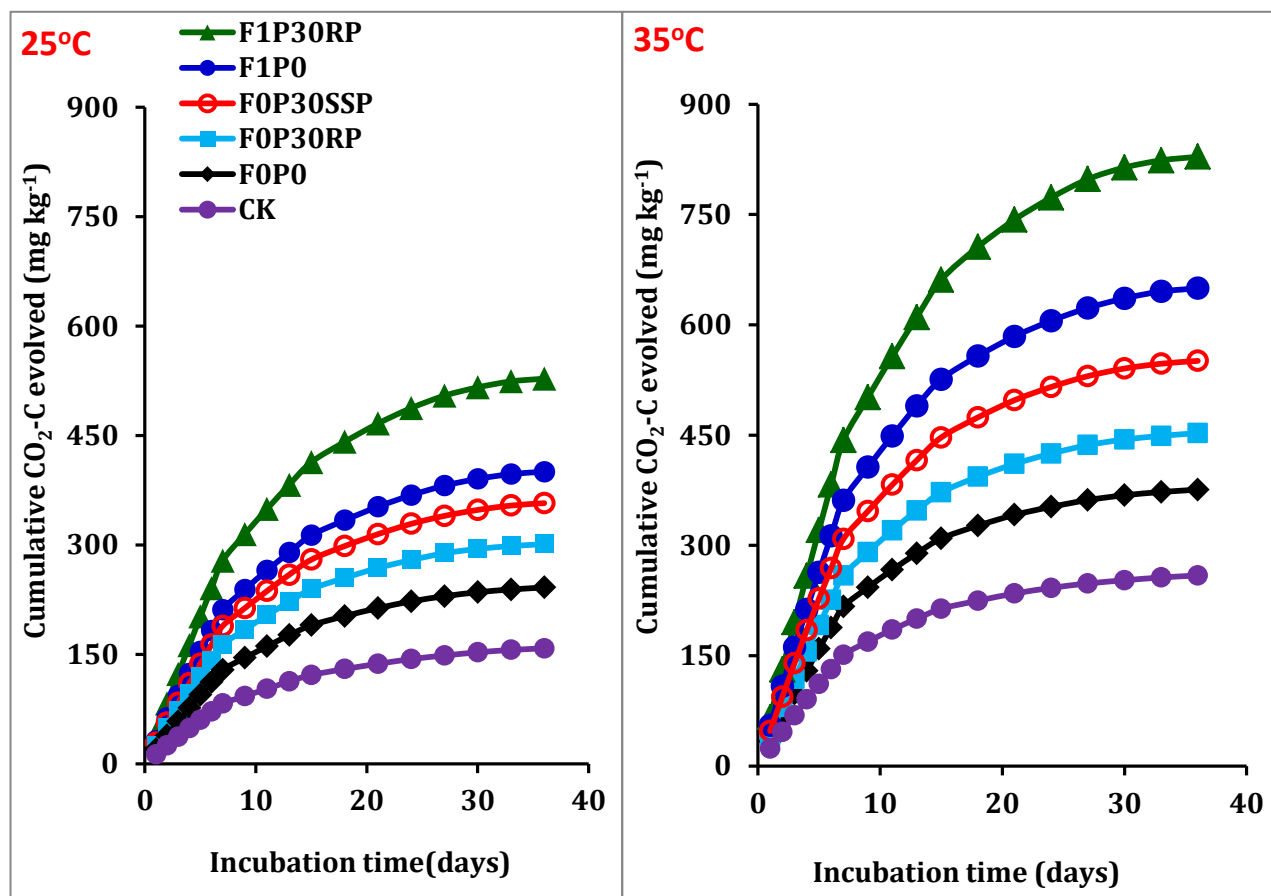


Fig 4.13 Effect of amount and source of P application on time course of CO₂-C evolved during decomposition of soils (0-15 cm) at 25 and 35°C after 7 cycles of rice-wheat cropping

The correlation matrix depicting relationship between various soil P fractions and soil C pools (Table 4.11) revealed highly significant positive correlation. Except humic bound inorganic P, all the P fractions were significantly correlated with soil C pools. This shows that soil organic matter under different treatments had significant influence on P mineralization process and governing the existence of P among different fractions. This indicates that several P containing organic compounds dominate the soils and on mineralization will be available to crops. Similar information has earlier reported by Devra *et al* (2014).

Farmyard manure and rock phosphate application improved soil properties to a greater extent than their individual applications, indicating the need for combined use of FYM and RP in these alluvial soils.

Table 4.10 Correlation matrix depicting relationship among different soil carbon pools and soil properties

Soil property	SOC	KMnO ₄ -C	WEOC	HWSC	TOC	Av. P	Av. K	MBC	NH ₄ ⁺ -N	NO ₃ ⁻ -N
SOC										
KMnO ₄ -C	0.97**									
WEOC	1.0**	0.97**								
HWSC	0.99**	0.98**	0.99**							
TOC	0.99**	0.98**	0.99**	0.99**						
Av. P	0.99**	0.98**	0.99**	0.99**	0.99**					
Av. K	0.93**	0.92*	0.93**	0.94**	0.92**	0.93**				
MBC	0.99**	0.95**	0.99**	0.99**	0.99**	0.98**	0.95**			
NH ₄ ⁺ -N	0.96**	0.98**	0.96**	0.97**	0.97**	0.97**	0.88*	0.95**		
NO ₃ ⁻ -N	0.98**	0.98**	0.98**	0.99**	0.99**	0.98**	0.95**	0.98**	0.98**	

*Correlation is significant at $p < 0.05$ level (2-tailed)**Correlation is significant at $p < 0.01$ level (2-tailed)**Table 4.11 Correlation matrix depicting relationship between soil phosphorus fractions and carbon pools in a soil plough depth (0-15 cm)**

Soil carbon pool	Soil phosphorus pools														
	H ₂ O-Pi [*]	H ₂ O-Po [*]	Ca-EDTA-Pi [†]	Ca-EDTA-Po [†]	Na-EDTA-Pi [‡]	Na-EDTA-Po [‡]	H ₂ SO ₄ -Po [‡]	C _T TCA-Po [▲]	H _T TCA-Po [▼]	NaOH-Pi [►]	NaOH-Po [►]	Res-P [◄]	TPo [★]	TPi [♥]	Total P
WEOC	0.99**	0.98**	0.97**	0.97**	0.97**	0.93**	0.99**	0.95**	0.97**	0.75	0.98**	0.90*	0.97**	0.99**	0.98**
HWSC	0.99**	0.98**	0.97**	0.97**	0.97**	0.92**	0.99**	0.96**	0.96**	0.74	0.98**	0.92**	0.97**	0.99**	0.98**
MBC	0.98**	0.96**	0.96**	0.97**	0.96**	0.91*	0.99**	0.93**	0.95**	0.71	0.98**	0.90*	0.95**	0.99**	0.96**
KMnO ₄ -C	0.98**	0.97**	0.99**	0.96**	0.98**	0.90*	0.96**	0.97**	0.94**	0.79	0.95**	0.96**	0.98**	0.98**	0.98**
SOC	0.98**	0.97**	0.97**	0.97**	0.97**	0.93**	0.99**	0.95**	0.97**	0.75	0.98**	0.91*	0.97**	0.99**	0.98**
TOC	0.99**	0.98**	0.98**	0.96**	0.98**	0.94**	0.99**	0.97**	0.97**	0.77	0.97**	0.92**	0.98**	0.99**	0.99**

^{*}H₂O-Pi/Po=Water soluble inorganic and organic P, [†]Ca-EDTA-Pi/Po=Iron associated inorganic and organic P, [‡]Na-EDTA-Pi/Po=Calcium-aluminium associated inorganic and organic P, [‡]H₂SO₄-Po=Acid soluble organic P, [▲]C_TTCA-Po=Sugar bound organic P, [▼]H_TTCA-Po=Nucleic acid organic P and polyphosphate, [►]NaOH-Pi/Po=Humic bound inorganic and organic P, [◄]Res-P=Residual P, [★]TPo= organic P, [♥]TPi= inorganic P

*Correlation is significant at $p < 0.05$ level (2-tailed)**Correlation is significant at $p < 0.01$ level (2-tailed)

4.2 Effect of nutrient management practices on soil phosphorus and carbon fractions under basmati-wheat cropping system

Effect of inorganic and organic fertilizers application in basmati-wheat sequence was studied on general soil properties, soil P fractions and labile pools of soil organic carbon (SOC).

4.2.1 General soil properties

4.2.1.1 Soil reaction and electrical conductivity

Soil pH was 7.01-7.04 in the surface (0-7.5 cm) soil and 7.10-7.13 in the subsurface (7.5-15 cm) soil. Irrespective of the treatment, soil pH increased slightly with soil depth, and ranged between 7.14 and 7.21 at the lower depths (Table 4.12). Soil electrical conductivity ranged between 0.17 and 0.20 dS m⁻¹ in the surface and subsurface layers, respectively. Under all the treatments soil EC decreased with depth and ranged between 0.09 and 0.17 dS m⁻¹ at the lower depth (Table 4.12). Application of NPK, NPK plus FYM (INM) and organic sources viz. FYM, RSC and VC did not influence soil pH and EC. Several studies have reported increase in soil pH and decrease in EC with depth (Bhat 2013, Dhaliwal 2014 and Yadav 2014). The increase in pH with depth may be attributed to i) leaching of bases from the surface to lower layers. ii) decrease in SOC concentration with depth (Singh *et al* 2008, Kumar and Singh 2010) and iii) decrease in oxidation of ammonium to nitrate (Schoenau 2006). The decrease in EC with depth shows decrease in salt content of the soil. The results on pH and EC show that the experimental soil was free from acidity/alkalinity and salinity problems.

Table 4.12 Effect of nutrient management practices on soil pH and EC (dS m⁻¹) at different soil depths under basmati -wheat cropping

Treatment	pH				EC			
	Depth (cm)							
	0-7.5	7.5-15	15-30	30-60	0-7.5	7.5-15	15-30	30-60
CK	7.04 ^a	7.13 ^a	7.17 ^a	7.21 ^a	0.20 ^a	0.19 ^a	0.16 ^a	0.12 ^a
NPK	7.03 ^a	7.10 ^a	7.16 ^a	7.19 ^a	0.18 ^a	0.17 ^a	0.15 ^a	0.11 ^a
INM [#]	7.03 ^a	7.11 ^a	7.14 ^a	7.20 ^a	0.19 ^a	0.18 ^a	0.14 ^a	0.09 ^a
FYM [†]	7.02 ^a	7.12 ^a	7.15 ^a	7.18 ^a	0.18 ^a	0.19 ^a	0.16 ^a	0.11 ^a
RSC ^Δ	7.01 ^a	7.11 ^a	7.14 ^a	7.19 ^a	0.17 ^a	0.16 ^a	0.15 ^a	0.10 ^a
VC [¶]	7.02 ^a	7.12 ^a	7.15 ^a	7.18 ^a	0.18 ^a	0.17 ^a	0.16 ^a	0.12 ^a

[#]INM=Integrated nutrient management, [†]FYM=Farm yard manure applied to supply 400 kg N ha⁻¹, ^ΔRSC=Rice straw compost applied to supply 400 kg N ha⁻¹, [¶]VC=Vermicompost applied to supply 400 kg N ha⁻¹ [Mean values in a column followed by same letter are not significantly different (p<0.05) by Duncan's multiple range test (DMRT)]

4.2.1.2 Ammonical and nitrate-N distribution

The NH₄⁺-N concentration ranged between 30 to 100 and 28 to 95mg N kg⁻¹ soil in 0-7.5 and 7.5-15 cm soil depth, respectively (Table 4.13, Figure 4.14). In 0-7.5 cm soil, NH₄⁺-N concentration was significantly lower (30 mg N kg⁻¹) in the absolute control and increased by 90% with NPK application. The NH₄⁺-N concentration increased by 75% in plots receiving NPK plus FYM (INM) compared to plots

receiving NPK alone. The NH_4^+ -N concentration also increased significantly in plots amended with organic sources viz. FYM, RSC and VC compared to plots amended with NPK, however, it was significantly lower than the plots amended with NPK plus FYM (INM) (Table 4.13). In sub- surface soil (7.5-15 cm), effect of different treatments was similar to that observed in surface soil (0-7.5 cm). At 15-30 and 30-60 cm soil depth, NH_4^+ -N concentration ranged between 22.2 to 53.6 and 15.9 to 47.8 mg N kg^{-1} , respectively. At both the soil depths (15-30 and 30-60 cm), NH_4^+ -N concentration was significantly lower in the CK compared to all other treatments. Application of NPK, RSC and VC exhibited similar NH_4^+ -N concentration. Plots amended with either FYM alone or in conjunction with NPK did not differ significantly (Figure 4.14).

The NO_3^- -N concentration ranged between 13.6 and 47.4 and 10.5 and 36.9 mg N kg^{-1} soil in 0-7.5 and 7.5-15 cm soil depth, respectively (Table 4.13). In 0-7.5 cm soil, NO_3^- -N concentration was significantly higher (20.2 mg N kg^{-1}) in plots receiving NPK compared with unfertilized plots (13.6 mg N kg^{-1}). The NO_3^- -N concentration increased by 134.6% in plots receiving NPK plus FYM (INM) compared to plots receiving NPK alone. The NO_3^- -N concentration also increased significantly in plots amended with organic manures (FYM, RSC, VC) compared to plots amended with NPK alone. The comparison of organic manure treated plots revealed that NH_4^+ -N and NO_3^- -N was significantly higher in soil receiving 400 kg N ha^{-1} through FYM, followed by RSC and the lowest in VC. In 7.5-15 cm soil Plots amended with either RSC or VC showed similar effect on NO_3^- -N concentration. Effect of NPK, FYM and INM on NO_3^- -N concentration was similar to those observed in 0-7.5 cm soil. At 15-30 and 30-60 cm soil depth, NO_3^- -N concentration ranged between 9.3 and 24.1 and 8.6 and 18.3 mg N kg^{-1} , respectively. In 15-30 cm soil depth, NO_3^- -N concentration increased significantly with application of either FYM alone or in combination with NPK compared to NPK alone and unfertilized plots. Plots amended with FYM, INM, RSC and VC showed significant increase in NO_3^- -N concentration compared to CK in 30-60 cm soil depth (Figure 4.14). The profile distribution of NH_4^+ -N and NO_3^- -N concentration is shown in figure 4.14. Evidently, the concentration of NH_4^+ -N and NO_3^- -N was higher in the surface soil, and it decreased with depth, under all the treatments. Significant increase in NH_4^+ -N concentration might be due to the favourable conditions for microbial activity and increase in N mineralization in the presence of FYM (Dinesh and Dubey 1999, Zhang *et al* 2009). Application of organic sources accelerates nitrification and amonification leading to greater release of mineral N (Kumar *et al* 1988, Jagtap *et al* 2007, Vimlesh and Giri 2009). Increase in soil mineral N with manure application either alone or in conjunction with fertilizers have has been reported in several studies (Tabassum *et al* 2010).

4.2.1.3 Available phosphorus and potassium

Available P concentration in soil under different treatments ranged between 5.7 and 11.4 mg P kg^{-1} in 0-7.5 cm soil depth and between 5.4 and 10.7 mg P kg^{-1} in 7.5-15 cm soil depth, respectively (Table

4.14, Figure 4.15). Available P concentration increased significantly with application of inorganic and organic fertilizers compared to unamended control. The lowest concentration of P was observed in unamended control and the highest in INM plots. While recommended rate of NPK application increased available P by 72-75% at two surface soil depths over control, the adoption of INM increased P concentration by 98-100%. The three organic sources viz. FYM, RSC and VC did not differ significantly from each other as well as from NPK and INM treatments (Table 4.14). Pizzeghello *et al* (2011) has reported 6-fold increase in available P concentration in FYM amended soils compared to unamended soils. Application of inorganic and organic fertilizer significantly improved available P in soil (Erich *et al* 2002, Pizzeghello *et al* 2011, Stroia *et al* 2013). Manure alone has a low potential of supplying the required P demand for plant growth though it enhances P availability (Nyambega *et al* 2014). Favourable effect of INM practices on available P has earlier been reported by Bhattacharyya *et al* (2008). Benbi and Biswas (1999) reported that the application of FYM in conjunction with NPK for 32 years in maize-wheat sequence led to greater accumulation of available P compared to NPK alone. Significant increase in concentration of available P in soils receiving organic manures either alone or in combination with inorganic fertilizers may be ascribed to addition of P through these, mineralization of organic P, decreased rate of P sorption and solubilization of native-P (Sharpley *et al* 1984, Sui and Thompson 2000, Gaston *et al* 2003, Singh *et al* 2010). The profile distribution of available P concentration in soils showed that it decreased with depth. It ranged between 4.64 and 6.46 mg P kg⁻¹ soil (Figure 4.15). Available P concentration decreased sharply below 15 cm soil depth, and all the treatments exhibited similar available P concentration. Higher available P concentration in the plough layer could be due to the application/mixing of fertilizer-P and organic manures viz. FYM, RSC and VC in the upper 0-15 cm soil depth. Further, a greater microbial activity in the 0-15 cm soil depth results in higher rates of P mineralization in the plots receiving organic manures (Stevenson 1982, Dash *et al* 2014).

Table 4.13 Effect of nutrient management practices on NH₄⁺-N, NO₃⁻-N and mineral N concentration (mg P kg⁻¹) in the surface (0-7.5 cm) and subsurface soil (7.5-15 cm) under basmati-wheat cropping

Treatment	NH ₄ ⁺ -N		NO ₃ ⁻ -N		Mineral N	
	0-7.5 cm	7.5-15 cm	0-7.5 cm	7.5-15 cm	0-7.5 cm	7.5-15 cm
CK	30 ^{a†}	28 ^a	13.6 ^a	10.5 ^a	43.6 ^a	38.5 ^a
NPK	57 ^b	52 ^b	20.2 ^b	17.5 ^b	77.2 ^b	69.5 ^b
INM [#]	100 ^f	95 ^f	47.4 ^f	36.9 ^e	147.4 ^f	131.9 ^f
FYM [†]	84 ^e	77 ^e	39.6 ^e	31.1 ^d	123.6 ^e	108.1 ^e
RSC ^Δ	73 ^d	66 ^d	32.7 ^d	25.7 ^c	105.7 ^d	91.7 ^d
VC [¶]	63 ^c	58 ^c	26.4 ^c	20.1 ^{bc}	89.4 ^c	78.1 ^c

[#]INM=Integrated nutrient management, [†]FYM=Farm yard manure applied to supply 400 kg N ha⁻¹, ^ΔRSC=Rice straw compost applied to supply 400 kg N ha⁻¹, [¶]VC=Vermicompost applied to supply 400 kg N ha⁻¹ [†Mean values within a column followed by different letters differ significantly ($p < 0.05$) by Duncan's multiple range test (DMRT)]

Table 4.14 Effect of nutrient management practices on available P and available K concentration in the surface (0-7.5 cm) and subsurface (7.5-15 cm) soil under basmati-wheat cropping

Treatment	Available P (mg kg ⁻¹)		Available K (mg kg ⁻¹)	
	0-7.5 cm	7.5-15 cm	0-7.5 cm	7.5-15 cm
CK	5.7 ^a	5.4 ^a	55 ^a	47 ^a
NPK	10.0 ^b	9.3 ^b	86 ^{cd}	70 ^{cd}
INM [#]	11.4 ^c	10.7 ^c	108 ^e	94 ^e
FYM [†]	10.7 ^{bc}	10.0 ^{bc}	83 ^{bc}	63 ^{bc}
RSC ^Δ	10.4 ^{bc}	9.6 ^{bc}	91 ^d	77 ^d
VC [¶]	10.2 ^{bc}	9.5 ^{bc}	77 ^b	57 ^b

[#]INM=Integrated nutrient management, [†]FYM=Farm yard manure applied to supply 400 kg N ha⁻¹, ^ΔRSC=Rice straw compost applied to supply 400 kg N ha⁻¹, [¶]VC=Vermicompost applied to supply 400 kg N ha⁻¹ [[†]Mean values within a column followed by different letters differ significantly ($p < 0.05$) by Duncan's multiple range test (DMRT)]

Available K concentration ranged between 55 and 108 mg K kg⁻¹ in 0-7.5 cm soil depth and between 47 and 94 mg K kg⁻¹ soil in 7.5-15 cm soil depth, respectively (Table 4.14). Application of inorganic fertilizer (NPK) significantly increased the concentration of available K by 56.4 and 48.9% at 0-7.5 and 7.5-15 cm soil depth, respectively, over unfertilized plots. The INM resulted in further significant improvement in available K concentration by 25.6 and 34.3%, respectively over NPK treatment. Application of FYM and RSC did not differ significantly from NPK application but plots amended with RSC showed significantly higher available K concentration compared to FYM and VC amended plots. Available K responded significantly to the nature of applied organic manure viz. FYM, RSC and VC. In subsurface soil (7.5-15 cm), effect of different treatments was similar to those observed in 0-7.5 cm soil depth. Several studies (Singh *et al* 2001, Yaduvanshi 2001, Jatav *et al* 2010, Venkatakrishnan and Ravichandran 2012) have reported higher available K in soils under long-term fertilizers, manures application and INM. At 15-30 cm soil depth, available K concentration ranged between 31.7 to 47.5 mg K kg⁻¹ soil and adoption of INM significantly increased available K concentration compared to application of NPK alone and CK. Application of RSC showed significant increase in available K concentration compared to CK. The profile distribution of available K showed that its concentration decreased with depth particularly below 15 cm soil depth (Figure 4.15). Available K concentration ranged between 25 and 26.7 mg K kg⁻¹ soil in 30-60 cm soil depth and all the treatments showed similar available K concentration in soil. Decrease in available K concentration with depth suggests that K movement did not occur in any treatment. The build-up of soil available K due to green manuring or organics application may be ascribed to the addition of K through these sources and the solubilizing action of certain organic acids produced during FYM decomposition and its greater capacity to hold K in the available form. Singh *et al* (2008) observed increase in available K in soils, which were dressed with FYM, vermicompost, green manure and rice residue.

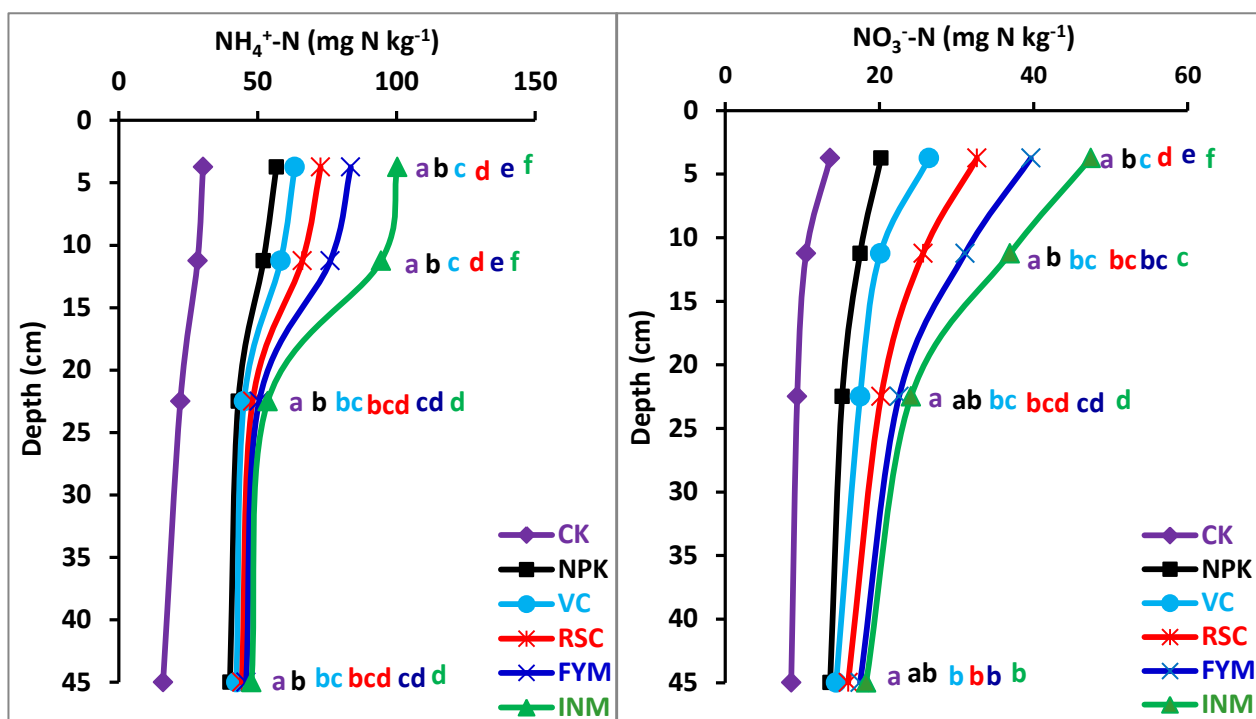


Fig 4.14 Effect of different treatments on profile distribution of NH₄⁺-N and NO₃⁻-N concentration in soil under basmati-wheat cropping [Mean values for a soil property at a given depth followed by different letters differ significantly ($p < 0.05$) by Duncan's multiple range test (DMRT)]

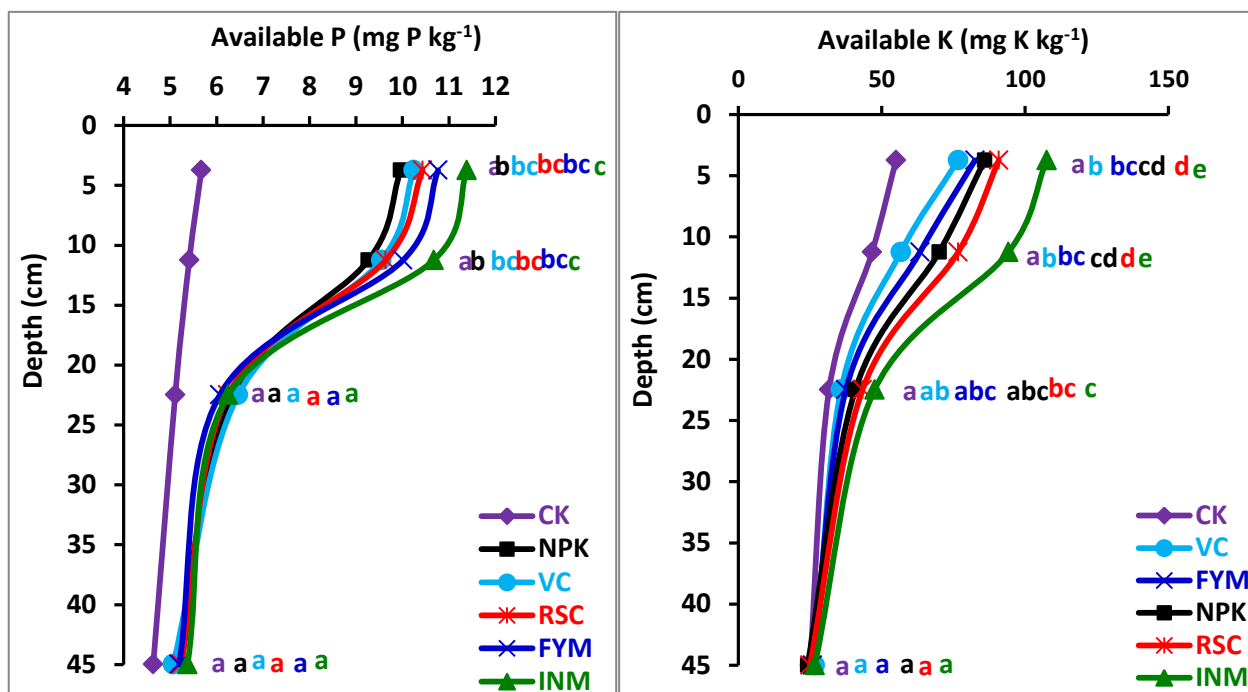


Fig 4.15 Effect of different treatments on profile distribution of available P and available K concentration in soil under basmati-wheat cropping [Mean values for a soil property at a given depth followed by different letters differ significantly ($p < 0.05$) by Duncan's multiple range test (DMRT)]

4.2.1.4 Soil bulk density

The data on effect of different nutrient management practices on soil bulk density (D_b) are shown in figure 4.16. In surface soil (0-7.5 cm), the lowest D_b (1.43 Mg m^{-3}) was observed in plots receiving FYM alone and the highest (1.54 Mg m^{-3}) in unamended control. Application of FYM and VC significantly decreased soil D_b compared to NPK application and unamended control. Soil D_b did not differ significantly in plots receiving FYM, VC, RSC and FYM plus NPK (INM). Soil D_b ranged between 1.46 to 1.59 Mg m^{-3} in 7.5-15 cm depth and it decreased significantly in FYM, VC, RSC and FYM plus NPK (INM) amended plots compared to NPK amended plots. Soil D_b in NPK treated plots was similar to CK. Soil D_b increased with depth and ranged between 1.66 and 1.71 in lower soil layer. It may be due to decrease in SOC with depth. Several researchers have reported decrease in soil D_b with NPK, FYM and NPK+FYM application (Hati *et al* 2008, Nayak *et al* 2012, Gami *et al* 2009). Application of manure increases soil porosity leading to better soil aggregation (Benbi and Senapati 2010, Selvi *et al* 2005), which tends to decrease soil D_b (Halvorson *et al* 1999).

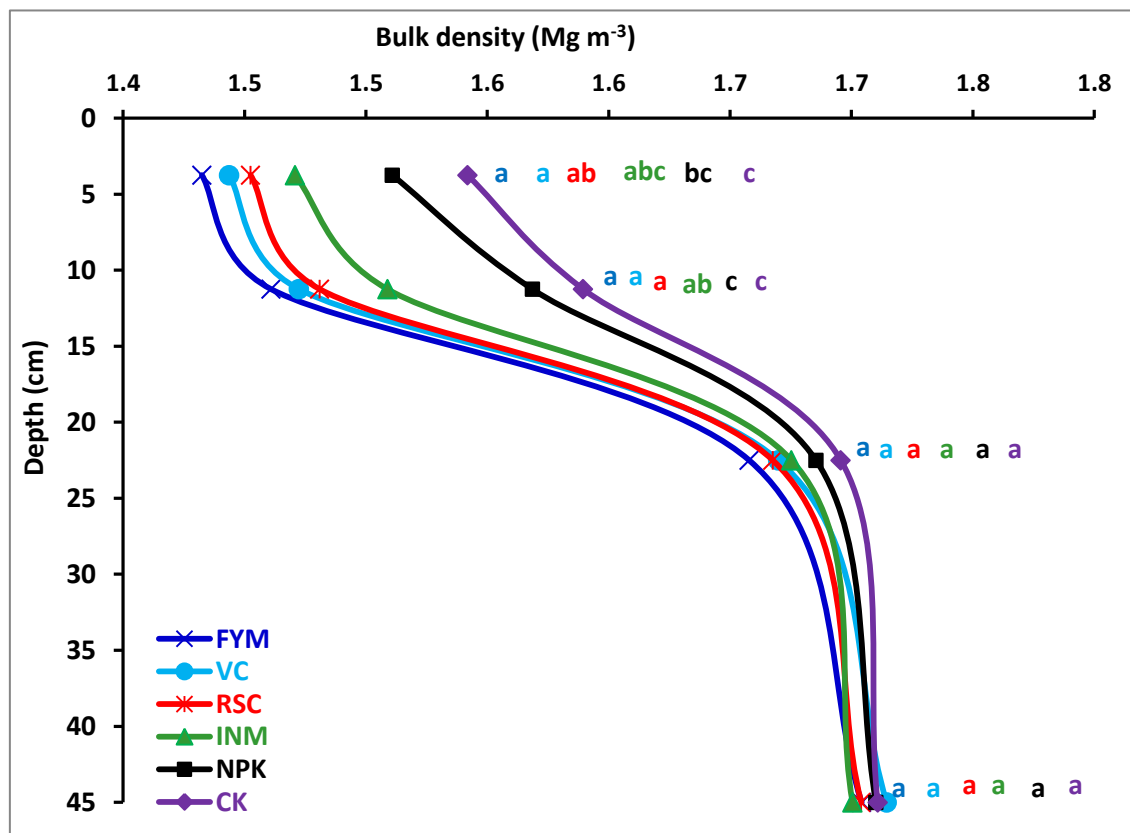


Fig 4.16 Effect of different treatments on bulk density (D_b) at different soil depths under basmati-wheat cropping [Mean values for a soil property at a given depth followed by different letters differ significantly ($p < 0.05$) by Duncan's multiple range test (DMRT)]

4.2.1.5 Soil porosity

The effect of different treatments on soil porosity is shown in figure 4.17. Soil porosity ranged between 41.8 and 45.9 and 40.0 and 44.9% in 0-7.5 and 7.5 -15 cm soil depth, respectively. Application of FYM, RSC and VC significantly increased soil porosity compared to CK. Soil porosity in plots amended either with NPK alone or in combination with FYM (INM) did not differ significantly compared to plots amended with VC. In 7.5-15 cm soil, effect of different treatments was similar to that observed in 0-7.5 cm soil. Evidently, soil porosity decreased with depth and ranged between 35.3 to 36.0% in lower soil layers, though all treatments exhibited similar soil porosity. A smaller change in soil porosity at lower soil depths could be due to the least disturbance of soil, compared to the plough layer. The change in soil porosity with manure application reflects the change in soil D_b due to the addition of more fibrous material. Lee *et al* (2009) reported significant increase in soil porosity with NPK and compost application compared with unfertilized soils. Dudal and Deckers (1993) reported that application of manure improves soil aeration.

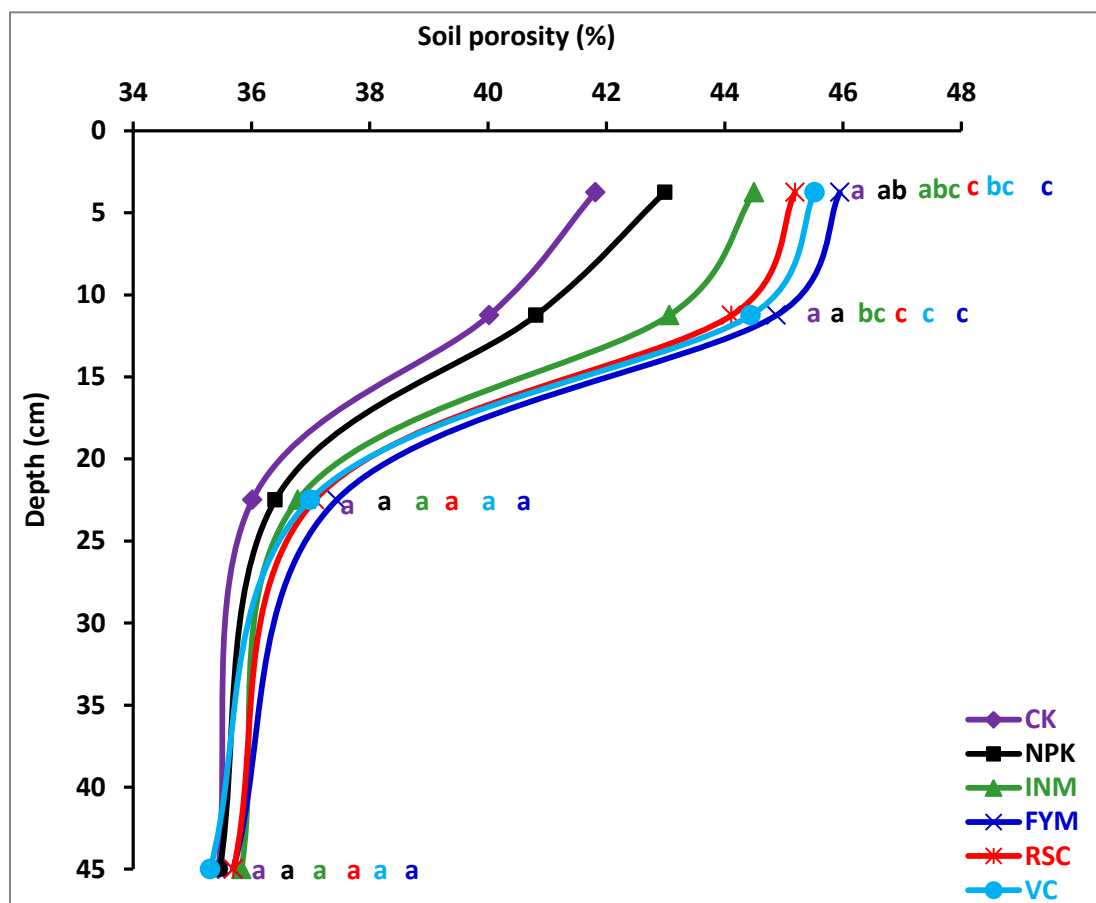


Fig 4.17 Effect of different treatments on soil porosity at different soil depths under basmati-wheat cropping [Mean values for a soil property at a given depth followed by different letters differ significantly ($p < 0.05$) by Duncan's multiple range test (DMRT)]

4.2.2 Soil phosphorus fractions

Total P ranged between 355 and 921 mg P kg⁻¹ in 0-7.5 cm depth, 320 and 765 mg P kg⁻¹ in 7.5-15 cm depth and 305 to 472 mg P kg⁻¹ in 15-30 cm depth under different treatments (Table 4.15). Inorganic P constituted 74.8 to 90.5 percent of total P and organic P constituted 8.0 to 23.9 % of total P at different soil depths. Inorganic, organic and total P concentrations were similar in range to that reported earlier for the soils in this region (Aulakh *et al* 2003). This indicates that unused manure and fertilizer P is mainly inorganically bound (Gudmundsson *et al* 2014). In surface soil (0-7.5 cm), application of NPK either alone or along with FYM significantly increased the concentration of inorganic, organic and total P compared to unfertilized soils. Plots amended with organic manure alone showed significantly higher concentration of inorganic, organic and total P compared to plots amended with FYM plus NPK (INM). Application of FYM, RSC and VC exhibited similar inorganic and total P concentration while organic P concentration was significantly higher in plots amended with VC compared to plots amended with RSC. It may be due to addition of higher amount of P through VC. In subsurface soil (7.5-15 cm), effect of different treatment on organic and total P concentration was similar to those observed in 0-7.5 cm depth though inorganic P concentration did not differ significantly in plots amended with manure either alone or in conjunction with inorganic fertilizers (Table 4.15). In 15-30 cm depth, application of NPK alone or in conjunction with FYM significantly increased the inorganic and total P concentration compared to CK. Plots receiving RSC, VC, FYM alone or FYM plus NPK showed similar total P concentration. Application of FYM alone or FYM plus NPK (INM) exhibited similar effect on inorganic P concentration but in INM plots inorganic P concentration was significantly higher than RSC and VC amended plots. Organic P concentration in plots treated with NPK alone did not differ significantly with CK, however, application of organic manure alone or in combination with inorganic fertilizers showed significant effect on organic P. Averaged across 0-7.5 and 7.5-15 cm soil depths, organic P, inorganic P and total P concentration in the plough layer (0-15 cm) was the highest under VC and the lowest in unfertilized control (Figure 4.18).

In surface soil (0-7.5 cm), water soluble inorganic and organic P concentrations ranged between 0.73 and 2.06 and between 0.59 and 1.78 mg P kg⁻¹, respectively. Water soluble inorganic and organic P concentration significantly increased with application of inorganic and organic fertilizers compared to unamended control. Iron associated inorganic and organic P concentration ranged between 45.8 and 125.3 and 2.65 and 22.8 mg P kg⁻¹, respectively. Application of NPK significantly increased iron associated inorganic P concentration compared to CK and adoption of INM or application of organic manure showed significant increase in iron associated inorganic and organic P concentration. Calcium-aluminium associated inorganic and organic P concentration ranged between 238 and 537 and 4.87 and 44.7 mg P kg⁻¹, respectively. Plots receiving either organic or inorganic fertilizers showed significant increase in calcium-

aluminium associated inorganic P concentration but organic sources did not differ significantly. Calcium-aluminium associated organic P concentration increased with manure application. Acid soluble organic P ranged between 3.17 and 15.5 mg P kg⁻¹ and increased with the application of manure and fertilizers. Sugar-bound organic P and nucleic acid-organic P and polyphosphate concentration ranged between 3.21 and 17.9 and 1.58 and 6.17 mg P kg⁻¹. Plots treated with NPK showed significant increase in sugar bound organic P and nucleic acid organic P and polyphosphate concentration. Plots amended with VC showed significantly higher concentration of these fractions. Humic-bound inorganic and organic P concentration ranged between 36.5 and 58.6 and 12.5 and 106.7 mg P kg⁻¹ soil, respectively.

In subsurface soil (7.5-15 cm), water soluble inorganic and organic P concentration ranged between 0.60 to 1.96 and between 0.46 to 1.62 mg P kg⁻¹, respectively. Water soluble inorganic and organic P concentration increased significantly with the application of inorganic and organic fertilizers compared to unamended control. Iron associated inorganic and organic P concentration ranged between 40.7 and 104.2 and 2.54 and 18 mg P kg⁻¹, respectively. Effect of different nutrient management practices was similar to that observed in 0-7.5 cm soil depth. Calcium-aluminium associated inorganic and organic P concentration ranged between 214 to 458 and 4.65 to 41.5 mg P kg⁻¹, respectively. Plots receiving either organic or inorganic fertilizers showed significant increase in calcium-aluminium associated inorganic P concentration. Calcium-aluminium associated organic P concentration increased with manure application. Acid soluble organic P ranged between 2.81 and 13.8 mg P kg⁻¹ and increased with the application of inorganic or organic sources of nutrient. Sugar-bound organic P and nucleic acid-organic P and polyphosphate concentration ranged between 2.68 to 13.7 and 1.31 to 4.94 mg P kg⁻¹, respectively. Plots treated with NPK showed significant increase in sugar-bound organic P and nucleic acid-organic P and polyphosphate concentration, while the magnitude was higher in plots amended with application of manure alone followed by FYM plus NPK (INM). Plots amended with VC showed significantly higher concentration of these fractions. Humic-bound inorganic and organic P concentration ranged between 33.8 to 48.2 and 11.2 to 88.9 mg P kg⁻¹ soil, respectively.

In 15-30 cm depth, water soluble inorganic and organic P concentration ranged between 0.53 to 1.39 and between 0.33 to 1.09 mg P kg⁻¹, respectively. Water soluble inorganic and organic P concentration significantly increased with application of inorganic and organic fertilizers compared to unamended control. Iron associated inorganic and organic P concentration ranged between 39.4 to 73.7 and 2.43 to 11 mg P kg⁻¹, respectively. Plots amended with inorganic fertilizers showed significant increase in iron-associated inorganic P concentration compared to unamended control. Further, adoption of INM and application of organic manure viz. FYM, RSC and VC led to significant increase compared to inorganically treated plots. Iron-associated inorganic P concentration increased significantly with organic manures application. Calcium-aluminium associated inorganic and organic P concentration ranged between 207 to 283 and 4.46 to

23.6 mg P kg⁻¹, respectively. Plots receiving either organic or inorganic fertilizers showed significant increase in Calcium-aluminium associated inorganic P concentration. Calcium-aluminium associated organic P concentration increased significantly with manure application. Acid-soluble organic P ranged between 2.73 and 8.80 mg P kg⁻¹ and increased significantly in organically treated plots as well as in INM treatments. Sugar-bound organic P and nucleic acid-organic P and polyphosphate concentration ranged between 2.70 to 8.22 and 1.23 to 2.95 mg P kg⁻¹, respectively. Plots treated with NPK showed significant increase in sugar-bound organic P and nucleic acid-organic P and polyphosphate concentration. Plots amended with VC showed significantly higher concentration of these fractions compared to RSC or VC application. Humic-bound inorganic and organic P concentration ranged between 28.7 to 32.6 and 10.5 to 45.9 mg P kg⁻¹ soil, respectively. Adoption of INM significantly increased these fractions compared to CK. Plots amended with organic manures showed significant increase in humic-bound organic P concentration compared to INM.

Irrespective of treatment and soil depth, relative abundance of different inorganic P fractions in these soils followed the order calcium-aluminium associated inorganic P > iron associated inorganic P > humic bound inorganic P > water soluble inorganic P. The data revealed that calcium-aluminium associated inorganic P fraction alone represented 74.5% of inorganic P (Table 4.15). Averaged across treatments, organic P concentration followed the order humic bound organic P > calcium-aluminium associated organic P > sugar-bound organic P > iron-associated organic P > acid-soluble organic P > nucleic acid-organic P and polyphosphate > water-soluble organic P. Humic-bound organic P and calcium-aluminium associated organic P fractions constituted major proportion (68.0%) of organic P (Table 4.15). Higher proportion of calcium associated inorganic P may be attributed to the existence of primary calcium P minerals, indicating their weak weathering nature (Jalali and Ranjbar 2010, Adhami *et al* 2014). In weakly weathered soils, high inorganic P (73 to 98% of total P) concentration has earlier been reported by Floate (1965). Several studies (Boschetti *et al* 2009, Aulakh *et al* 2003) reported that in less weathered and subtropical soils, the excess P from fertilizer tends to accumulate as calcium P, whereas, Alleoni *et al* (2012) reported predominant fraction of P was iron P, followed by aluminium P and calcium P. Large additions of manure increased soil P fractions and led to shift in P chemistry and reaction products from aluminium and iron dominated product to calcium minerals (Sharpley *et al* 2004). Takahashi and Anwar (2006) evaluated soil P fractions after 23 years of annual fertilizer application to the soil and reported with fertilizers P application, soil total P (calcium P +aluminium P +iron P) increased due to unutilized P transformation mainly to calcium P, aluminium P and iron P. Several studies have reported (Park *et al* 2004, Sihag *et al* 2005, Boschetti *et al* 2009, Huang *et al* 2011) significant increase in calcium-P, aluminium-P and iron-P with P application through manure or fertilizers.

Significant improvement in the concentration of organic P fractions with the application of organic manures viz. FYM, RSC and VC is because of the existence of organic-P compounds with rapidly to slowly

decomposable organic molecules, such as nucleic acids, phospholipids, sugar phosphates, inositol phosphates, and recalcitrant humic substances (Hedley *et al* 1982). The release of organic acids during the decomposition of organic matter solubilize native as well as applied P and thus governs the dynamics of P in soils (Wang *et al* 1967, Singh *et al* 2010). Wright and Reddy (2008) reported that decomposition of organic P, as found in humic and fulvic acids, and lignin-containing residual fractions, depends on chemical composition and heterotrophic microbial activity. Increase in organic P fractions might buffer available P and inorganic P fractions to a large extent through mineralization (Nwoke *et al* 2004). Favourable effects of manure and fertilizer application on different inorganic P fractions may be due to increase in SOC, root biomass and decrease in P sorption or P transforms mainly into inorganic P fractions in these soils (Song *et al* 2007, Tang and Armstrong 2008). There are several reports that applications of organic (Ballamy *et al* 1995, Chen *et al* 2003, Blair *et al* 2006, Sigua *et al* 2009) and inorganic fertilizers (Ma *et al* 2011, Liang *et al* 2014) or adoption of INM (Banger *et al* 2009, Benbi and Senapati 2010, Liang *et al* 2014) lead to increase in SOC. During decomposition of SOM organic acids are released, which mobilize P by ligand exchange, ligand-induced dissolution and complexation of cations bound to P such as iron, aluminium and calcium, releasing phosphate molecules into soil solution which can be used by plants (Dhillon and Dev 1986, Lambers *et al* 2006, Zhou *et al* 2009). Organic anions mobilize residual/native P from soil (Sarora and Vig 1992) and/or may cover the soil surface (Stevenson 1982) consequently, improve soil inorganic and organic P fractions (Ranatunga *et al* 2013, Sharma and Verma 2000) and P availability in soils (Majumdar *et al* 2007, Boschetti *et al* 2009). Because strongly sorbed non-labile P is composed of less soluble P pools viz. calcium-P, iron-P and aluminium-P that gradually become plant available over many cropping seasons, and is only slowly released and made available to plants (Buresh 1997). Beneficial effect of inorganic and organic fertilizers application on different P fractions in lower soil layer may be due to 1) less mining of P from lower layers because of greater application at the surface layer 2) mixing of P during cultivation and 3) movement of P from organic sources during crop growth period.

4.2.3 Phosphorus stocks in soils

Phosphorus stocks in soils (0-7.5 and 7.5-15 cm) under different treatments are shown in figure 4.19. In surface soil (0-7.5 cm), total P stock ranged between 411 and 997 kg P ha⁻¹. Application of inorganic fertilizers increased total P stock by 14% compared to unfertilized plots. Adoption of INM showed significantly higher (72%) total P stock compared to NPK treated plots. Plots amended with manure viz. FYM, RSC and VC exhibited significant increase in total P stock compared to INM plots. Inorganic P stocks ranged between 371 to 775 kg P ha⁻¹ and the effect of different nutrient management practices was similar to that observed in 0-7.5 cm soil for total P stocks. Organic P stocks ranged between 33-234 kg P ha⁻¹. Plots receiving inorganic fertilizers showed significant increase in organic P stock by 24% compared to CK and

further, adoption of INM increased organic P stocks significantly by 78% compared to inorganic fertilized plots. Application of FYM, RSC and VC significantly increased organic P stocks by 126, 168 and 220% compared to INM treatment. Soil P stocks decreased with depth and total P stocks ranged between 381 to 845 kg P ha⁻¹ in subsurface soil (7.5-15 cm). Effect of different nutrient management practices on total P stocks was similar to those observed in 0-7.5 cm soil. Inorganic P stocks ranged between 345 to 659 kg P ha⁻¹. Similar to 0-7.5 cm soil layer, NPK and INM treatment showed significantly higher inorganic P stock compared to CK. Application of organic manure did not differ significantly with each other as well as from INM treatment. Organic P stocks ranged between 31 to 202 kg P ha⁻¹ and trends were same as observed in 0-7.5 cm depth (Figure 4.19). Increase in P stocks may be due to application of inorganic and organic fertilizers. Because, application of FYM and fertilizer P increases organic and inorganic P fractions in soil (Kolawole *et al* 2003, Devra *et al* 2014, Garg and Aulakh 2010, Ranatunga *et al* 2013) thus tends to increase different P stocks in soils (Jiao *et al* 2010, Costa *et al* 2014). Tiessen *et al* (1984) concluded that organic matter variations alter soil P transformation dynamics and its stocks. Increase in soil P stocks with fertilizer and manure applications has earlier reported by Holmes *et al* (2005), Gudmundsson *et al* 2014, Wright (2009).

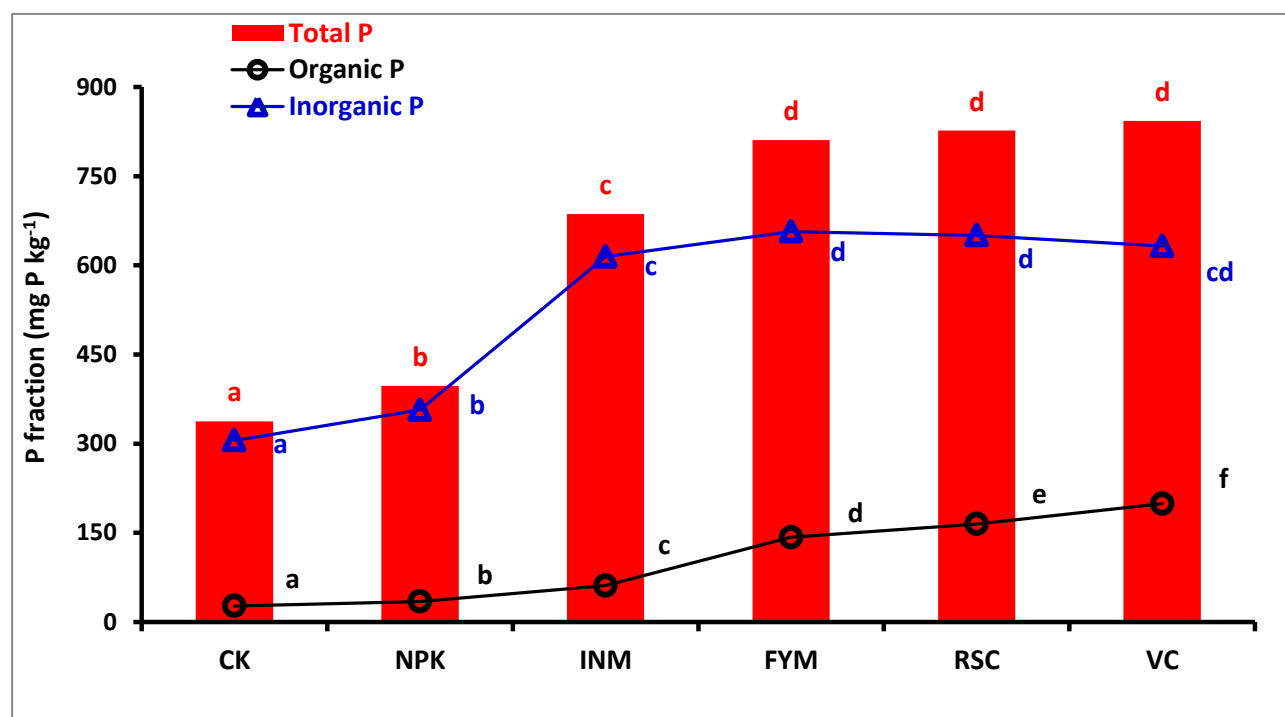


Fig 4.18 Effect of different treatments on the concentration of total P, inorganic P and organic P in plough layer (0-15 cm) under basmati-wheat cropping[Mean values for a soil property followed by different letters differ significantly ($p < 0.05$) by Duncan's multiple range test (DMRT)]

Table 4.15 Effect of nutrient management practices on inorganic (Pi) and organic (Po) P fractions (mg kg⁻¹) in different layers of soil profile under basmati-wheat cropping

Treatment	Inorganic P					Organic P									
	H ₂ O-Pi*	Ca-EDTA-Pi†	Na-EDTA-Pi‡	NaOH-Pi►	▼TPi	H ₂ O-Po*	Ca-EDTA-Po†	Na-EDTA-Po‡	H ₂ SO ₄ -Po§	cTCA-Po▲	hTCA-Po▼	NaOH-Po►	▲TPo	Res-P◄	Total P
0-7.5 cm soil depth															
CK	0.73 ^a	45.8 ^a	238 ^a	36.5 ^a	321 ^a	0.59 ^a	2.65 ^a	4.87 ^a	3.17 ^a	3.21 ^a	1.58 ^a	12.5 ^a	28.5 ^a	5.54 ^a	355 ^a
NPK	1.06 ^b	57.1 ^b	276 ^b	36.8 ^a	371 ^b	0.82 ^b	2.95 ^a	6.20 ^a	3.69 ^b	6.11 ^b	2.21 ^b	14.3 ^a	36.3 ^b	6.30 ^b	414 ^b
INM [#]	2.30 ^e	117.5 ^c	480 ^c	58.6 ^c	658 ^c	1.68 ^c	5.40 ^b	8.82 ^b	7.30 ^c	10.96 ^c	4.19 ^c	27.7 ^b	66.1 ^c	11.1 ^c	735 ^c
FYM [†]	1.93 ^c	116.3 ^c	537 ^d	56.6 ^c	712 ^d	1.72 ^c	12.4 ^c	32.8 ^c	9.73 ^d	16.74 ^d	5.78 ^d	74.6 ^c	153.8 ^d	12.1 ^d	878 ^d
RSC ^Δ	2.06 ^d	120.8 ^d	532 ^d	56.2 ^c	711 ^d	1.72 ^c	16.2 ^d	40.7 ^d	12.5 ^e	17.0 ^d	5.78 ^d	86.0 ^d	179.9 ^e	12.9 ^e	904 ^d
VC [¶]	1.99 ^d	125.3 ^e	513 ^d	51.8 ^b	692 ^d	1.78 ^c	22.8 ^e	44.7 ^e	15.5 ^f	17.9 ^e	6.17 ^e	106.7 ^e	215.7 ^f	12.7 ^e	921 ^d
7.5-15 cm soil depth															
CK	0.60 ^a	40.7 ^a	214 ^a	33.8 ^a	290 ^a	0.46 ^a	2.54 ^a	4.65 ^a	2.81 ^a	2.68 ^a	1.31 ^a	11.2 ^a	25.6 ^a	4.75 ^a	320 ^a
NPK	0.86 ^b	50.2 ^b	255 ^b	35.7 ^a	342 ^b	0.82 ^b	2.70 ^a	5.35 ^a	3.35 ^b	5.57 ^b	1.88 ^b	12.9 ^a	32.5 ^b	5.90 ^b	380 ^b
INM [#]	1.96 ^e	104.2 ^c	417 ^c	47.4 ^b	571 ^c	1.35 ^c	4.69 ^b	7.99 ^b	5.67 ^c	8.81 ^c	3.29 ^c	24.2 ^b	56.0 ^c	9.90 ^c	637 ^c
FYM [†]	1.71 ^d	93.5 ^e	458 ^d	48.2 ^b	602 ^c	1.25 ^c	9.12 ^c	30.9 ^c	10.4 ^d	11.2 ^d	4.67 ^d	63.5 ^c	131.1 ^d	10.8 ^e	743 ^d
RSC ^Δ	1.76 ^d	98.1 ^d	442 ^{cd}	47.8 ^b	589 ^c	1.32 ^c	13.1 ^d	34.5 ^d	12.0 ^e	12.8 ^e	4.73 ^d	71.3 ^d	149.7 ^e	10.4 ^d	749 ^d
VC [¶]	1.52 ^c	103.0 ^e	424 ^c	43.9 ^b	572 ^c	1.62 ^d	18.0 ^e	41.5 ^e	13.8 ^f	13.7 ^f	4.94 ^e	88.9 ^e	182.5 ^f	10.3 ^d	765 ^d
15-30 cm soil depth															
CK	0.53 ^a	39.4 ^a	207 ^a	28.7 ^a	276 ^a	0.33 ^a	2.43 ^a	4.46 ^a	2.73 ^a	2.70 ^a	1.23 ^a	10.5 ^a	24.3 ^a	4.59 ^a	305 ^a
NPK	0.76 ^b	46.8 ^b	235 ^b	30.3 ^{ab}	313 ^b	0.63 ^b	2.52 ^a	4.83 ^a	2.73 ^a	5.09 ^b	1.50 ^b	11.3 ^a	28.6 ^a	5.66 ^b	347 ^b
INM [#]	1.39 ^e	73.7 ^e	291 ^d	32.6 ^b	399 ^d	0.79 ^c	3.28 ^a	5.61 ^a	4.03 ^b	6.22 ^c	2.13 ^c	16.7 ^b	38.7 ^b	6.83 ^c	444 ^c
FYM [†]	1.09 ^d	63.4 ^{cd}	283 ^{cd}	31.4 ^{ab}	379 ^{cd}	0.63 ^b	6.93 ^b	23.1 ^b	6.38 ^c	6.83 ^d	2.69 ^d	38.9 ^c	85.4 ^c	7.08 ^d	472 ^c
RSC ^Δ	1.02 ^{cd}	60.6 ^c	275 ^{cd}	30.7 ^{ab}	368 ^c	0.89 ^c	7.94 ^b	22.3 ^b	7.43 ^d	7.75 ^e	2.81 ^{de}	43.2 ^d	92.3 ^d	7.33 ^d	467 ^c
VC [¶]	0.96 ^c	64.4 ^d	263 ^c	29.1 ^a	358 ^c	1.09 ^d	11.0 ^c	23.6 ^b	8.80 ^e	8.22 ^f	2.95 ^e	45.9 ^d	101.6 ^e	7.33 ^d	467 ^c

*H₂O-Pi/Po=Water soluble inorganic and organic P, †Ca-EDTA-Pi/Po=Iron associated inorganic and organic P, ‡Na-EDTA-Pi/Po=Calcium-aluminium associated inorganic and organic P, §H₂SO₄-Po=Acid soluble organic P, ▲cTCA-Po=Sugar bound organic P, ▼hTCA-Po=Nucleic acid organic P and polyphosphate, ►NaOH-Pi/Po=Humic bound inorganic and organic P, ◄Res-P=Residual P, ▲TPo=Organic P, ▼TPi=Inorganic P

[#]INM=Integrated nutrient management, [†]FYM=Farm yard manure applied to supply 400 kg N ha⁻¹, ^ΔRSC=Rice straw compost applied to supply 400 kg N ha⁻¹, [¶]VC=Vermicompost applied to supply 400 kg N ha⁻¹ [Mean values for a soil property within a column followed by different letters differ significantly ($p<0.05$) by Duncan's multiple range test (DMRT)]

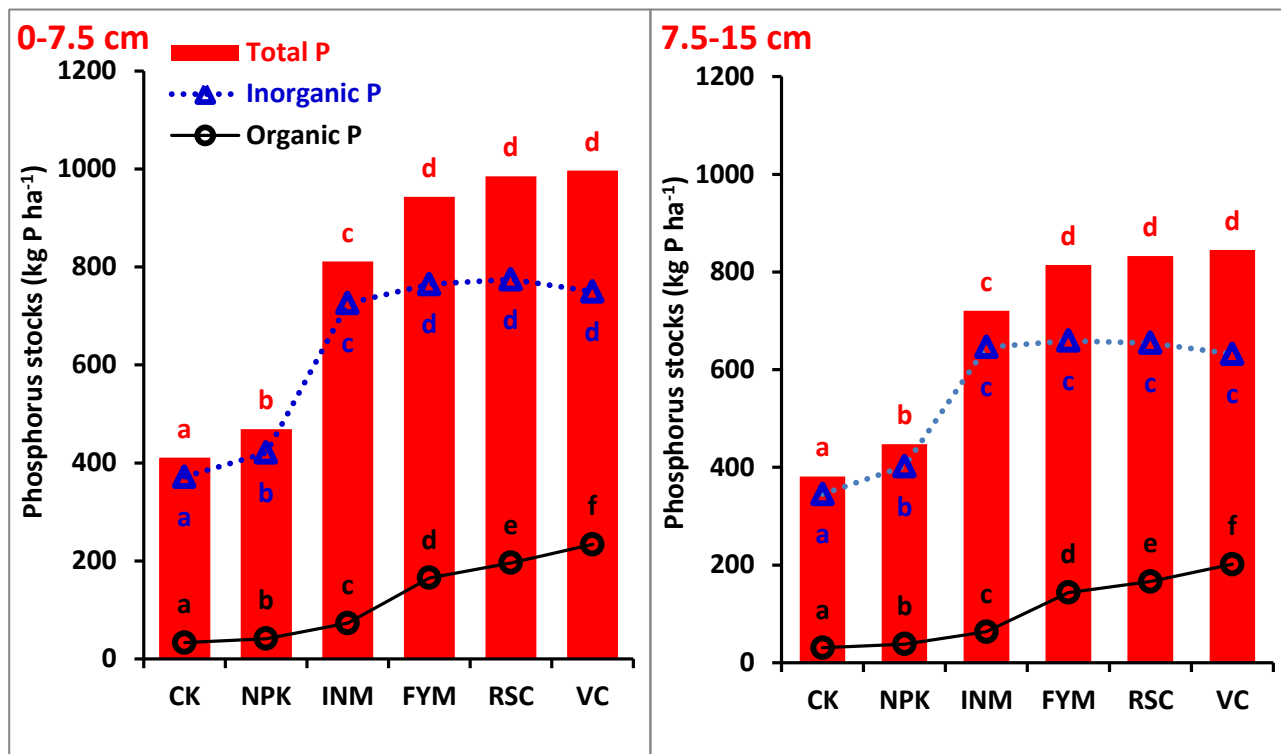


Fig 4.19 Effect of different treatments on total P, inorganic P and organic P stocks in 0-7.5 cm and 7.5-15 cm soil depth under basmati-wheat cropping [Mean values for a soil property at a given depth followed by different letters differ significantly ($p < 0.05$) by Duncan's multiple range test (DMRT)]

4.2.4 Phosphorus enrichment in soils

Phosphorus enrichment in the plough layer (0-15 cm) was calculated as difference in the concentration of P fraction in the treated and control soils (Table 4.16, Figure 4.20). Inorganic P enrichment ranged between 51 and 351 mg kg⁻¹ (17 to 115%) for different treatments. It was highest in plots amended with FYM followed by RSC, VC INM and NPK. Organic P enrichment ranged between 7 and 172 mg kg⁻¹ (27 to 634%) under different treatments and followed the order VC>RSC>FYM>INM>NPK. Total P enrichment ranged between 60 and 505 mg kg⁻¹ (18 to 149%) for different treatments and different treatments followed the same order as observed for organic forms. Phosphorus enrichment as water soluble inorganic and organic P ranged between 0.30 and 1.47 mg kg⁻¹ (45 to 224%) for different treatments. Phosphorus enrichment as iron associated inorganic P ranged between 10.4 and 70.9 mg kg⁻¹ (24 to 163%) and as iron associated organic P fraction showed enrichment between 0.23 and 17.8 mg kg⁻¹ (9 to 686%). P enrichment in calcium-aluminium associated inorganic P ranged between 39 and 271 mg kg⁻¹ (17-120%) and calcium-aluminium associated organic P fraction showed an enrichment ranged between 1.02 and 21 mg kg⁻¹ (21-806%) for different treatments. Humic-bound inorganic P enrichment ranged between 1.2 and 17.9 mg

kg⁻¹ (3 to 51%) and other (acid-soluble organic P, sugar-bound organic P, nucleic acid-organic P and polyphosphate, humic- bound organic P) organic P fractions ranged between 0.53 and 86 mg kg⁻¹ (15 to 726%) (Table 4.16).

The enrichment of water-soluble inorganic P was relatively higher than humic-bound inorganic P for different treatments. The relative enrichment of different organic P fractions in soil followed the order; calcium-aluminium associated organic P > humic bound organic P > iron associated organic P > sugar bound organic P > acid soluble organic P > nucleic acid organic P > water soluble organic P. Maximum enrichment of P among different inorganic and organic P fractions occurred in the soils receiving P through organic manures (FYM/RSC/VC). Phosphorus enrichment in soils involving INM was considerably higher than the control (CK) and soils receiving balanced fertilization (NPK), but was considerably lower than the soils receiving P through organic manures alone. Enrichment in total P concentration with adoption of INM compared to NPK alone has earlier been reported by Yan *et al* (2013). Improvement in SOC with organic manure and P fertilizer application enhances soil microbial biomass, and thereby alters P availability (Chen *et al* 2003, Sigua *et al* 2009). Application of organic manure to soil along with inorganic P fertilizers causes significant enrichment in P fractions (Ranatunga *et al* 2013, Devra *et al* 2014, Tang and Armstrong 2008). Garg and Aulakh (2010) reported higher enrichment of inorganic and organic P fractions in fertilizer P and FYM amended soils compared to unamended soils under maize–wheat and rice–wheat rotation. They also observed that the magnitude of P enrichment was directly proportional to applied P rate and frequency.

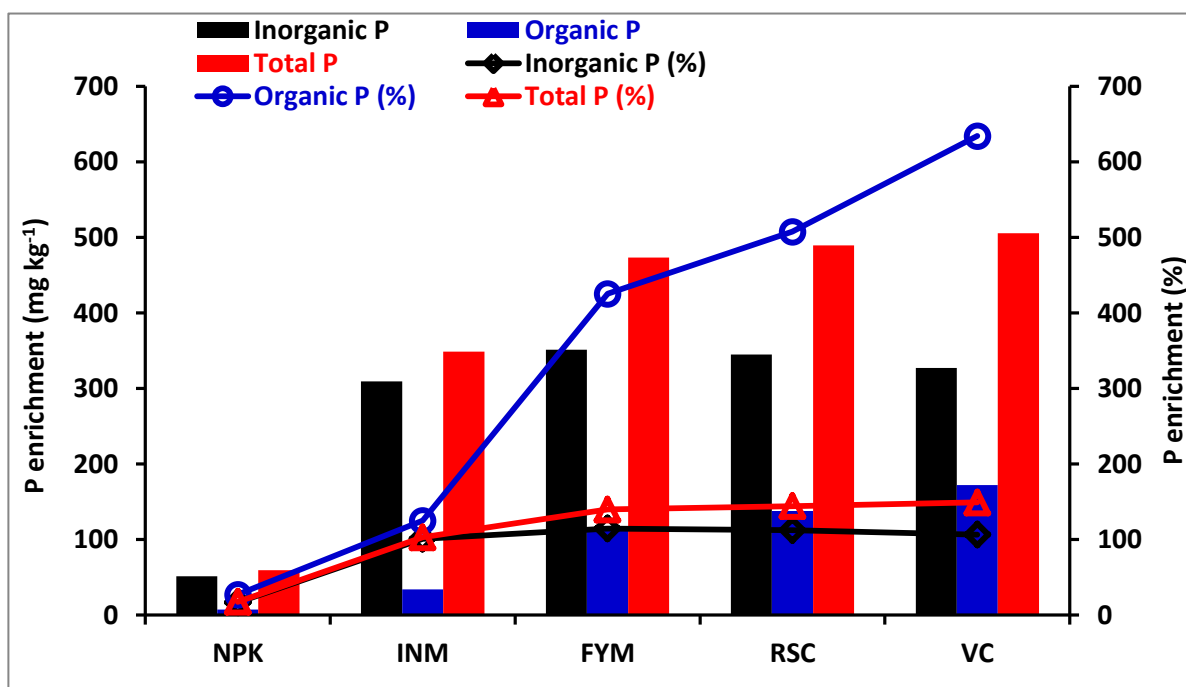


Fig 4.20 Effect of different treatments on phosphorus enrichment in total P, inorganic P and organic P pools in soils (0-15 cm) under basmati-wheat cropping

Table 4.16 Phosphorus enrichment in soil plough layer (0-15 cm) as influenced by nutrient management practices under basmati-wheat cropping

Treatment	Inorganic P					Organic P									
	H ₂ O-Pi [*]	Ca-EDTA-Pi [†]	Na-EDTA-Pi [‡]	NaOH-Pi [►]	▼TPi	H ₂ O-Po [*]	Ca-EDTA-Po [†]	Na-EDTA-Po [‡]	H ₂ SO ₄ -Po [‡]	cTCA-Po [▲]	hTCA-Po [▼]	NaOH-Po [►]	▲TPo	Res-P [◄]	Total P
P enrichment (mg kg ⁻¹) in 0-7.5 cm soil depth															
NPK	0.30	10.4	39	1.2	51	0.29	0.23	1.02	0.53	2.9	0.60	1.8	7	0.96	60
INM [#]	1.47	67.6	222	17.9	309	0.99	2.45	3.65	3.49	6.9	2.30	14.1	34	5.37	349
FYM [†]	1.16	61.7	271	17.3	351	0.96	8.17	27.1	7.09	11.0	3.78	57.3	115	6.30	473
RSC ^Δ	1.25	66.2	261	16.9	345	0.99	12.0	32.9	9.26	12.0	3.81	66.8	138	6.51	489
VC [¶]	1.10	70.9	242	12.7	327	1.17	17.8	38.4	11.7	12.9	4.11	86.0	172	6.33	505
P enrichment (%) in 0-7.5 cm soil depth															
NPK	45	24	17	3	17	58	9	21	18	99	42	15	27	19	18
INM [#]	223	156	98	51	101	187	94	77	116	235	159	119	125	105	103
FYM [†]	176	142	120	49	115	179	314	569	239	370	262	484	425	123	140
RSC ^Δ	190	153	115	48	112	186	462	690	311	404	264	564	507	126	144
VC [¶]	165	163	107	36	107	224	686	806	390	435	284	726	634	123	149

^{*}H₂O-Pi/Po=Water soluble inorganic and organic P, [†]Ca-EDTA-Pi/Po=Iron associated inorganic and organic P, [‡]Na-EDTA-Pi/Po=Calcium-aluminium associated inorganic and organic P, [§]H₂SO₄-Po=Acid soluble organic P, [▲]cTCA-Po=Sugar bound organic P, [▼]hTCA-Po=Nucleic acid organic P and polyphosphate, [►]NaOH-Pi/Po=Humic bound inorganic and organic P, [◄]Res-P=Residual P, [▲]TPo=Organic P, [▼]TPi=Inorganic P

[#]INM=Integrated nutrient management, [†]FYM=Farm yard manure applied to supply 400 kg N ha⁻¹, ^ΔRSC=Rice straw compost applied to supply 400 kg N ha⁻¹,

[¶]VC=Vermicompost applied to supply 400 kg N ha⁻¹

4.2.5 Phosphorus release kinetics

Kinetics of P release was studied in surface soils (0-15 cm) collected from different treatments involving balanced fertilization (NPK), INM, application of organic manures viz. FYM, RSC and VC and an absolute control (CK). P release increased with increasing shaking time (Figure 4.21). Phosphorus release proceeded in two phases: an initial rapid release phase followed the period of slow release after 12-24 hours of shaking. Several studies (Abdu 2009 and 2013, Jalali and Ranjbar 2011) have reported similar P release pattern. Initially fast release was due to the release of P from the labile P pools and slower P release was due to the conversion of non-labile to the labile P pools (Hundal *et al* 1988). The initial faster reaction corresponds to rapid dissolution of poorly crystalline and amorphous phosphates in soil (Griffin and Jurinak 1974) and which results in release of large amount of P in the equilibrium solution. Lookman *et al* (1995) has reported that initial fast P release refers primarily to P bound to the reactive surfaces which are in direct contact in aqueous phase while slow P release is slow dissolution kinetics or slow diffusion from interior sites inside soil aggregates. Cumulative P released ranged between 5.6 to 14.7, 9.7 to 18.9, 11.1 to 25.2, 10.4 to 22.9, 10.0 to 22.2 and 9.9 to 21.9 ($\mu\text{g P ml}^{-1}$) in CK, NPK, INM, FYM, RSC and VC amended plots, respectively. Amount of cumulative P released was lowest in the control (CK) treatment, and increased considerably with fertilizer and manure application (Figure 4.21).

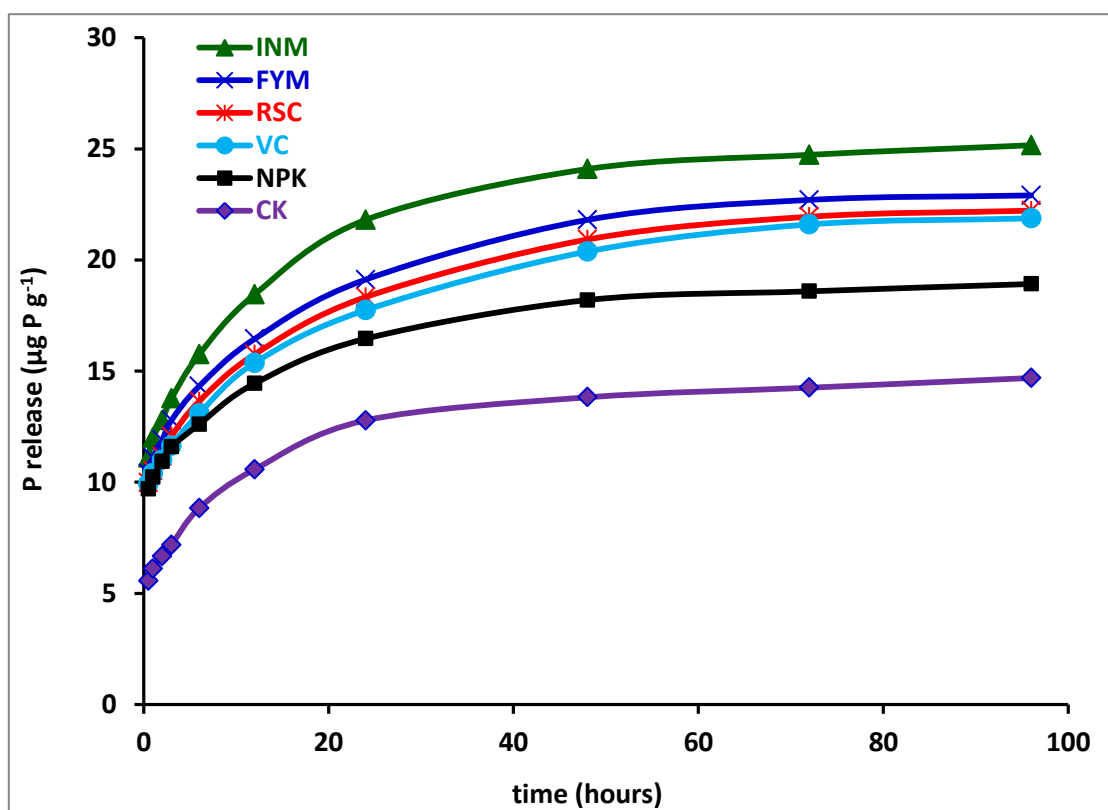


Fig 4.21 Effect of nutrient management practices on kinetics of phosphorus release in surface soils (0-15 cm) under basmati-wheat cropping

Regardless of the shaking time, cumulatively released P was higher in the soils involving INM, followed by the soils receiving of organic manures viz. FYM, RSC and VC and then soils receiving balanced fertilizers (NPK). Comparatively higher amounts of cumulative P released from the soils involving INM is due to the application of fertilizer P along with FYM. Fertilizer P enhances the amount of labile-P pool in the soils, and further the conjunction of FYM reduces P sorption on the soil matrix, because of liberation of organic acids upon its decomposition and mineralization of organic P (Laboski and Lamb 2003, Gorgin *et al* 2011). Pandian (2009) observed that P release of sorbed P was higher in manured soils (11.5%) compared to unmanured soils (4.1%). Decrease in P released may have coincided with a decrease in the quantity of more soluble forms of P or a decrease in P release rates. Because P release depend on labile P status of soil (Wang *et al* 2011). Soil organic matter being a source of organic P, influences availability of P by (i) converting insoluble phosphates to soluble forms, (ii) producing humate ions that compete with phosphate ions for sorption sites (iii) releasing carbon dioxide, which increases solubility of Ca-P and (iv) producing organic acids that cover colloidal sesquioxides surface (Stevenson 1982).

4.2.5.1 Modelling kinetics of phosphorus release

Six kinetic models viz. zero order, first order, second order, power function, Elovich and parabolic diffusion equations were tested by linear least square method for describing P release in soil (Figure 4.22). Release of P with time was best described by power and Elovich function closely followed by parabolic diffusion equation (Table 4.17). The release constants estimated from Elovich equation, parabolic diffusion and power function equations were lowest for the control soils (CK) (Table 4.18). The release constants increased with inorganic and organic fertilizers application. Comparison of the three organic sources revealed that higher P release occurred from soils amended with FYM and lowest from soil treated with VC. Replenishment of P concentration in soil solution occurs predominately through the release of P organic matter (Goh *et al* 1986, Jalali and Ranjbar 2010). This controls short- and long-term P availability in soils (Messiga *et al* 2012). Different kinetic equations such as first order, second order, Elovich, power function and parabolic diffusion equations have been proposed to quantify P release from soil (Toor and Bahl, 1999, Abdu, 2013). However, superiority of Elovich equation in describing P release kinetics in soils (Ghosh and Singh 2000).

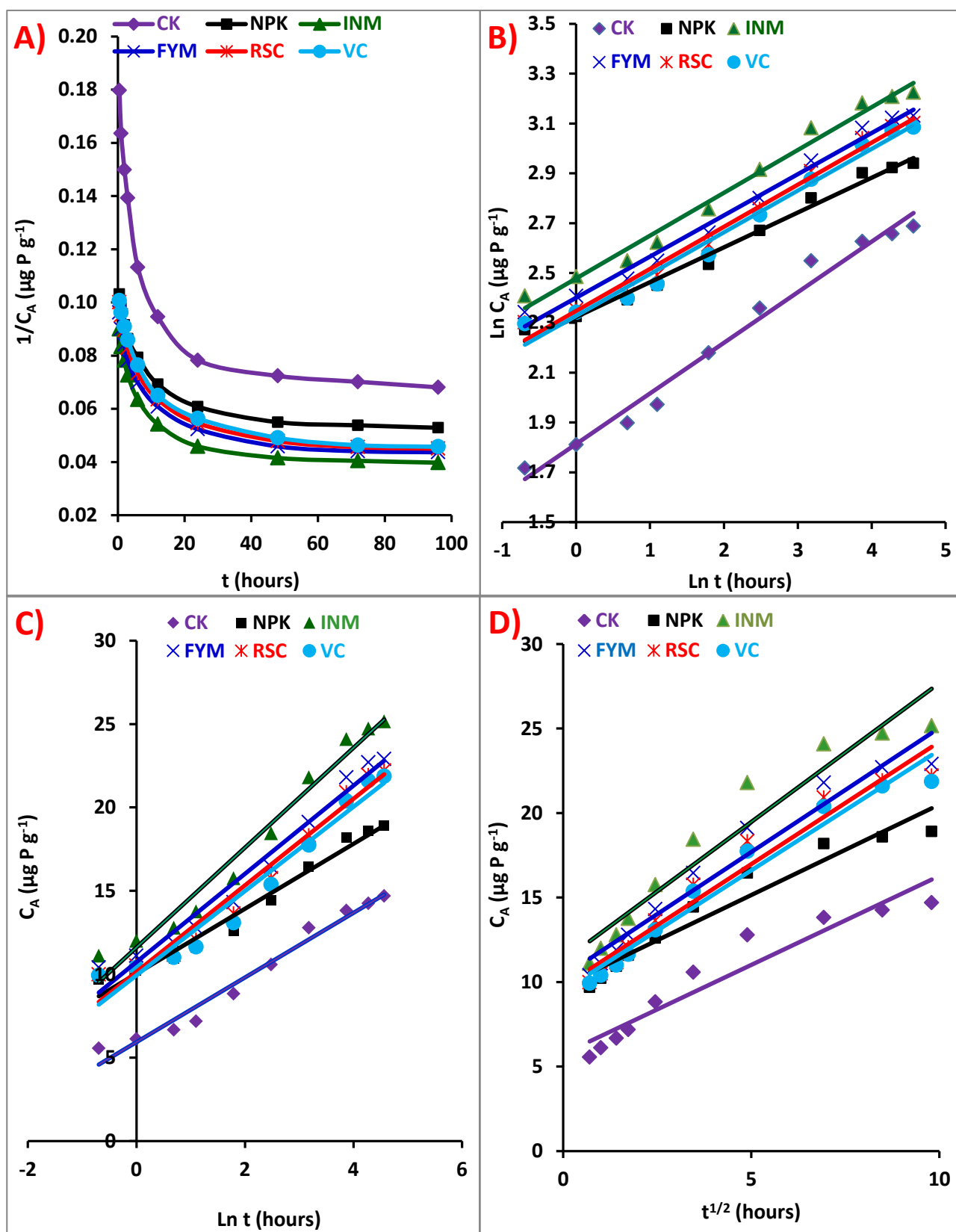


Fig 4.22 Effect of nutrient management practices on time dependent phosphorus release from soils under basmati-wheat cropping system (C_A =amount of P release, t =time, A=second order equation, B=Power function equation, C=Elovich equation, and D=Parabolic diffusion equation)

Table 4.17 Statistical criteria for judging the suitability of different kinetic models fitted to describe the kinetics of P release data in surface (0-15 cm) soils under basmati-wheat cropping

Treatment	Zero order equation			First order equation			Second order Equation			Parabolic diffusion equation			Power function equation			Elovich equation		
	S.E. _M [¶]	S.D. _M [†]	R ^{2‡}	S.E. _M	S.D. _M	R ²	S.E. _M	S.D. _M	R ²	S.E. _M	S.D. _M	R ²	S.E. _M	S.D. _M	R ²	S.E. _M	S.D. _M	R ²
CK	1.14	3.62	0.77**	0.120	0.380	0.69*	0.013	0.042	0.61*	1.14	3.62	0.92**	0.119	0.378	0.98**	1.14	3.62	0.97**
NPK	1.15	3.63	0.80**	0.082	0.260	0.75**	0.006	0.019	0.69*	1.15	3.63	0.94**	0.082	0.259	0.99**	1.15	3.63	0.97**
INM [#]	1.77	5.60	0.79**	0.101	0.319	0.72**	0.006	0.019	0.66*	1.77	5.60	0.93**	0.101	0.319	0.98**	1.77	5.60	0.97**
FYM [†]	1.56	4.95	0.82**	0.097	0.307	0.76**	0.006	0.020	0.69*	1.56	4.95	0.95**	0.097	0.306	0.99**	1.56	4.95	0.97**
RSC ^Δ	1.54	4.87	0.83**	0.099	0.314	0.77**	0.007	0.021	0.70*	1.54	4.87	0.96**	0.099	0.314	0.98**	1.54	4.87	0.97**
VC [¶]	1.51	4.76	0.85**	0.099	0.314	0.79**	0.007	0.021	0.72*	1.51	4.76	0.97**	0.099	0.312	0.99**	1.51	4.76	0.96**

[¶]S.E._M=Standard error of mean, [†]S.D._M=Standard deviation of mean, [‡]R²=Coefficient of determination

[#]INM=Integrated nutrient management, [†]FYM=Farm yard manure applied to supply 400 kg N ha⁻¹, ^ΔRSC=Rice straw compost applied to supply 400 kg N ha⁻¹,

[¶]VC=Vermicompost applied to supply 400 kg N ha⁻¹

*Relationship significant at $p < 0.05$

**Relationship significant at $p < 0.01$

Table 4.18 Effect of nutrient management practices on phosphorus release constants of different kinetics models in surface soils (0-15 cm) under basmati-wheat cropping

Treatment	Elovich Equation (EE)		Parabolic diffusion Equation (PDE)		Power function Equation (PFE)	
	α ($\mu\text{g g}^{-1} \text{h}^{-1}$)	β ($\mu\text{g g}^{-1}$)	R ($\mu\text{g g}^{-1} \text{h}^{-1/2}$)	C ($\mu\text{g g}^{-1}$)	K_A ($\mu\text{g g}^{-1} \text{h}^{-1}$)	b ($\mu\text{g g}^{-1}$)
CK	1.94	5.93	1.05	5.74	0.203	1.81
NPK	1.95	10.02	1.07	9.79	0.139	2.32
INM [#]	3.00	11.59	1.64	11.25	0.171	2.48
FYM [†]	2.64	10.72	1.47	10.34	0.165	2.40
RSC ^Δ	2.60	10.13	1.45	9.74	0.169	2.35
VC [¶]	2.53	9.93	1.42	9.49	0.167	2.32

[#]INM=Integrated nutrient management, [†]FYM=Farm yard manure applied to supply 400 kg N ha⁻¹, ^ΔRSC=Rice straw compost applied to supply 400 kg N ha⁻¹,

[¶]VC=Vermicompost applied to supply 400 kg N ha⁻¹

4.2.6 Soil carbon pools

4.2.6.1 Total and water extractable organic carbon

The effect of different treatments on the concentration of total organic C (TOC) in surface (0-7.5 cm) and subsurface soil (7.5-15 cm) is given in table 4.19. In surface soil (0-7.5 cm), the highest (6.48 g C kg^{-1}) concentration of TOC was observed in FYM amended plots and the lowest (6.48 g C kg^{-1}) in unamended plots. Concentration of TOC increased significantly in soils receiving manure alone or INM treatment. Banger *et al* (2009) reported the significant increase in SOC with FYM and NPK+FYM over CK. The magnitude of this increase in TOC was significantly higher in soils receiving organic manures alone (FYM, RSC and VC), compared to INM. Increase in TOC with FYM, crop residues and VC application has earlier been reported in several studies (Beri *et al* 1995, Benbi and Senapati 2010). Sodhi *et al* (2009) reported significant increase in TOC with regular application of RSC in sandy loam soils under rice-wheat system. The variation in SOC increase in under different organics receiving soils may be due to the variation in their qualities (Huang *et al* 2014). Because, manure is a source of plant nutrients and make valuable contribution to soil organic matter (SOM) (Blair *et al* 2006). A significant increase in soil organic C concentration in the soils involving INM and application of organic manures (FYM/RSC/VC) could be due to the application of already stabilized material. Further, fertilizer application also stimulates crop biomass production and thus increases the amount of residue being retained in the soil and therefore, enhances C accumulation in the soil (Schuman *et al* 2002). Significant linear relationship between cumulative C input to the soil and amount of C sequestered in soils under rice-wheat cropping system has been reported in several studies (Mandal *et al* 2007, Majumder *et al* 2007, 2008, Srinavasarao *et al* 2012, Benbi *et al* 2012). Balanced fertilization (NPK) did not differ significantly from CK. Several studies reported a non-significant change in TOC concentration in soils receiving NPK after 6 years (Moharana *et al* 2012, Nyambega *et al* 2014). This can be attributed to short duration of fertilizer application (Buol and Stokes 1997). Giller *et al* (1997) reported that C sequestration is slow process and would require long term use of inorganic and organic sources to realize remarkable increase. On the contrary, other researchers have reported a significant increase in soil organic C concentration in soils under balanced fertilization over a long period of application (Nayak *et al* 2012, Brar *et al* 2013). In subsurface soil (7.5-15 cm), TOC concentration ranged between 4.80 to 5.75 g C kg^{-1} . Application of manure either alone or along with inorganic fertilizers significantly increased TOC concentration. The profile distribution of TOC showed decrease with depth (Figure 4.23). Total organic C ranged between 3.15 to 4.30 g C kg^{-1} in lower soil layers. It is because of the fact that C input through all exogenous sources viz. plant biomass as well as applied inorganic and organic fertilizers is restricted to the soil plough depth (0-15 cm) (Ingram and Fernandes 2001, Aulakh and Garg 2007, Aulakh *et al* 2007). In our study, the TOC concentration significantly increased in soils involving INM and manure, as reported by several researchers (Mikha and Rice 2004, Rudrappa *et al* 2006, Yan *et al* 2007).

Table 4.19 Effect of nutrient management practices on total organic carbon (TOC), water soluble carbon (WEOC) and hot water soluble carbon (HWSC) in the surface (0-7.5 cm) and subsurface (7.5-15 cm) soil under basmati-wheat cropping

Treatment	TOC		WEOC		HWSC	
	g C kg ⁻¹		mg C kg ⁻¹			
	0-7.5 cm	7.5-15 cm	0-7.5 cm	7.5-15 cm	0-7.5 cm	7.5-15 cm
CK	5.13 ^{a†}	4.80 ^a	27.7 ^a	26.1 ^a	239 ^a	223 ^a
NPK	5.43 ^a	5.15 ^a	29.5 ^b	27.6 ^{ab}	252 ^b	233 ^a
INM [#]	5.83 ^b	5.53 ^c	31.3 ^c	29.3 ^{bc}	269 ^c	250 ^b
FYM [†]	6.48 ^d	5.75 ^c	34.3 ^d	31.6 ^c	293 ^d	268 ^c
RSC ^Δ	5.95 ^{bc}	5.68 ^c	32.1 ^c	31.3 ^c	273 ^c	255 ^b
VC [¶]	6.20 ^{cd}	5.68 ^c	32.7 ^{cd}	30.7 ^c	277 ^c	261 ^{bc}

[#]INM=Integrated nutrient management, [†]FYM=Farm yard manure applied to supply 400 kg N ha⁻¹, ^ΔRSC=Rice straw compost applied to supply 400 kg N ha⁻¹, [¶]VC=Vermicompost applied to supply 400 kg N ha⁻¹ [[†]Mean values within a column followed by different letters differ significantly ($p<0.05$) by Duncan's multiple range test (DMRT)]

Water extractable organic C responded significantly to the nutrient management practices (Table 4.19, Figure 4.23). In surface soil (0-7.5 cm), the WEOC concentration ranged between 27.7 to 34.3 mg C kg⁻¹. Water extractable organic C responded significantly to inorganic or organic fertilizers application. Plots receiving inorganic fertilizers showed significant increase in WEOC compared to unfertilized plots. Therefore, WEOC may be used as a sensitive indicator of nutrient management induced changes in SOM under rice-wheat system (Benbi *et al* 2015b). Adoption of INM significantly increased WEOC compared to NPK application while INM treatments did not differ significantly with plots receiving RSC and VC. Plots amended with FYM showed significantly higher WEOC concentration compared to INM treatments. In subsurface soil (7.5-15 cm), WEOC concentration ranged between 26.1 to 31.6 mg C kg⁻¹. Adoption of INM significantly increased WEOC concentration compared to CK though INM and NPK treated plots were statistically at par. Plots amended with organic manure showed significant increase in WEOC concentration compared to plots amended with NPK. The three organic sources viz. FYM, RSC and VC did not differ significantly from each other as well as from INM treatments. The WEOC decreased with depth and ranged between 17.7 to 24.9 mg C kg⁻¹ in lower soil layers (Figure 4.23). Below subsurface soil (7.5-15 cm) all the treatments exhibited similar WEOC concentration. On an average, WEOC comprised 0.53-0.60% of TOC concentration in the soil plough layer (0-15 cm) (Table 4.19). This is within the range (0.32-1.1% of TOC) reported under long-term fertilizer, FYM and rice straw applications under maize-wheat-cowpea/rice-wheat cropping system (Kaur *et al* 2008, Benbi *et al* 2015a and 2015b). The 0-7.5 cm soil depth had 94% higher WEOC than the 7.5-15 cm soil depth. However, WEOC was 76-89% higher in plough layer compared to the lower soil depths (Figure 4.23). It could be due to the addition of organic material which in fact stimulates microbial growth thereby enhanced SOM decomposition rate (Yagi *et al* 2005). A higher

increase in WEOC in FYM amended plots compared to NPK treatment suggests that added organic manure contains much soluble organic matter (Chantigny *et al* 2002).

4.2.6.2 Hot water soluble and microbial biomass carbon

According to Schulz *et al* (2011) HWSC is an indicator of decomposable SOC pools and serves as a source of nutrient supply during decomposition of SOC. In surface soil (0-7.5 cm), the HWSC concentration ranged between 239 and 293 mg C kg⁻¹ (Table 4.19, Figure 4.24). The HWSC responded significantly to inorganic or organic fertilizer application. Plots receiving inorganic fertilizer showed significant increase in HWSC concentration compared to unfertilized plots. Adoption of INM significantly increased its concentration compared to NPK application. Plots amended with FYM showed significantly higher HWSC concentration compared to INM treatments. In subsurface soil (7.5-15 cm), HWSC concentration ranged between 223 and 268 mg C kg⁻¹. Adoption of INM showed significant increase in HWSC concentration compared to inorganically fertilized or CK plots. Plots amended with FYM showed significant increase in HWSC compared to plots amended with RSC or INM. The profile distribution of HWSC revealed that it decreased with depth and ranged between 145 and 190 mg C kg⁻¹ in lower soil layers (Figure 4.24). Hot water soluble C was 4.37-4.69% of TOC and was relatively larger than WEOC. Benbi *et al* (2015b) reported that after 11 years of FYM and rice straw applications in rice-wheat cropping, HWSC comprised 2.2%-3.3% of TOC. Beneficial effect of manure application on HWSC has earlier been reported by Liang *et al* (2012). Simon (2008) reported significant increase in the HWSC concentration after 12 years of INM treatments compared to CK in a clay loam soil. Sodhi *et al* (2009) reported significant increase in KMnO₄-C with rice straw compost application under rice-wheat cropping system.

Soil MBC in soil ranged between 137 and 169 mg C kg⁻¹ in 0-7.5 cm soil depth and between 126 and 158 mg C kg⁻¹ in 7.5-15 cm soil depth (Figure 4.24). Application of inorganic fertilizers did not influence MBC significantly from unfertilized soils. Integrated nutrient management practice and organic manure application improved MBC. It may possibly due to a steady source of organic C to support the microbial community (Bhattacharyya *et al* 2005, Chen *et al* 2014). The three organic sources viz. FYM, RSC and VC did not differ significantly from each other as well as from INM treatments. Soil MBC concentration decreased with depth and in subsurface soil (7.5-15 cm), effect of different treatments was similar to that observed in 0-7.5 cm soil depth. Below subsurface soil, soil MBC concentration ranged between 84 to 116 mg C kg⁻¹ and there was no difference among treatments (Figure 4.24). Higher soil MBC in 0-7.5 cm soil layer could be attributed to higher SOC and microbial population than 7.5-15 cm soil depth (Benbi *et al* 2015b). Boyer and Groffman (1996) reported greater microbial activities in surface soil which decrease with soil depth. Favourable effects of FYM application on soil MBC in rice-wheat cropping system has earlier been reported by Kaur *et al* (2008) and in soybean-wheat cropping system by Aulakh *et al* (2010).

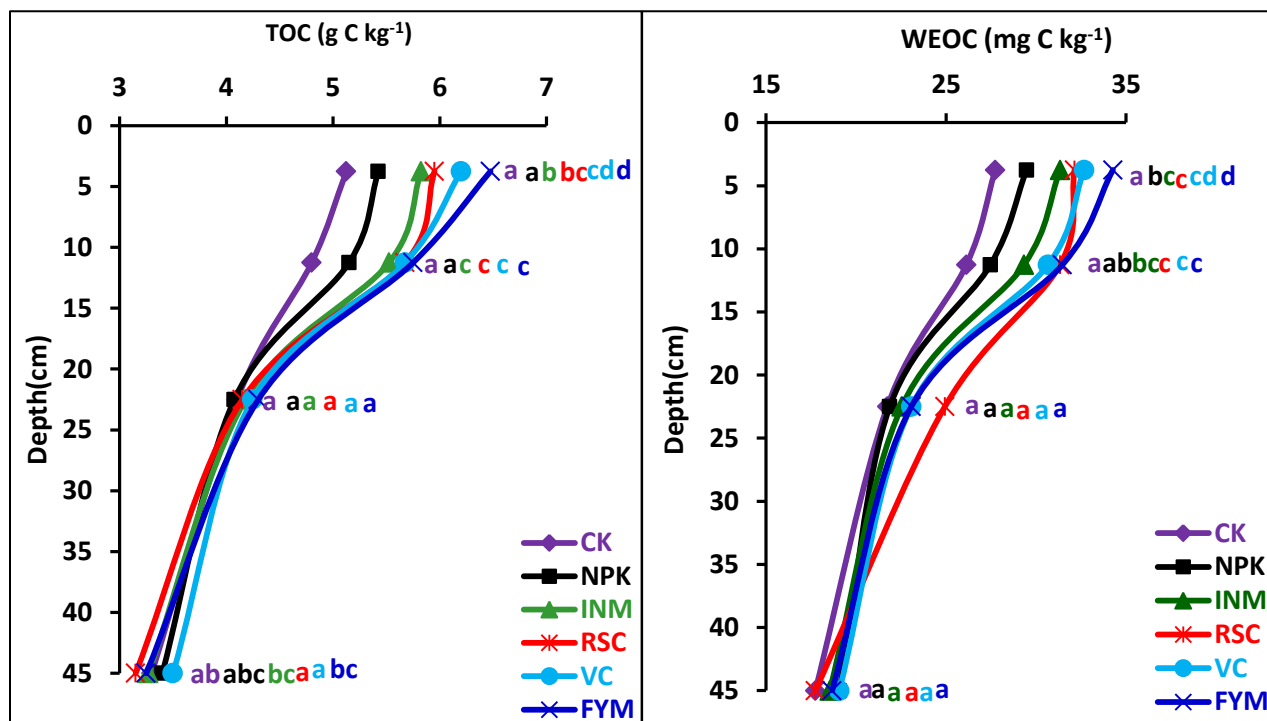


Fig 4.23 Effect of different treatments on profile distribution of total organic carbon (TOC) and water extractable organic carbon (WEOC) in soil under basmati-wheat cropping [Mean values for a soil property at a given depth followed by different letters differ significantly ($p < 0.05$) by Duncan's multiple range test (DMRT)]

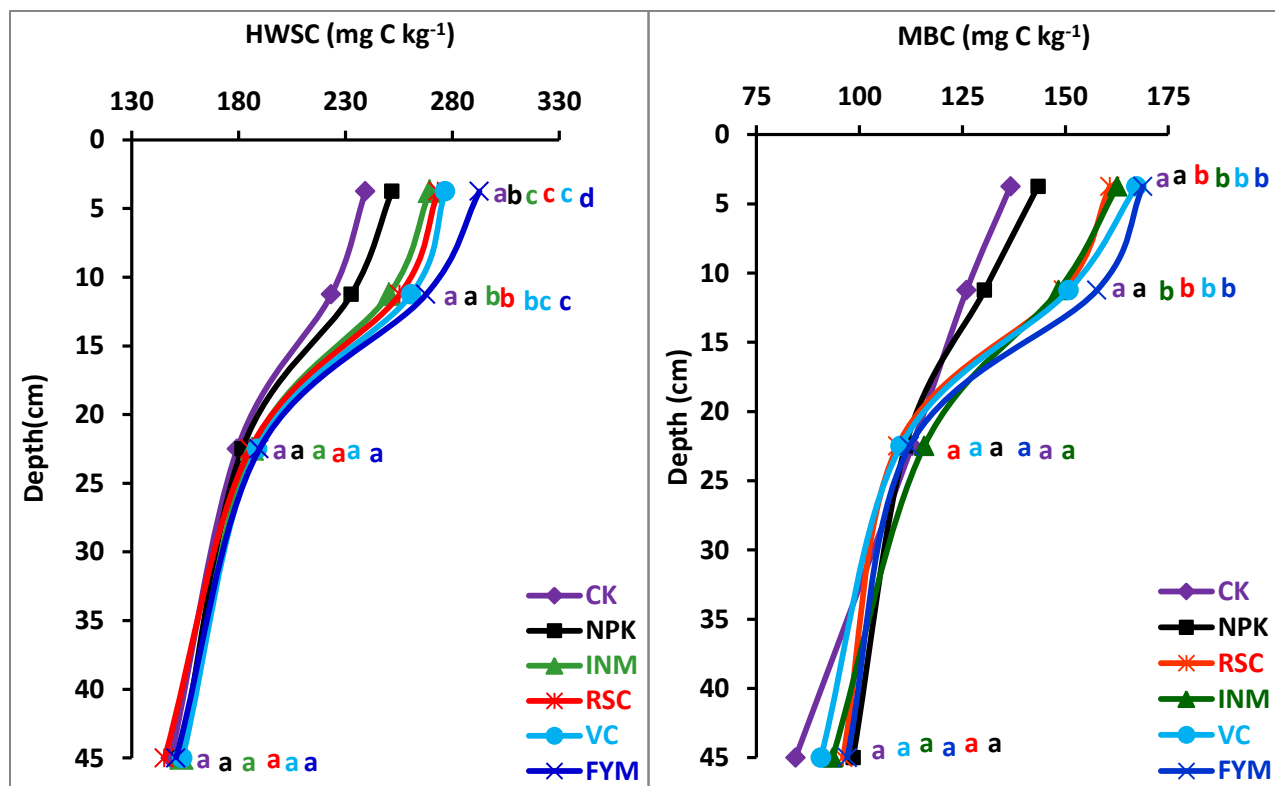


Fig 4.24 Effect of different treatments on profile distribution of hot water soluble carbon (HWSC) and microbial biomass carbon (MBC) in soil under basmati-wheat cropping [Mean values for a soil property at a given depth followed by different letters differ significantly ($p < 0.05$) by Duncan's multiple range test (DMRT)]

4.2.6.3 Potassium permanganate oxidizable and non-labile C

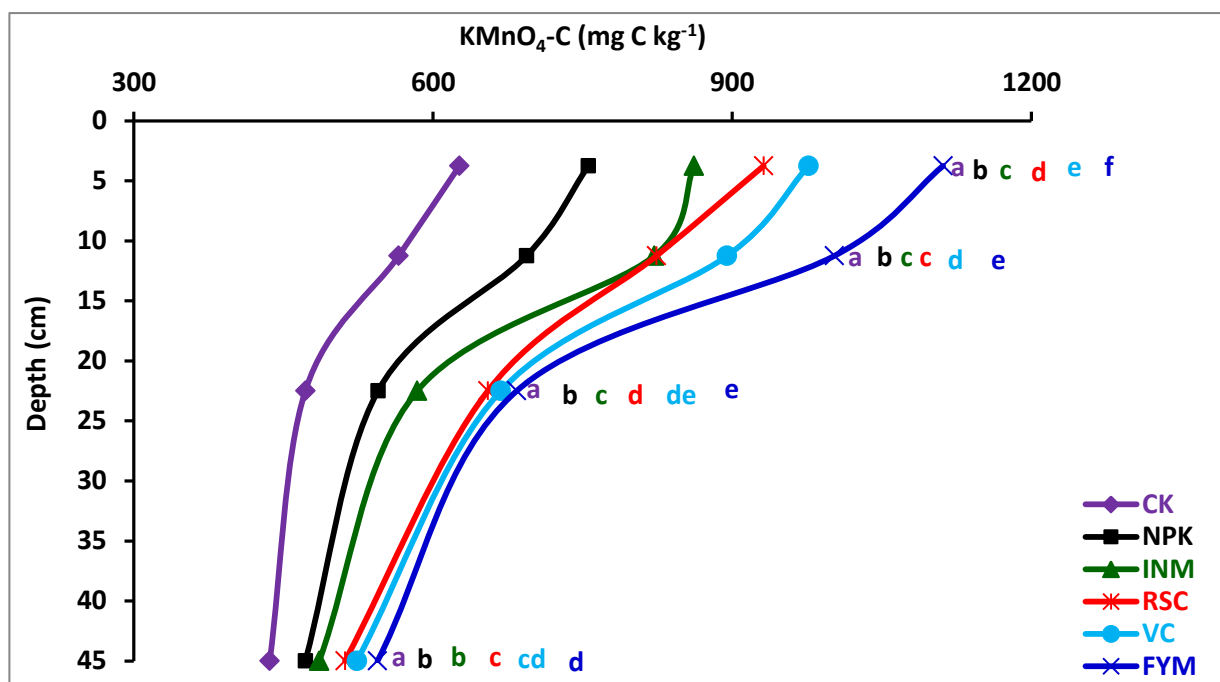
Potassium permanganate oxidizable carbon ($\text{KMnO}_4\text{-C}$) increased significantly with fertilizer and manure application (Table 4.20, Figure 4.25). In surface soil (0-7.5 cm), $\text{KMnO}_4\text{-C}$ concentration ranged between 626 to 1111 mg C kg^{-1} and was higher by 20.8% in plots receiving inorganic fertilizers compared to CK. Adoption of INM increased $\text{KMnO}_4\text{-C}$ by 14% compared to NPK application. Application of FYM, RSC and VC significantly increased $\text{KMnO}_4\text{-C}$ by 29, 8 and 13% compared to INM treatment. In subsurface soil (7.5-15 cm), $\text{KMnO}_4\text{-C}$ concentration ranged between 565 and 1002 mg C kg^{-1} . The effect of different treatments was similar to that observed for 0-7.5 cm soil depth. In 15-30 cm soil depth, $\text{KMnO}_4\text{-C}$ ranged between 472 and 684 mg C kg^{-1} . The effect of different treatments was similar to that observed for upper two soil depths. In 30-60 cm soil depth, $\text{KMnO}_4\text{-C}$ ranged between 436 and 544 mg C kg^{-1} and significantly increased with inorganic and organic fertilizers application. Application of organic sources viz. FYM, RSC and VC showed significant increase in $\text{KMnO}_4\text{-C}$ compared to inorganic fertilizers. Plots receiving RSC did not differ significantly from plots receiving VC. Profile distribution of $\text{KMnO}_4\text{-C}$ showed that it decreased with depth (Figure 4.25). Lou *et al* (2011) reported that $\text{KMnO}_4\text{-C}$ concentration was significantly higher in soils receiving compost compared to CK. Sodhi *et al* (2009) reported significant increase in $\text{KMnO}_4\text{-C}$ with regular application of RSC in sandy loam soils under rice-wheat cropping system.

In surface soil (0-7.5 cm), non-labile C ranged between 4.50 and 5.36 g C kg^{-1} under different treatments. Effect of different treatments was similar to that observed on $\text{KMnO}_4\text{-C}$ in 0-7.5 cm soil. Non-labile C ranged between 4.23 and 4.75 g C kg^{-1} under different treatments. Higher concentration of non-labile C in the treatments involving organic manures application shows the stabilization of organic C in soil. The C lability, lability index (LI), C pool index (CPI) and C management index (CMI) also improved considerably with balanced fertilizers application (NPK), INM (NPK+FYM) and application of organic sources viz. FYM, RSC and VC) at both the soil depths (Table 4.20). The value of these indices was considerably higher in soils receiving organic manures alone compared to the soils receiving INM. Carbon management index (CMI) can be used to monitor the soil over time and indicates about declining or rehabilitating the soil (Sodhi *et al* 2009). Farmyard manure applications resulted greater value of CMI followed by VC, RSC, INM and NPK, indicating greater rate of C rehabilitation under FYM amended plots than other treatments. Therefore, application of FYM in these soils has more potential to C sequestration.

4.1.6.4 Carbon mineralization

Cumulative amount of $\text{CO}_2\text{-C}$ evolved from soils under different treatments ranged between 362.7 and 700.4 mg C kg^{-1} at 25°C , and between 500.2 and 1020 mg C kg^{-1} at 35°C (Figure 4.26). Carbon mineralization was higher at 35°C , than at 25°C , but the magnitude varied with the treatment. Regardless of the temperature, C mineralization was lower in unamended soils and increased with inorganic and organic fertilizers applications. Cumulative C evolved from the soils, regardless of the incubation, followed the

order FYM>VC>RSC>INM>NPK>CK. The time course of C mineralization showed that mineralization was rapid during initial period of incubation followed by a relatively slower rate thereafter (Figure 4.26). This indicates decomposition of the readily digestible (labile) materials such as simple sugars, organic acids and proteins in initial period of study (Collins *et al* 1992). Greater C mineralization at 35°C than at 25°C and 15°C temperature has been reported by Benbi *et al* (2014), Benbi and Khosa (2014). The process of organic matter decomposition is triggered at higher temperature, because of the change in the composition of organic matter (Dalias *et al* 2001) and microbial activities. Dash *et al* (2014) reported that organics application to soil had a significant effect on CO₂ production due to increase in microbial activity. Marinari *et al* (2010) reported that the cumulative CO₂ production was significantly higher in organically treated than chemically fertilized soils. Chen *et al* (2008) observed the greater C mineralization under combined application of chemical fertilizers and manure or straw. The difference in C mineralization in organic treatments may be related to their chemical composition of the organic sources (Benbi and Khosa 2014, Miller *et al* 2004) and the amount of SOM (Saggar *et al* 2000). Ghosh *et al* (2012) observed the increase in both MBC and mineralizable carbon receiving additional organic inputs. Mohanty *et al* (2013) reported higher C mineralization under combined application of N+FYM or NPK+FYM compared to CK. Higher CO₂ evolution rates for the soils receiving leaf-litter, compared to CK soils has earlier been reported by Dumale *et al* (2008).



4.25 Effect of long term fertilizer management practices on potassium permanganate oxidizable carbon (KMnO₄-C) in soil profile under basmati-wheat cropping system [Mean values for a soil property at a given depth followed by different letters differ significantly ($p < 0.05$) by Duncan's multiple range test (DMRT)]

Table 4.20 Effect of nutrient management practices on $\text{KMnO}_4\text{-C}$ (g kg^{-1}), non-labile C (g kg^{-1}), lability, lability index (LI), soil carbon pool index (CPI) and carbon management index (CMI) in the surface (0-7.5 cm) and subsurface (7.5-15 cm) soil under basmati-wheat cropping

Treatment	KMnO ₄ -C		Non-labile C		Lability		LI		CPI		CMI	
	Depth (cm)											
	0-7.5	7.5-15	0-7.5	7.5-15	0-7.5	7.5-15	0-7.5	7.5-15	0-7.5	7.5-15	0-7.5	7.5-15
CK	0.626 ^a	0.565 ^a	4.50 ^a	4.23 ^a	0.139	0.134	--	--	--	--	--	--
NPK	0.756 ^b	0.694 ^b	4.67 ^b	4.46 ^b	0.162	0.156	1.16	1.17	1.06	1.07	123.0	125.1
INM [#]	0.862 ^c	0.822 ^c	4.96 ^c	4.70 ^c	0.174	0.175	1.25	1.31	1.14	1.15	141.7	150.6
FYM [†]	1.111 ^f	1.002 ^e	5.36 ^f	4.75 ^e	0.207	0.211	1.49	1.58	1.26	1.20	188.0	189.4
RSC ^Δ	0.931 ^d	0.824 ^c	5.02 ^d	4.85 ^c	0.186	0.170	1.33	1.27	1.16	1.18	154.7	150.4
VC [¶]	0.976 ^e	0.895 ^d	5.22 ^e	4.78 ^d	0.187	0.187	1.34	1.40	1.21	1.18	162.4	165.7

[#]INM=Integrated nutrient management, [†]FYM=Farm yard manure applied to supply 400 kg N ha⁻¹, ^ΔRSC=Rice straw compost applied to supply 400 kg N ha⁻¹, [¶]VC=Vermicompost applied to supply 400 kg N ha⁻¹ [[†]Mean values within a column followed by different letters differ significantly ($p < 0.05$) by Duncan's multiple range test (DMRT)]

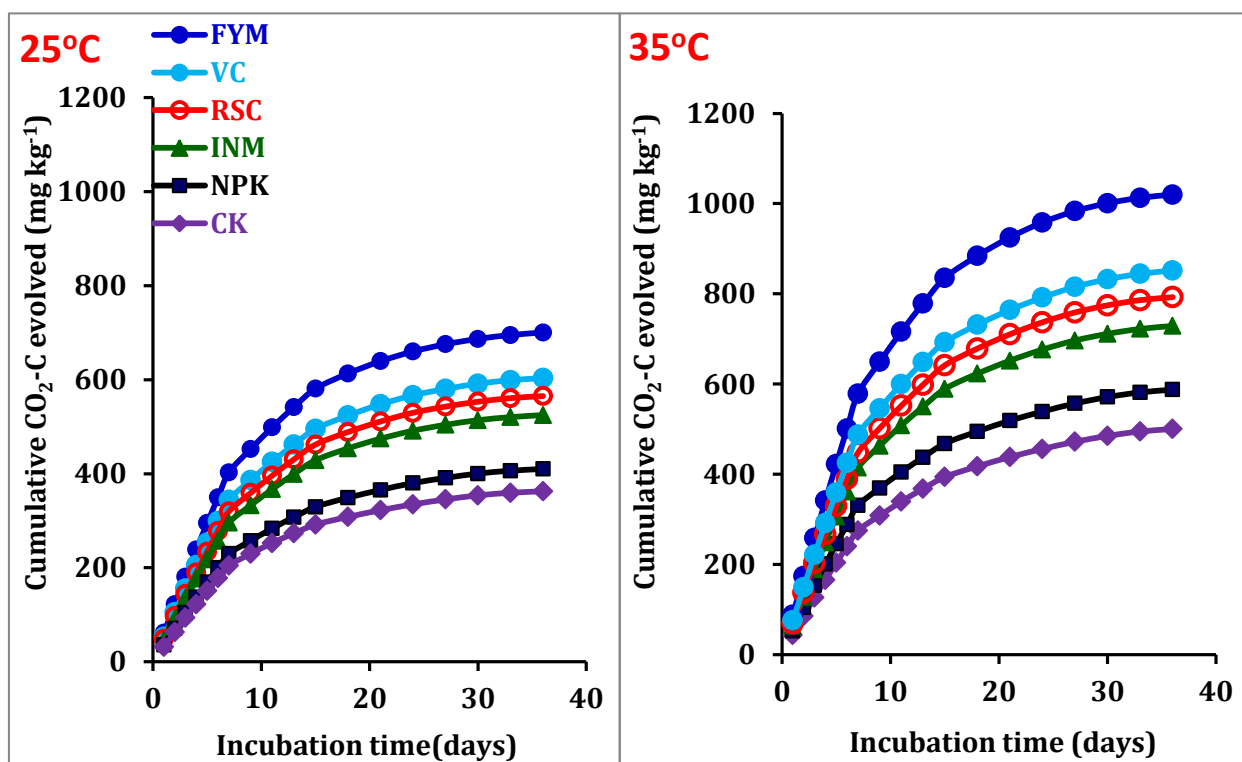


Fig 4.26 Effect of different treatments on time course of CO₂-C evolved during decomposition of soils (0-15 cm) at 25 and 35°C under basmati-wheat cropping

4.2.7 Correlation among different soil phosphorus and organic carbon pools and soil properties

Highly significant positive correlation was observed among different soil C pools (Table 4.21). Soil C pools did not show a significant relationship with available P, available K, NO₃⁻-N and NH₄⁺-N). However, there was a significant positive relationship between available P and available K, NO₃⁻-N and NH₄⁺-N.

Except calcium-aluminium and iron associated organic P, all the P fractions were significantly correlated with TOC (Table 4.22). Except iron associated organic P, all the P fractions showed significant positive correlation with WEOC. Mostly P fractions were significantly positively correlated with MBC, except calcium-aluminium, iron and humic bound organic P. Except water soluble inorganic P, all P fraction showed significant and positive correlation with KMnO₄-C. Organic and total P were significantly and positively correlated with TOC and labile C pools. Inorganic P was significantly correlated with WEOC.

Integrated nutrient management resulted higher increase in mineral N, available P, available K, compared to FYM applications. Effect of different treatments on TOC, labile C fractions and C mineralization followed the order FYM>VC>RSC>INM>NPK>CK. Compared to INM, farmyard manure, RSC and VC applications showed significant increase in inorganic, organic and total P pools in soil. Therefore, integrated nutrient management practice is important to enhance P availability in soil. However, manure applications build-up the soil P pools and organic C pools as well.

Table 4.21 Correlation matrix depicting relationship among different soil carbon pools and nutrient availability

Soil property	SOC	KMnO ₄ -C	WEOC	HWSC	TOC	Av. P	Av. K	MBC	NH ₄ ⁺ -N	NO ₃ ⁻ -N
SOC										
KMnO ₄ -C	0.99**									
WEOC	0.99**	0.98**								
HWSC	1.0**	0.99**	0.99**							
TOC	0.99**	0.99**	0.99**	0.99**						
Av. P	0.75	0.75	0.76	0.76	0.79					
Av. K	0.36	0.33	0.39	0.38	0.40	0.82*				
MBC	0.98**	0.95**	0.96**	0.98**	0.98**	0.74	0.42			
NH ₄ ⁺ -N	0.70	0.68	0.69	0.72	0.72	0.90*	0.88*	0.76		
NO ₃ ⁻ -N	0.72	0.69	0.70	0.73	0.72	0.82*	0.82*	0.78	0.99**	

*Correlation is significant at $p < 0.05$ level (2-tailed)

**Correlation is significant at $p < 0.01$ level (2-tailed)

Table 4.22 Correlation matrix depicting relationship between soil phosphorus fractions and carbon pools in a soil plough depth (0-15 cm)

Soil carbon pool	Soil phosphorus pools														
	H ₂ O-Pi [*]	H ₂ O-Po [*]	Ca-EDTA-Pi [†]	Ca-EDTA-Po [†]	Na-EDTA-Pi [‡]	Na-EDTA-Po [‡]	H ₂ SO ₄ -Po [§]	C _T TCA-Po [▲]	H _T TCA-Po [▼]	NaO-H-Pi [►]	NaOH-Po [►]	Res-P [◄]	TPo [◆]	TPi [♥]	Total P
WEOC	0.85*	0.92*	0.90*	0.75	0.96**	0.83*	0.85*	0.95**	0.97**	0.88*	0.84*	0.96**	0.95**	0.85*	0.96**
HWSC	0.85*	0.91*	0.90*	0.71	0.95**	0.78	0.81	0.92**	0.94**	0.88*	0.80	0.94**	0.94**	0.81	0.94**
MBC	0.91*	0.95**	0.95**	0.72	0.98**	0.77	0.83*	0.92**	0.95**	0.94**	0.80	0.97**	0.98**	0.81	0.96**
KMnO ₄ -C	0.80	0.87*	0.85*	0.69	0.92*	0.77	0.78	0.90*	0.92*	0.83*	0.79	0.90*	0.90*	0.79	0.91*
SOC	0.85*	0.91*	0.90*	0.73	0.96**	0.80	0.83*	0.93**	0.95**	0.88*	0.82*	0.94**	0.95**	0.83*	0.95**
TOC	0.86*	0.93**	0.91*	0.75	0.96**	0.81	0.84*	0.95**	0.96**	0.88*	0.83*	0.95**	0.95**	0.84*	0.96**

^{*}H₂O-Pi/Po=Water soluble inorganic and organic P, [†]Ca-EDTA-Pi/Po=Iron associated inorganic and organic P, [‡]Na-EDTA-Pi/Po=Calcium-aluminium associated inorganic and organic P, [§]H₂SO₄-Po=Acid soluble organic P, [▲]C_TTCA-Po=Sugar bound organic P, [▼]H_TTCA-Po=Nucleic acid organic P and polyphosphate, [►]NaOH-Pi/Po=Humic bound inorganic and organic P, [◄]Res-P=Residual P, [◆]TPo=Total organic P, [♥]TPi=Total inorganic P

*Correlation is significant at $p < 0.05$ level (2-tailed)

**Correlation is significant at $p < 0.01$ level (2-tailed)

4.3 Phosphorus and carbon fractions in soils under different land-uses at farmers' fields

4.3.1 General soil properties

The basic properties of the surface soils under different land-uses viz. rice-wheat, maize-wheat and cotton-wheat cropping systems and a poplar based agroforestry system are presented in table 4.23. The soils under all the land-uses were non-saline and near-neutral to alkaline in reaction. However, the soils under agroforestry had significantly lower pH than the other land-uses that did not differ significantly. The electrical conductivity (EC) was significantly lower in soils under cotton-wheat than the other land-uses. Soils under all the land-uses were sandy loam in texture with sand content ranging between 60 and 64.6% and silt content between 21.8 and 25.1%. Soils under all the land-uses were medium to high (9.8 to 16.0 mg P kg⁻¹) in available P and high in available K (83 to 100 mg K kg⁻¹). However, available P concentration was significantly lower in soils under agroforestry, compared to the other land-uses. The relatively greater P concentration under sole cropping systems may be attributed to regular use of organic manure (FYM) and fertilizer P during crop production. Contrarily, available P concentration was significantly lower in soils under agroforestry, compared to the other land-uses. Lower concentration of available P in soils under agroforestry may be due to wide C: P ratio. Wide C: P ratio reduces P mineralization leading to decrease in available P concentration in soil (Broder *et al* 2012). Available K concentration was significantly higher in soils under agroforestry compared with other land-uses. The CaCO₃ concentration in soils under different land-uses did not differ significantly and ranged between 0 and 19.5 g kg⁻¹ soil

4.3.2 Soil phosphorus fractions

Total P concentration ranged between 352-655, 298-549, 322-597 and 457-742 mg P kg⁻¹, with an average of 517, 449, 462 and 569 mg P kg⁻¹ in soils under rice-wheat, maize-wheat, cotton-wheat and agroforestry systems, respectively (Table 4.24 and Figure 4.27). It was significantly higher in soils under agroforestry than the other land-uses. Among the sole cropping systems rice-wheat exhibited significantly greater total P concentration than soils under maize-wheat and cotton-wheat cropping systems that did not differ significantly. Inorganic P was the dominant fraction that represented 92.3, 94.0 and 94.6% of total P in soils under rice-wheat, maize-wheat and cotton-wheat cropping systems. However, soils under agroforestry had relatively lower proportion (72.9%) of inorganic P and had relatively higher proportion of organic P (27%) compared to other land-uses (6-7.7%). The concentration of total P and inorganic P observed in present study was within the range reported for the soils of experimental region by other researchers (Aulakh *et al* 2003, Singh and Singh 2007).

Significantly lower proportion of inorganic P in soils under agroforestry may be ascribed to relatively lower fertilizer P application than the other land-uses, higher uptake of P by poplar trees and wide C:P ratio of soil. Further, higher organic P concentration in soils under agroforestry may be attributed to the greater addition of organic P through plant biomass (roots and leaves) in agroforestry systems than the other land-uses.

Table 4.23 Range and mean of physical and chemical properties of the surface (0-15 cm) soils under different land-use in Indian Punjab. Numbers in parenthesis indicate standard error.

Soil properties	Land use							
	Rice-wheat		Maize-wheat		Cotton-wheat		Agroforestry	
	Range [†]	Mean [‡]	Range	Mean	Range	Mean	Range	Mean
pH	7.26-8.24	7.76 ^b (0.05)	7.24-8.23	7.73 ^b (0.06)	7.24-8.23	7.72 ^b (0.06)	7.13-7.63	7.29 ^a (0.03)
E.C. (dS m ⁻¹)	0.23-0.43	0.31 ^{ab} (0.01)	0.25-0.48	0.34 ^b (0.01)	0.21-0.45	0.28 ^a (0.01)	0.25-0.45	0.33 ^b (0.01)
Sand (%)	47.8-71.5	60.0 ^a (1.4)	53.4-72.0	63.0 ^{ab} (1.1)	56.1-74.5	63.3 ^{ab} (1.2)	53.4-73.3	64.6 ^b (1.2)
Silt (%)	18.4-30.5	25.1 ^b (0.72)	17.1-27.8	23.1 ^{ab} (0.62)	16.4-27.9	23.3 ^{ab} (0.70)	17.7-27.5	21.8 ^a (0.63)
Clay (%)	8.2-21.7	14.1 ^a (0.79)	9.5-18.9	13.1 ^a (0.58)	8.1-20.1	13.5 ^a (0.64)	8.2-19.9	13.6 ^a (0.69)
Available P (mg kg ⁻¹)	5.1-26.4	16.0 ^b (1.2)	6.2-19.6	14.1 ^b (0.74)	7.1-21.2	14.9 ^b (0.81)	5.1-25.1	9.8 ^a (0.91)
Available K (mg kg ⁻¹)	58-128	87 ^{ab} (4.3)	48-115	87 ^{ab} (3.9)	48-120	83 ^a (4.6)	58-143	100 ^b (6.0)
CaCO ₃ (g kg ⁻¹)	0-12.3	1.41 ^a (0.08)	0.0-18.3	2.53 ^a (0.12)	0.0-17.3	1.22 ^a (0.08)	0.0-19.5	1.73 ^a (0.10)

[†]Range represents the minimum-maximum values in the data set

[‡]Mean values for a soil property in a row followed by different letter are significantly ($p < 0.05$) different by Duncan's multiple range test (DMRT).

Another reason for lower inorganic P under agroforestry soils could be immobilization of P by microorganisms in their structural development to mineralize the organic residues added into the soil (Xavier *et al* 2011). Immobilization-mineralization of microbial P are the major processes regulating P cycling and availability from organic material in the soil (Oberson and Joner 2005, Bunemann *et al* 2006).

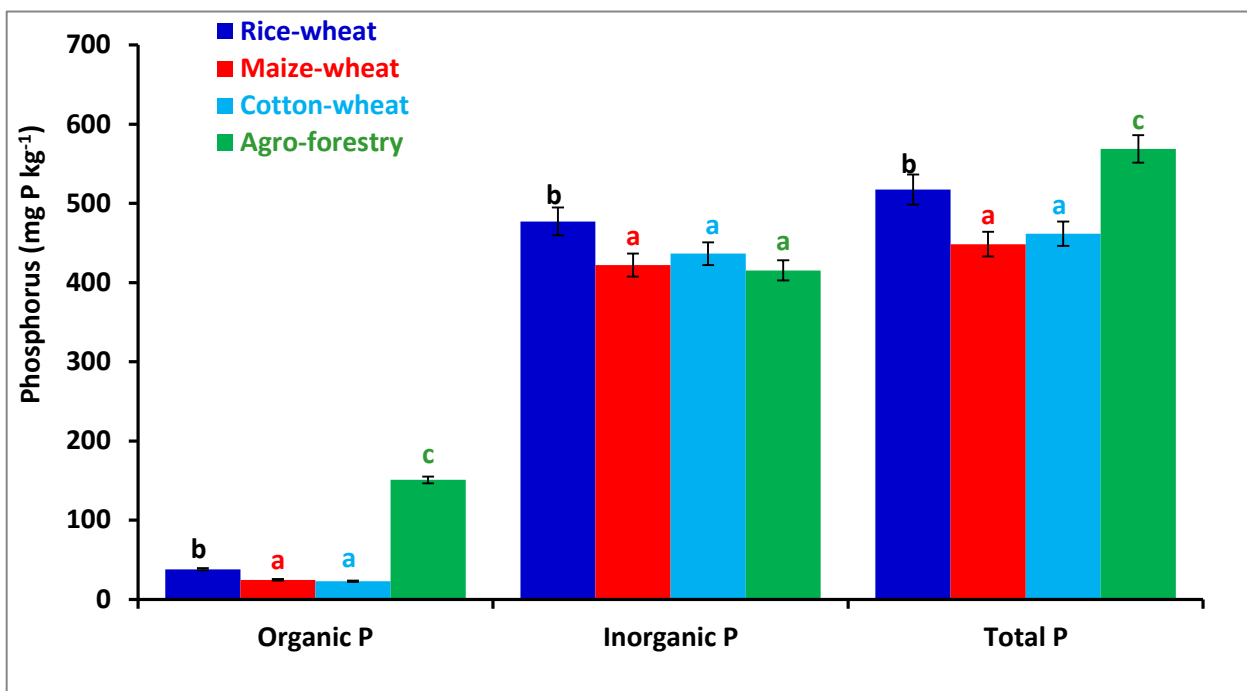


Fig 4.27 Distribution of organic, inorganic and total P pools in surface (0-15 cm) soils under rice-wheat, maize-wheat, cotton-wheat and agroforestry systems. Line bars represent standard error of mean. Mean values for a given soil phosphorus pool for different land-uses followed by different letters differ significantly ($p < 0.05$) by Duncan's multiple range test (DMRT)

Higher proportion of organic P relative to total P in the soils under agroforestry compared with conventional cropping has been attributed to the effect of agroforestry on the dynamics of P in the soils, through the conversion of inorganic P into organic P (Cardoso *et al* 2001) and the reduced tillage and higher deposition of root and leaf litters on the surface (Lobato *et al* 2014). In the present study, soil sampling sites under poplar based agroforestry were selected where this land-use was in progress for more than 15 years. Poplar being a deciduous tree shed its leaves during the winter season particularly in the months of December and January. Perrot *et al* (1992) reported that greater root biomass and increase in SOC under agroforestry favour microbial growth and microbial P immobilization and thus increase organic P accumulation (Beck and Sanchez 1994). Greater accumulation of organic, inorganic and total P in soils under rice-wheat compared with maize-wheat and cotton-wheat cropping systems may be attributed to the application of higher amount of organic manure ($8-9 \text{ Mg ha}^{-1} \text{ yr}^{-1}$) coupled with greater addition of plant biomass (roots and leaves) under rice-wheat system.

Water soluble inorganic P fraction represented 0.22, 0.19, 0.13 and 0.26% of inorganic P in soils under rice-wheat, maize-wheat, cotton-wheat and agroforestry systems, respectively. Iron associated inorganic P fraction represented 14.3, 16.4, 16.3 and 17.6% of inorganic P in soils under rice-wheat, maize-wheat, cotton-wheat and agroforestry systems, respectively. Calcium-aluminium associated inorganic P represented 74.8, 74.2, 75.0 and 73.5% of inorganic P in soils under rice-wheat, maize-wheat, cotton-wheat and agroforestry systems, respectively. Humic bound inorganic P represented 10.9, 9.2, 8.5 and 8.9% of inorganic P in soils under rice-wheat, maize-wheat, cotton-wheat and agroforestry systems, respectively.

The water soluble organic P fraction alone represented 2.42, 2.88, 3.17 and 0.71% of organic P in soils under rice-wheat, maize-wheat, cotton-wheat and agroforestry systems, respectively. Iron associated organic P fraction represented 7.0, 7.7, 6.3 and 3.8 % of organic P in soils under rice-wheat, maize-wheat, cotton-wheat and agroforestry systems, respectively. Calcium-aluminium associated organic P represented 18.9, 18.1, 14.6 and 17.61% of organic P in soils under rice-wheat, maize-wheat, cotton-wheat and agroforestry systems, respectively. Humic bound organic P represented 45.0, 38.4, 41.3 and 53.4% of organic P in soils under rice-wheat, maize-wheat, cotton-wheat and agroforestry systems, respectively. Acid soluble organic P represented 10.1, 11.2, 14.4 and 9.73% of organic P in soils under rice-wheat, maize-wheat, cotton-wheat and agroforestry systems, respectively. Sugar bound organic P represented 10.4, 11.3, 11.1 and 11.8% of organic P in soils under rice-wheat, maize-wheat, cotton-wheat and agroforestry systems, respectively. Nucleic acid organic P and polyphosphate represented 6.1, 9.0, 8.7 and 2.8% of organic P in soils under rice-wheat, maize-wheat, cotton-wheat and agroforestry systems, respectively.

Water soluble inorganic P concentration was significantly lower in soils under cotton-wheat, compared with other land-uses. It was higher by 44.6, 87.5 and 91.1% in maize-wheat, rice-wheat and agroforestry land-use systems, compared to cotton-wheat system. Water soluble organic P was significantly higher in soils under agroforestry, compared to other land-uses. Soils under rice-wheat showed significantly higher water soluble organic P concentration than the other two sole cropping systems. Iron associated inorganic P concentration did not differ significantly among different land-uses (Table 4.24). However, the concentration of iron associated organic P was significantly lower in soils under cotton-wheat cropping system, and was 81.5, 32.2 and 292.5% higher in soils under rice-wheat, maize-wheat and agroforestry compared to cotton-wheat cropping system. The concentration of calcium- aluminium associated inorganic P was significantly higher in soils under rice-wheat cropping system compared to other land-use. Irrespective of the land-use, the relative abundance of different inorganic P fractions followed the order calcium-aluminium associated inorganic P > iron associated inorganic P > humic bound inorganic P > water soluble inorganic P. Several studies (Aulakh *et al* 2003, Castillo and Wright 2008, Trivedi *et al* 2010, Dunne *et al* 2011, Jalali and Martin 2013) have reported similar trends of Ca-P, Al-P and Fe-P fractions in soils.

Table 4.24 Concentration (mean and range) of organic, inorganic and total P pools in the surface (0-15 cm) soils under different land-use. Numbers in parenthesis represent standard error.

P fractions (mg kg ⁻¹)	Land-use							
	Rice-wheat		Maize-wheat		Cotton-wheat		Agroforestry	
	Range [♦]	Mean [◇]	Range	Mean	Range	Mean	Range	Mean
H ₂ O-Pi [*]	0.52-1.38	1.05 ^c (0.04)	0.52-1.06	0.81 ^b (0.03)	0.32-0.83	0.56 ^a (0.03)	0.83-1.35	1.07 ^c (0.03)
Ca-EDTA-Pi [†]	47-87	68 ^a (2.6)	48-83	69 ^a (2.3)	49-93	71 ^a (2.4)	58-96	73 ^a (2.3)
Na-EDTA-Pi [‡]	242-451	357 ^b (13.0)	206-382	313 ^a (10.8)	229-423	328 ^{ab} (10.9)	247-394	305 ^a (9.5)
NaOH-Pi [►]	36-65	52 ^b (1.9)	25-48	39 ^a (1.4)	25-47	37 ^a (1.2)	29-48	37 ^a (1.1)
TPi [▼]	325-604	477 ^b (17.6)	280-514	422 ^a (14.5)	304-564	437 ^a (14.5)	335-539	415 ^a (12.9)
H ₂ O-Po [*]	0.59-1.14	0.92 ^b (0.04)	0.49-0.92	0.72 ^a (0.03)	0.52-0.93	0.73 ^a (0.03)	0.83-1.46	1.07 ^c (0.03)
Ca-EDTA-Po [†]	1.78-3.26	2.65 ^c (0.09)	1.33-2.34	1.93 ^b (0.07)	1.06-1.84	1.46 ^a (0.05)	4.61-7.42	5.73 ^d (0.18)
Na-EDTA-Po [‡]	5.09-9.08	7.18 ^b (0.24)	2.92-5.84	4.54 ^a (0.16)	2.74-4.28	3.36 ^a (0.09)	21.4-35.8	26.6 ^c (0.87)
H ₂ SO ₄ -Po [‡]	2.64-4.84	3.82 ^b (0.14)	1.96-3.44	2.79 ^a (0.10)	2.37-4.25	3.31 ^{ab} (0.11)	11.8-19.3	14.7 ^c (0.46)
_C TCA-Po [▲]	2.68-4.91	3.94 ^b (0.14)	1.88-3.37	2.82 ^a (0.10)	1.82-3.18	2.56 ^a (0.08)	14.4-23.2	17.8 ^c (0.55)
_H TCA-Po [▼]	1.69-2.91	2.33 ^b (0.08)	1.58-2.69	2.26 ^b (0.07)	1.41-2.51	2.00 ^a (0.06)	3.40-5.49	4.23 ^c (0.13)
NaOH-Po [►]	11.2-21.9	17.10 ^b (0.65)	7-13.8	9.60 ^a (0.44)	6.9-12.8	9.50 ^a (0.39)	64.1-106.7	80.6 ^c (2.2)
TPo [★]	26-48	38 ^b (1.3)	17-32	25 ^a (0.91)	17-30	23 ^a (0.78)	121-199	151 ^c (4.4)
Res-P [◄]	1.23-2.94	2.23 ^b (0.09)	0.90-2.36	1.82 ^a (0.08)	1.42-2.86	2.12 ^b (0.09)	1.97-3.43	2.52 ^c (0.09)
Total P	352-655	517 ^b (18.9)	298-549	449 ^a (15.4)	322-597	462 ^a (15.3)	457-742	569 ^c (17.3)

^{*}H₂O-Pi/Po=Water soluble inorganic and organic P, [†]Ca-EDTA-Pi/Po=Iron associated inorganic and organic P, [‡]Na-EDTA-Pi/Po=Calcium-aluminium associated inorganic and organic P, [‡]H₂SO₄-Po=Acid soluble organic P, [▲]_CTCA-Po=Sugar bound organic P, [▼]_HTCA-Po=Nucleic acid organic P and polyphosphate, [►]NaOH-Pi/Po=Humic bound inorganic and organic P, [◄]Res-P=Residual P, [★]TPo=Organic P, [▼]TPi=Inorganic P

[♦] Range represents the minimum-maximum values in the data set

[◇] Mean values for a given P fraction followed by different letters differ significantly ($p<0.05$) by Duncan's multiple range test (DMRT)

The calcium-aluminium associated inorganic P fraction represented 69.1, 69.7, 75.0 and 53.6% of total P in soils under rice-wheat, maize-wheat, cotton-wheat and agroforestry systems, respectively. This could be attributed to the formation of insoluble Ca-P compounds in these soils having calcareous nature as Ca^{2+} activity in the liquid phase is mainly responsible for formation of insoluble Ca-phosphate mineral in calcareous soil (Tunesi *et al* 1999). In calcareous soils, the accumulation of CaCO_3 is believed to govern soil P reactions (Lindsay 1979) because of its adsorption and precipitation on the CaCO_3 surface (Freeman and Rowell 1981, Amer *et al* 1985). Relatively lower proportion of calcium-aluminium associated inorganic P in soils under agroforestry may be attributed to the effect of organic matter returned to the soil through litter fall and root biomass that has the ability to solublize the native soil P (Gaume *et al* 2001, Boschetti *et al* 2009). Apatite is the primary mineral of P which represents the calcium associated P in soils, P from this mineral is not readily available to plants (Williams *et al* 1980). Organic acids such as oxalic and citric acids are released during the decomposition of soil organic matter and ectomycorrhizal fungi, may increase calcium phosphate dissolution. Excretion of carboxylate, enzymes, and protons by roots and fungi participate in ligand exchange reactions with sesquioxides thereby increases the P molecules into soil solution (Gaume *et al* 2001, Zhou *et al* 2009). Several studies (Aulakh and Pasricha 1991, Guo *et al* 2000) have reported that in less weathered and subtropical soils, the excess P from fertilizer tends to accumulate as calcium associated inorganic P with fertilizer P and organic manure application. After that unused P tends to transform into iron and aluminium P in non-calcareous and calcareous soils (McLaughlin *et al* 2011). In slightly weathered soils calcium associated inorganic P can be gradually convert into available P (Guo *et al* 2000). Humic bound P pools acts as a P sink when the system is fertilized and as a source when available P is being depleted (Beck and Sanchez 1994).

Concentration of organic P fractions viz. calcium associated organic P, acid soluble organic P, sugar bound organic P, nucleic acid organic P and polyphosphate, and humic bound organic P was significantly higher in soils under agroforestry than other land-uses. Except nucleic acid organic P and polyphosphate, all the organic P fractions were significantly higher under rice-wheat compared to other two cropping systems (Table 4.2). Hedley *et al* (1982) has reported that organic P compounds are mainly associated with rapidly to slowly decomposable organic molecules, such as nucleic acids, phospholipids, sugar phosphates, inositol phosphates, and recalcitrant humic substances.

Phosphorus dynamics in soil are controlled by the combinations of dissolution-precipitation, sorption-desorption and mineralization-immobilization reactions (Frossard *et al* 2000) which in turn influenced by the soil properties such as soil texture, SOC, CaCO_3 (Trivedi *et al* 2010, Hadgu *et al* 2014) and available P that respond to agricultural management and land-use change (Aguar *et al* 2013). The change with time in applied P in soil is governed by organic matter content, application of organics, cropping systems and fertilizer P (Reddy *et al* 1999). Improvement in SOC with organic manure application enhances soil microbial biomass,

and thereby alters P availability through mineralization-immobilization reactions (Chen *et al* 2003, Sigua *et al* 2009).

4.3.3 Soil organic carbon pools

The effect of different land-use systems on SOC concentration and its labile pools viz. HWSC and $\text{KMnO}_4\text{-C}$ are given in table 4.25. Averaged across sites, SOC concentration was the highest under agroforestry and the lowest under cotton-wheat cropping system. While maize-wheat and cotton-wheat system exhibited similar SOC concentration. The rice-wheat system had significant higher SOC concentration than two cropping systems but significantly lower than agroforestry systems. Significantly higher concentration of SOC in soils under agroforestry compared to sole cropping systems could be attributed to the effect of large return of plant biomass C through leaf litter and reduced tillage practices under agroforestry.

Bene *et al* (2011) has reported that soil organic matter is closely related to the amount of above and below ground organic matter inputs. Lobato *et al* (2014) has reported that reduced tillage and its duration tends to build-up SOC under agroforestry than the sole cropping systems. In many long-term experiments, researchers have shown a significant relationship between C input through plant biomass and organic manures with SOC sequestration (Benbi *et al* 2012, Huang *et al* 2014). The results of the present investigation corroborates the findings of Benbi *et al* (2012), who also reported higher SOC concentration under agroforestry than in soils under rice-wheat cropping system. The comparison of three cropping systems revealed significantly higher SOC concentration in the soils under rice-wheat than the maize-wheat and cotton-wheat cropping systems. This could be attributed to retarded rate of soil organic matter decomposition due to prevailing anaerobic conditions during rice cultivation (Manlay *et al* 2002). Since rice-wheat cropping involves cultivation of wetland and upland crops in sequence, it experiences alternate wetting and drying and thus differential stabilization of soil organic matter, compared to the other two cropping systems which are grown under upland conditions.

The concentration of HWSC was significantly higher in soils under agroforestry and rice-wheat than the maize-wheat and cotton-wheat cropping systems (Table 4.25). Lower HWSC under sole cropping systems than agroforestry could be possibly due to intensive cultivation which includes several times tillage practices per year leads to greater breakdown of SOM or decomposition of native SOC (Wardle 1992, Haynes 2000, Ghani *et al* 2003, Shi *et al* 2015). Greater rhizo-deposition of root mass and exudates in soils under agroforestry also influences turnover rate of C (Kuzyakov *et al* 2001).

The concentration of $\text{KMnO}_4\text{-C}$ was significantly higher in soils under agroforestry than the other land-uses. The soils under maize-wheat and cotton-wheat cropping systems did not differ significantly for their effect on $\text{KMnO}_4\text{-C}$. Higher concentration of HWSC and $\text{KMnO}_4\text{-C}$ in soils under agroforestry indicates the quantitative as well as qualitative differences in soil organic matter compared to other land-uses.

Table 4.25 Mean and range values of soil organic carbon (SOC), hot water soluble carbon (HWSC) and potassium permanganate oxidizable carbon (KMnO₄-C) in the surface (0-15 cm) soils under different land-uses

Soil carbon pool	Land-use							
	Rice-wheat		Maize-wheat		Cotton-wheat		Agroforestry	
	Range [¶]	Mean [†]	Range	Mean	Range	Mean	Range	Mean
SOC (g C kg ⁻¹)	2.83-6.35	4.74 ^b (0.02) ^Δ	2.15-5.45	3.98 ^a (0.02)	2.38-5.68	3.94 ^a (0.02)	3.05-7.18	5.78 ^c (0.02)
HWSC (mg C kg ⁻¹)	168-327	246 ^b (10.4)	117-267	197 ^a (9.1)	111-264	193 ^a (9.5)	159-324	267 ^b (10.9)
KMnO ₄ -C (mg C kg ⁻¹)	557-1048	819 ^b (0.03)	206-974	665 ^a (0.04)	408-959	681 ^a (0.04)	566-1213	922 ^c (0.04)

[¶]Range represents the minimum-maximum values in the data set

[†]Mean values for a soil property followed by different letters differ significantly ($p < 0.05$) by Duncan's multiple range test (DMRT)

^Δ Value represents standard error from mean

4.3.4 Descriptive and multivariate statistical analysis

4.3.4.1 Correlation analysis

The descriptive and multivariate statistical analyses of various soil physical and chemical properties including soil P and C pools were carried out to understand the nature of relationship among different properties. The correlation analysis for various soil properties was performed for the data pooled across land-uses (Table 4.26). The correlation analysis revealed highly significant positive correlation between soil clay content and SOC concentration for soils under rice-wheat ($r=0.84^{**}$), maize-wheat ($r=0.65^{**}$), cotton-wheat ($r=0.59^{**}$) and agroforestry ($r=0.75^{**}$) systems. These results corroborate the findings of Singh and Singh (2007), who also observed a significant positive relationship between clay content and SOC. Silt content also showed highly significant correlation for all land-uses. However, there existed a significant negative correlation between SOC and sand content (Table 4.26). Labile pools of C viz. HWSC and $\text{KMnO}_4\text{-C}$ also exhibited significant correlation with clay content in all land-use systems. Further, SOC also exhibited a significant correlation with labile C pools, emphasizing the dynamic relationship among three pools. These results are in conformity with Yang *et al* (2012) who also reported that SOC is the major determinant of the amount of soil labile C fractions. Available P exhibited a significant positive correlation with clay content in soils under rice-wheat, maize-wheat and cotton-wheat cropping systems. However, non-significant correlation among soil available P and clay content for soils under agroforestry could be due to entirely different soil management system under agroforestry, compared with field crops. Further, regular application of fertilizer-P in soils under field crops might be the reason for significant relationship among these two soil properties (Table 4.26).

The relationship of soil P fractions with different soil physical and chemical properties of soil is presented in table 4.27. Soil organic carbon and labile C pools were significantly correlated with soil P pools. Water soluble inorganic and organic P showed significant correlation (0.53^{**} and 0.58^{**} , $p<0.01$) with soil clay content, indicating that the soils with higher clay content had higher concentration of water soluble inorganic and organic P. Iron and calcium-aluminium associated inorganic P also showed significantly linear relationship with soil clay content. The humic bound inorganic P exhibited a significant positive correlation with soil clay content, indicating the formation of clay-humus complexes in the soils affecting P availability in the soils (Table 4.27). On the contrary, these soil P pools had negative significant relationship with sand content.

The correlation matrix depicting relationship among soil organic C and P pools is given in table 4.28. In all the land-uses except for agroforestry, SOC, HWSC and $\text{KMnO}_4\text{-C}$ exhibited highly significant positive correlation with soil P fractions, indicating the role of SOC in determining P dynamics in soils.

Table 4.26 Correlation matrix depicting relationship among physical and chemical properties of soils under different land-uses

	pH	E.C.	Sand	Silt	Clay	SOC	KMnO ₄ -C	HWSC	Available P
Rice-wheat									
E.C.	-0.20								
Sand	0.17	-0.12							
Silt	-0.31	0.19	-0.94**						
Clay	-0.02	0.05	-0.95**	0.77**					
SOC	0.08	-0.28	-0.73**	0.53**	0.84**				
KMnO ₄ -C	0.11	-0.06	-0.80**	0.61**	0.88**	0.90**			
HWSC	-0.02	0.03	-0.83**	0.67**	0.87**	0.88**	0.95**		
Available P	0.09	0.03	-0.82**	0.64**	0.88**	0.76**	0.79**	0.76**	
Available K	0.04	0.17	-0.65**	0.46*	0.75**	0.71**	0.77**	0.76**	0.66**
Maize-wheat									
E.C.	-0.02								
Sand	-0.58**	0.16							
Silt	0.57**	-0.14	-0.94**						
Clay	0.50*	-0.16	-0.93**	0.75**					
SOC	0.26	-0.28	-0.60**	0.48*	0.65**				
KMnO ₄ -C	0.28	-0.23	-0.54**	0.46*	0.57**	0.92**			
HWSC	0.48*	-0.14	-0.71**	0.57**	0.77**	0.90**	0.87**		
Available P	0.42*	-0.36	-0.74**	0.63**	0.77**	0.61**	0.61**	0.72**	
Available K	0.45*	-0.11	-0.63**	0.46*	0.74**	0.60**	0.53**	0.63**	0.73**
Cotton-wheat									
E.C.	0.16								
Sand	-0.14	0.31							
Silt	0.22	-0.17	-0.88**						
Clay	0.01	-0.37	-0.86**	0.51*					
SOC	-0.03	-0.09	-0.40	0.12	0.59*				
KMnO ₄ -C	0.12	-0.01	-0.49*	0.20	0.66**	0.89**			
HWSC	0.00	-0.08	-0.56**	0.33	0.66**	0.89**	0.91**		
Available P	0.01	-0.26	-0.67**	0.56**	0.61**	0.56**	0.57**	0.57**	
Available K	0.09	-0.32	-0.44*	0.20	0.57**	0.65**	0.69**	0.60**	0.67**
Agroforestry									
E.C.	-0.17								
Sand	0.22	0.15							
Silt	-0.16	0.01	-0.92**						
Clay	-0.24	-0.28	-0.93**	0.71**					
SOC	-0.33	-0.18	-0.72**	0.58**	0.75**				
KMnO ₄ -C	-0.09	-0.15	-0.73**	0.63**	0.71**	0.89**			
HWSC	-0.25	-0.16	-0.71**	0.59**	0.72**	0.95**	0.88**		
Available P	0.30	-0.24	-0.17	0.01	0.29	-0.17	-0.07	-0.07	
Available K	-0.08	-0.24	-0.54**	0.28	0.69**	0.26	0.25	0.24	0.62**

Data pooled for different land-uses									
E.C.	-0.10								
Sand	-0.20*	0.14							
Silt	0.25	-0.08	-0.92						
Clay	0.12	-0.18	-0.92	0.69					
SOC	-0.31**	-0.06	-0.43**	0.24*	0.57**				
KMnO ₄ -C	-0.16	-0.05	-0.50	0.32	0.60	0.91			
HWSC	-0.18	-0.01	-0.57**	0.40**	0.66**	0.93**	0.91**		
Available P	0.40**	-0.25*	-0.63**	0.53**	0.62**	0.08	0.18	0.22*	
Available K	-0.06	-0.09	-0.48**	0.24*	0.64**	0.54**	0.54**	0.54**	0.44**

*Correlation is significant at $p < 0.05$ level (2-tailed)

**Correlation is significant at $p < 0.01$ level (2-tailed)

Table 4.27 Correlation matrix depicting relationship among physical and chemical properties of soils and various soil phosphorus fractions (Data pooled for different land-use)

Soil P pools	pH	Sand	Silt	Clay	SOC	KMnO ₄ -C	HWSC	Av. P	CaCO ₃
H ₂ O-Pi*	-0.14	-0.45**	0.29**	0.53**	0.63**	0.59**	0.65**	0.25*	0.06
H ₂ O-Po*	-0.27**	-0.48**	0.31**	0.58**	0.70**	0.68**	0.70**	0.22*	0.03
Ca-EDTA-Pi†	0.001	-0.66**	0.46**	0.76**	0.49**	0.56**	0.52**	0.57**	0.11
Ca-EDTA-Po†	-0.54**	-0.07	-0.06	0.19	0.67**	0.57**	0.58**	-0.22*	0.04
Na-EDTA-Pi‡	0.24*	-0.75**	0.59**	0.79**	0.37**	0.47**	0.47**	0.74**	0.09
Na-EDTA-Po‡	-0.58**	0.03	-0.14	0.09	0.63**	0.52**	0.52**	-0.31**	0.02
H ₂ SO ₄ -Po‡	-0.59**	0.03	-0.14	0.09	0.62**	0.51**	0.50**	-0.30**	0.02
cTCA-Po▲	-0.60**	0.05	-0.16	0.07	0.62**	0.50**	0.50**	-0.32**	0.02
H ₂ TCA-Po▼	-0.50**	-0.16	0.001	0.29**	0.68**	0.60**	0.59**	-0.12	0.05
NaOH-Pi►	0.29**	-0.69**	0.58**	0.70**	0.34**	0.42**	0.47**	0.65**	0.06
NaOH-Po►	-0.60**	0.06	-0.17	0.06	0.62**	0.49**	0.50**	-0.33**	0.01
Res-P◄	-0.22*	-0.51**	0.33**	0.61**	0.64**	0.66**	0.65**	0.33**	0.03
TPo♦	-0.59**	0.04	-0.15	0.08	0.63**	0.51**	0.51**	-0.32**	0.02
TPi♥	0.22*	-0.75**	0.59**	0.80**	0.40**	0.49**	0.50**	0.73**	0.09
Total P	-0.17	-0.59**	0.39**	0.69**	0.69**	0.70**	0.70**	0.40**	0.09

*H₂O-Pi/Po=Water soluble inorganic and organic P, †Ca-EDTA-Pi/Po=Iron associated inorganic and organic P, ‡Na-EDTA-Pi/Po=Calcium-aluminium associated inorganic and organic P, ‡H₂SO₄-Po=Acid soluble organic P, ▲cTCA-Po=Sugar bound organic P, ▼H₂TCA-Po=Nucleic acid organic P and polyphosphate, ►NaOH-Pi/Po=Humic bound inorganic and organic P, ◄Res-P=Residual P, ♦TPo=Organic P, ♥TPi=Inorganic P

*Correlation is significant at $p < 0.05$ level (2-tailed)

**Correlation is significant at $p < 0.01$ level (2-tailed)

The probable reason for relatively lower values of correlation coefficient (r) in soils under agroforestry is the prevailing entirely different soil management system, compared with the other cropping systems. Under agroforestry, soils are least disturbed because of restricted soil tillage, which affects the oxidative losses of SOC. The differences in soil management results in differential stabilization of soil organic matter (Benbi *et al* 2012), which affects the mineralization-immobilization processes in the soil

system (Cardoso *et al* 2001). Data pooled for different land-use systems further, revealed the significance of SOC and its labile pools in dictating the dynamics of soil P among different pools.

4.3.4.2 Discriminant Function Analysis (DFA)

Discriminant function analysis showed that a composite of soil indicators encompassing SOC, calcium carbonate and different P fractions could be used to distinguish different land-use (Table 4.29, Figure 4.28). The results of DFA revealed that three significant canonical functions involving different soil indicators could distinguish different land-use, appropriately grouping 100% of the samples. The first two functions (Function 1 and Function2) with Eigenvalues of 59.8 and 38.4 explained 53.6 and 34.5% of total variance in the data (Table 4.30). The third discriminant function (Function3) with an Eigenvalues of 13.3, explained only 11.9% of total variance. Rice-wheat, maize-wheat and cotton-wheat cropping systems, were clearly apart from agroforestry (Figure 4.28). The three sole cropping systems were however appeared within a single quadrant. This variation could be attributed to differences in soil management under agroforestry, compared with the other land-uses.

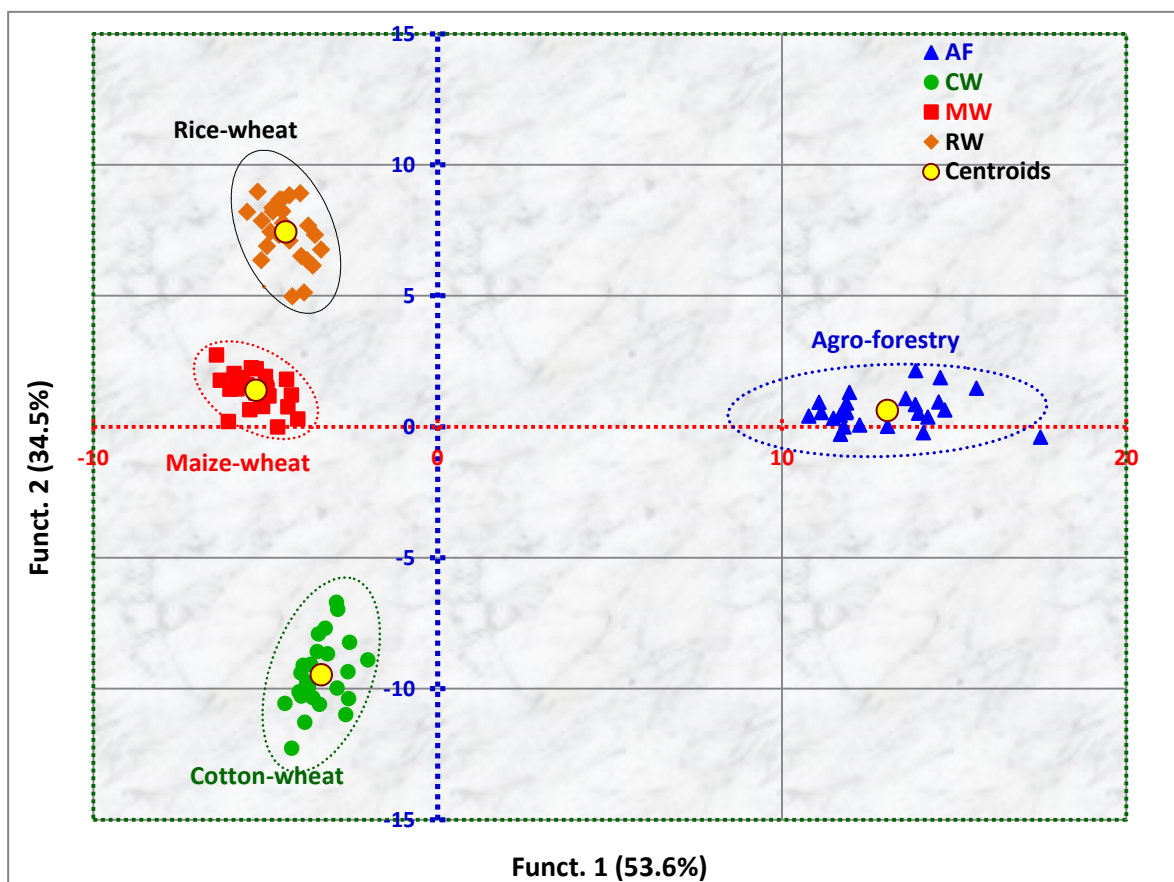


Fig 4.28 Plot of Canonical Discriminant Functions for separating soils under different land-use

Table 4.28 Correlation matrix depicting relationship between different soil organic carbon and phosphorus pools in soils under different land-uses

Soil carbon pool	Inorganic P					Organic P									Res-P	Total P
	H ₂ O-Pi	Ca-EDTA-Pi [†]	Na-EDTA-Pi [‡]	NaOH-Pi [►]	▼TPi	H ₂ O-Po	Ca-EDTA-Po [†]	Na-EDTA-Po [‡]	H ₂ SO ₄ -Po [‡]	cTCA-Po [▲]	hTCA-Po [▼]	NaOH-Po [►]	▲TPo			
Rice-wheat cropping system																
SOC	0.74**	0.66**	0.68**	0.64**	0.68**	0.64**	0.68**	0.60**	0.66**	0.67**	0.65**	0.74**	0.71**	0.68**	0.68**	
KMnO ₄ -C	0.71**	0.64**	0.67**	0.64**	0.66**	0.63**	0.67**	0.58**	0.64**	0.65**	0.63**	0.66**	0.66**	0.73**	0.66**	
HWSC	0.68**	0.64**	0.67**	0.64**	0.66**	0.67**	0.66**	0.58**	0.64**	0.66**	0.65**	0.68**	0.68**	0.76**	0.66**	
Maize-wheat cropping system																
SOC	0.58**	0.67**	0.68**	0.68**	0.68**	0.57**	0.69**	0.68**	0.71**	0.67**	0.65**	0.61**	0.68**	0.71**	0.69**	
KMnO ₄ -C	0.60**	0.69**	0.70**	0.71**	0.70**	0.65**	0.69**	0.72**	0.73**	0.67**	0.69**	0.59**	0.69**	0.70**	0.70**	
HWSC	0.65**	0.74**	0.76**	0.73**	0.76**	0.67**	0.79**	0.76**	0.76**	0.71**	0.71**	0.70**	0.77**	0.71**	0.76**	
Cotton-wheat cropping system																
SOC	0.53**	0.62**	0.60**	0.62**	0.61**	0.46**	0.58**	0.51**	0.59**	0.66**	0.55**	0.45**	0.53**	0.54**	0.61**	
KMnO ₄ -C	0.55**	0.67**	0.66**	0.67**	0.67**	0.56**	0.65**	0.62**	0.67**	0.69**	0.62**	0.51**	0.60**	0.60**	0.66**	
HWSC	0.53**	0.63**	0.63**	0.63**	0.63**	0.51**	0.62**	0.57**	0.62**	0.66**	0.58**	0.46**	0.56**	0.55**	0.63**	
Agroforestry																
SOC	0.21	0.36	0.30	0.34	0.31	0.38	0.32	0.35	0.33	0.33	0.33	0.32	0.33	0.26	0.32	
KMnO ₄ -C	0.33	0.46*	0.42*	0.50*	0.44*	0.46*	0.43*	0.48*	0.44*	0.44*	0.45*	0.39	0.43*	0.36	0.44*	
HWSC	0.25	0.41*	0.35	0.39	0.37	0.39	0.37	0.40	0.39	0.38	0.37	0.32	0.36	0.29	0.37	

*H₂O-Pi/Po=Water soluble inorganic and organic P, †Ca-EDTA-Pi/Po=Iron associated inorganic and organic P, ‡Na-EDTA-Pi/Po=Calcium-aluminium associated inorganic and organic P, §H₂SO₄-Po=Acid soluble organic P, ▲cTCA-Po=Sugar bound organic P, ▼hTCA-Po=Nucleic acid organic P and polyphosphate, ►NaOH-Pi/Po=Humic bound inorganic and organic P, ◀Res-P=Residual P, ▲TPo=Organic P, ▼TPi=Inorganic P

*Correlation is significant at $p < 0.05$ level (2-tailed)

**Correlation is significant at $p < 0.01$ level (2-tailed)

Table 4.29 Canonical Discriminant Function coefficients for group separation viz. rice-wheat, maize-wheat, cotton-wheat and agroforestry system

Variable	Standardized Canonical Discriminant Functions		
	Funct.1	Funct.2	Funct.3
SOC	0.20	0.12	0.12
H ₂ O-Pi [*]	-0.23	0.87	-0.06
H ₂ O-Po [*]	0.05	0.48	-0.59
Ca-EDTA-Pi [†]	0.56	-2.81	4.99
Ca-EDTA-Po [†]	-1.29	6.39	1.57
Na-EDTA-Pi [‡]	-0.22	-2.16	-7.27
Na-EDTA-Po [‡]	-1.26	0.79	-0.65
H ₂ SO ₄ -Po [‡]	-1.03	-3.61	-5.28
^c TCA-Po [▲]	4.47	-2.72	1.47
^H TCA-Po [▼]	-1.95	1.87	6.08
NaOH-Pi [#]	0.50	0.58	-0.65
NaOH-Po [#]	0.92	-0.06	-0.28

*H₂O-Pi/Po=Water soluble inorganic and organic P, †Ca-EDTA-Pi/Po=Iron associated inorganic and organic P, ‡Na-EDTA-Pi/Po=Calcium-aluminium associated inorganic and organic P, ‡H₂SO₄-Po=Acid soluble organic P, ▲^cTCA-Po=Sugar bound organic P, ▼^HTCA-Po=Nucleic acid organic P and polyphosphate, #NaOH-Pi/Po=Humic bound inorganic and organic P

Table 4.30 Eigenvalues, per cent variance, cumulative variance and canonical correlation for the first three functions used in Discriminant Function Analysis (DFA)

Canonical function	Eigen value	% of variance	Cumulative variance (%)	Canonical correlation
Funct. 1	59.8	53.6	53.6	0.992**
Funct. 2	38.4	34.5	88.1	0.987**
Funct. 3	13.3	11.9	100	0.964**

**Correlation significant at $p < 0.01$.

Total P concentration was the highest under agroforestry followed by rice-wheat, cotton-wheat, and the lowest under maize-wheat systems. Inorganic P was the dominant fraction, which accounted for more than 92% of total P in soils under sole cropping systems. However, soils under agroforestry had relatively smaller proportion (72.9%) of total P occurring as inorganic P. Therefore, agroforestry systems had relatively higher proportion of organic P (27%) than the other land-uses (6-7.7%). Water soluble inorganic P represented the smallest proportion (0.13-0.26%) of inorganic P in soils. Calcium-aluminium associated inorganic P represented the largest proportion (73.5-75%) of total inorganic P in soils under different land-uses. Humic-bound organic P represented the largest proportion (38.4-53.4%) of organic P in soils under different land-uses. Irrespective of the land-use, the relative abundance of different inorganic P fractions followed the order calcium-aluminium associated inorganic P > iron associated inorganic P > humic-bound inorganic P > water soluble inorganic P. Available P in soil was positively correlated with clay content in soils under sole cropping systems. Soil P fractions showed significant correlation with SOC. However, inorganic and available P were lower in soils under agroforestry, compared to other land-uses, suggesting that P cycling depends on the land-use and their nutrient management practices. Therefore, fertilizer-P application may be required for intercrop under agroforestry systems.

4.4 Phosphorus release and sorption-desorption kinetics in soils of differing clay, available P, organic carbon and CaCO₃ content

4.4.1 Basic soil properties

Important physical and chemical properties of the sixteen soils (0-15 cm depth) selected for studying P release and sorption-desorption kinetics are presented in table 4.31. The soils were non-saline and near neutral in reaction. The soil samples collected from different districts of Punjab were categorized into four groups based on in clay content (8-20%), available P (5-25 mg P kg⁻¹), soil organic carbon (2.2-7.2 g kg⁻¹), and calcium carbonate content (0-2%) (Table 4.31). Each group had four soils varying in a given property, with almost similar other properties. Soils in group-I and II were low in organic C (2.83-3.43 g kg⁻¹) and those in group-IV were in medium category (4.85-5.08 g kg⁻¹) (Table 4.31). All the soils in group I, II and III except soil-6 in group- II were non-calcareous (nil CaCO₃).

Table 4.31 Important physical and chemical properties of the surface (0-15 cm) soil samples selected for phosphorus release and sorption-desorption kinetics studies

Soil /Group	pH	EC (dS m ⁻¹)	SOC (g kg ⁻¹)	Available P (mg kg ⁻¹)	Calcium carbonate (%)	Soil texture		
						Sand (%)	Silt (%)	Clay (%)
Group-I								
Soil-1	7.6	0.30	3.05	10.4	0	71.5	20.3	8.2
Soil-2	7.4	0.36	3.13	11.0	0	58.5	29.0	12.6
Soil-3	7.8	0.37	3.13	9.4	0	59.6	24.1	16.2
Soil-4	7.6	0.24	3.43	11.2	0	56.3	23.7	20.1
Mean	7.6	0.32	3.18	10.5	0	61.5	24.3	14.3
Group-II								
Soil-5	7.7	0.26	2.98	5.11	0	67.2	22.6	10.2
Soil-6	7.7	0.31	2.83	12.4	0.1	64.6	25.0	10.4
Soil-7	7.5	0.24	3.13	18.3	0	65.9	23.6	10.6
Soil-8	7.6	0.31	3.05	25.1	0	68.4	21.0	10.6
Mean	7.6	0.28	2.99	15.2	0	66.5	23.1	10.4
Group-III								
Soil-9	7.8	0.28	2.15	15.9	0	62.8	23.0	14.3
Soil-10	7.6	0.34	3.95	16.3	0	65.2	20.3	14.4
Soil-11	7.3	0.26	5.68	16.8	0	69.4	16.4	14.2
Soil-12	7.2	0.29	7.18	15.7	0	66.1	19.2	14.7
Mean	7.5	0.29	4.74	16.2	0	65.9	19.7	14.4
Group-IV								
Soil-13	7.3	0.33	4.93	16.8	1.5	66.8	18.0	15.3
Soil-14	7.5	0.22	4.85	14.2	0.6	68.1	16.7	15.2
Soil-15	7.2	0.37	5.00	13.4	0	64.8	20.0	15.2
Soil-16	7.3	0.25	5.08	16.6	2.0	67.2	17.7	15.1
Mean	7.3	0.29	4.96	15.2	1.0	66.7	18.1	15.2

[†]EC=Electrical conductivity, [‡]SOC=Soil organic carbon

4.4.2 Kinetics of phosphorus release from soils

Cumulative P release increased with shaking time, indicating the mobilization and release of P (Figure 4.29). Amount of cumulative P released was the highest after 96 h of equilibration. Cumulative P release was more during the initial period and then gradually levelled off as the shaking time progressed. The release of P in these soils proceeded in two phases: an initial rapid release phase followed by a period of slow release. Initial fast P release from the soils was due to the release of P from the labile P pools, followed by a slower P release due to the conversion of non-labile (or semi-labile P pools) to labile P pools (Hundal *et al* 1988). The initial faster reaction corresponds to rapid dissolution of poorly crystalline and amorphous phosphates in the soil (Griffin and Jurinak 1974) and thus results in the release of greater release of P in the equilibrium solution.

In group-I, the amount of P released was the highest in Soil-1 having the lowest amount of clay. As the clay content increased, the amount of P released decreased (Figure 4.29). In general, the amount of P released followed the order Soil-1>Soil-2>Soil-3>Soil-4 in soils categorized under group-I. Wang *et al* (2011) has earlier reported P released declined more quickly from silt loam compared from silty clay loam soils. However, in the soils under group-II, the highest amount of P released was from Soil-8, having the highest concentration of available P among four soils group-II (Figure 4.29). In the soils under group-II, the amount of P released followed the order; Soil-8>Soil-7>Soil-6>Soil-5. Likewise, the amount of P released under group-III varying on the basis of SOC concentration and was the highest in Soil-12. The amount of P released was higher in soils with high SOC concentration (Soil-12>Soil-11>Soil-10>Soil-9). In the soils under group-IV, the highest amount of P released occurred from non-calcareous soil (Soil-15) and the lowest from the calcareous soil (Soil-16), having the highest concentration of CaCO_3 among the four soils in the group (Figure 4.29).

Six different kinetic models viz. zero order (Figure 4.29), first order (Figure 4.30), second order (Figure 4.31), power function (Figure 4.32), Elovich equation (Figure 4.33) and parabolic diffusion equations (Figure 4.34) were fitted by least square method. Phosphorus release was best described by Elovich and power function equations as indicated by higher coefficient of determination ($R^2 \geq 0.97^{**}$ for Elovich and $R^2 \geq 0.90^{**}$ for power function) closely followed by parabolic diffusion equation ($R^2 \geq 0.78^{**}$) (Table 4.32). Earlier, Chien and Clayton (1980) and Ghosh and Singh (2000) also observed superiority of Elovich equation over others models. The release constants estimated from Elovich equation, parabolic diffusion and power function equations are presented in table 4.33. Elovich equation constants ' α ' and ' β ' were the lowest for Soil-4 and the highest for Soil-1, indicating higher release from P from soil having low clay content (group-I), compared to the soil having higher clay content. The effect of available P on release constants of Elovich equation is clear from lowest values of ' α ' and ' β ' for Soil-5 and highest for Soil-8 (Table 4.33). Similarly, the soils with higher concentration of SOC had higher

values of ' α ' and ' β ', compared to the soils with lower concentration of SOC. Likewise, the values of ' α ' and ' β ' were considerably higher for non-calcareous soil (Soil-15), and decreased in all the calcareous soils in proportion to the increase in the concentration of CaCO_3 . The release constants deduced from parabolic diffusion equation (R and C) and power function equation (K_A and b), exhibited a similar trend to that of Elovich equation in response to the change in soil physical and chemical property (Table 4.33).

A stepwise regression analysis for Elovich coefficient ' α ' showed that inclusion of terms for clay, SOC and available P accounted for 55% variability in data ($R^2=0.55^*$, $n=16$) (Eq. 1, Table 4.34). Inclusion of a term for CaCO_3 in the equation improved the predictability to 70% ($R^2=0.70^{**}$, Eq. 2). The Elovich constant ' β ' showed higher relationship with soil properties than ' α '. Clay, SOC and available P accounted for 82% variation in β ($R^2=0.82^{**}$) and inclusion of CaCO_3 in equation improved the predictability to 90% ($R^2=0.90^{**}$). Parabolic diffusion constant ' R ' was relatively weakly correlated to soil properties. Clay, SOC and available P together accounted for 58% variation in Parabolic diffusion constant ' R ' ($R^2=0.58^*$; Eq. 5) and inclusion of a term for CaCO_3 improved the predictability to 71% ($R^2=0.71^{**}$, $p<0.01$). The predictability of Power function constant ' k_A ' did not change with the inclusion of CaCO_3 in the regression involving clay, SOC and available P ($R^2=0.91^{**}$, Eq. 9, and 10). However, the predictability of Power function constant ' b ' improved by about 5% with the inclusion of CaCO_3 in the equation ($R^2=0.81^{**}$, Eq. 12, Table 4.34).

These results suggest that soil clay content, available P, SOC and calcium carbonate content govern the availability of P in Indo-Gangetic alluvial soils.

4.4.3 Effect of different soil properties on phosphorus sorption

Soils showed wide variation in sorption behaviour (Figure 4.35). The equilibrium solution P concentration increased with increasing amount of P added. As the amount of P applied through CaCl_2 solution increased, the per cent of added P adsorbed in the soil decreased. The comparison of P sorption behaviour of soils groupified on the basis of clay content (Soils 1-4), revealed higher P sorption (at each applied P level) in soil having higher clay content. Greater P sorption in soils with higher clay content was because of higher active surface area that provided sites for P sorption. Adsorption being a surface phenomenon is directly related to surface area of the adsorbate. Wang *et al* (2011) reported that silt and clay particles have high specific surface area and high P retention capacity. In the soils of group-II, higher P sorption occurred in Soil-5, compared to other soils in the group, because of lower concentration of available P. Phosphorus sorption in soils of group-II decreased as the concentration of available P increased (Figure 4.35).

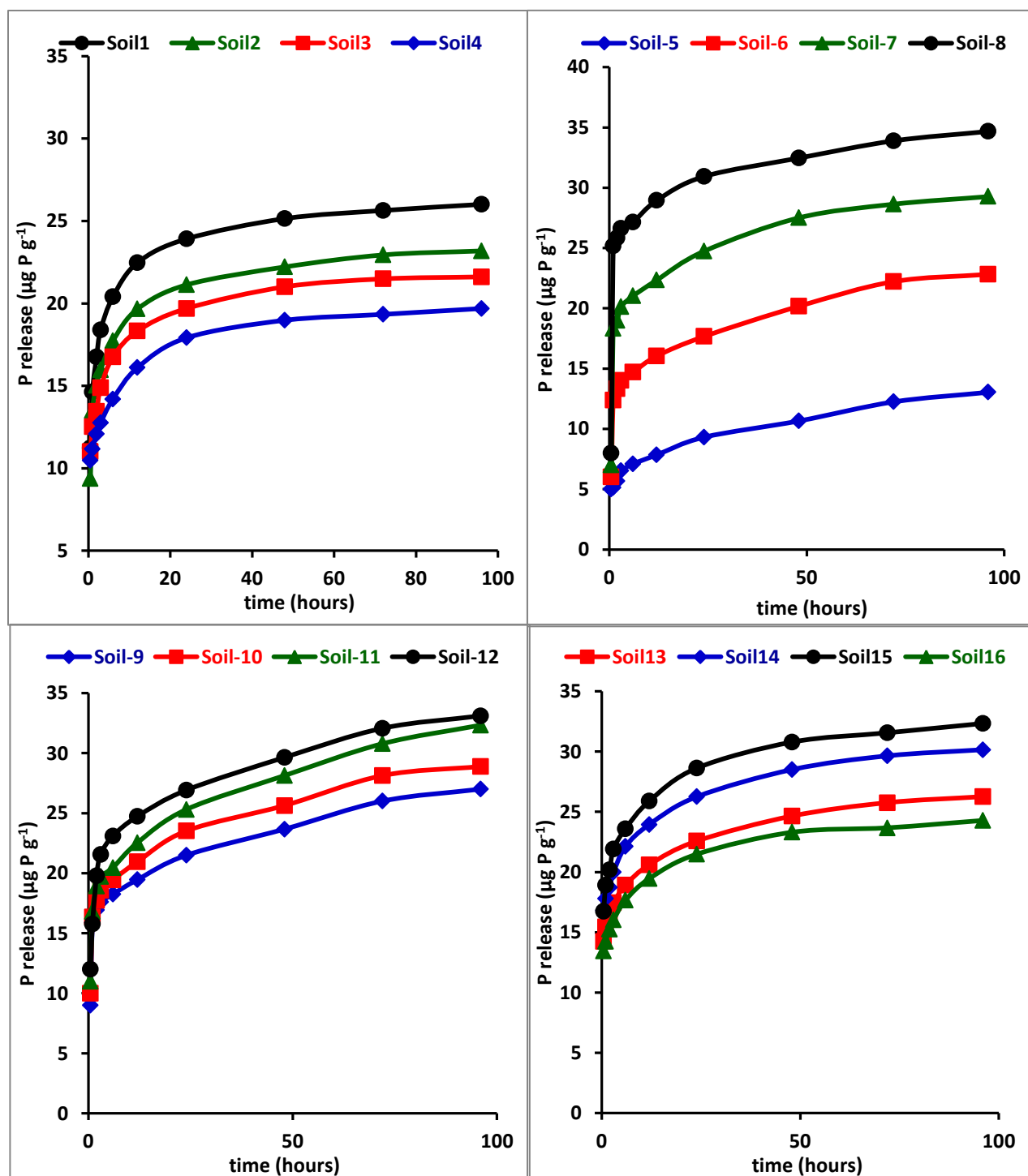


Fig 4.29 Time dependent change in P availability in soils varying in physical and chemical properties [Soils 1-4: based on soil clay content, Soil-5-8: based on available P concentration, Soils 9-12: based on soil organic carbon concentration, Soils 13-16: based on calcium carbonate concentration]

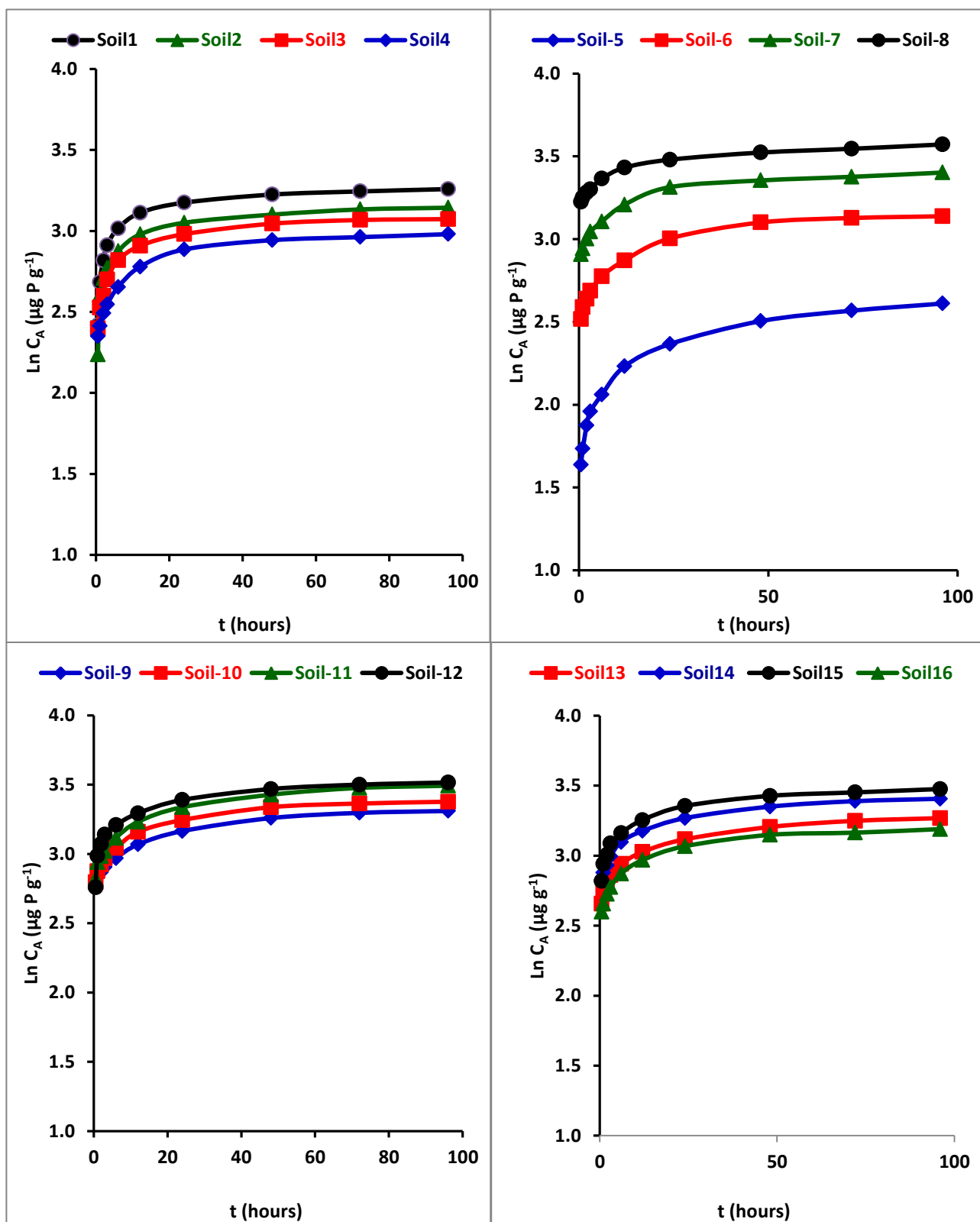


Fig 4.30 Kinetics of P release (First order kinetics) in soils varying in physical and chemical properties [C_A =amount of P release, t =time, Soils 1-4: based on soil clay content, Soil-5-8: based on available P concentration, Soils 9-12: based on soil organic carbon concentration, Soils 13-16: based on calcium carbonate concentration]

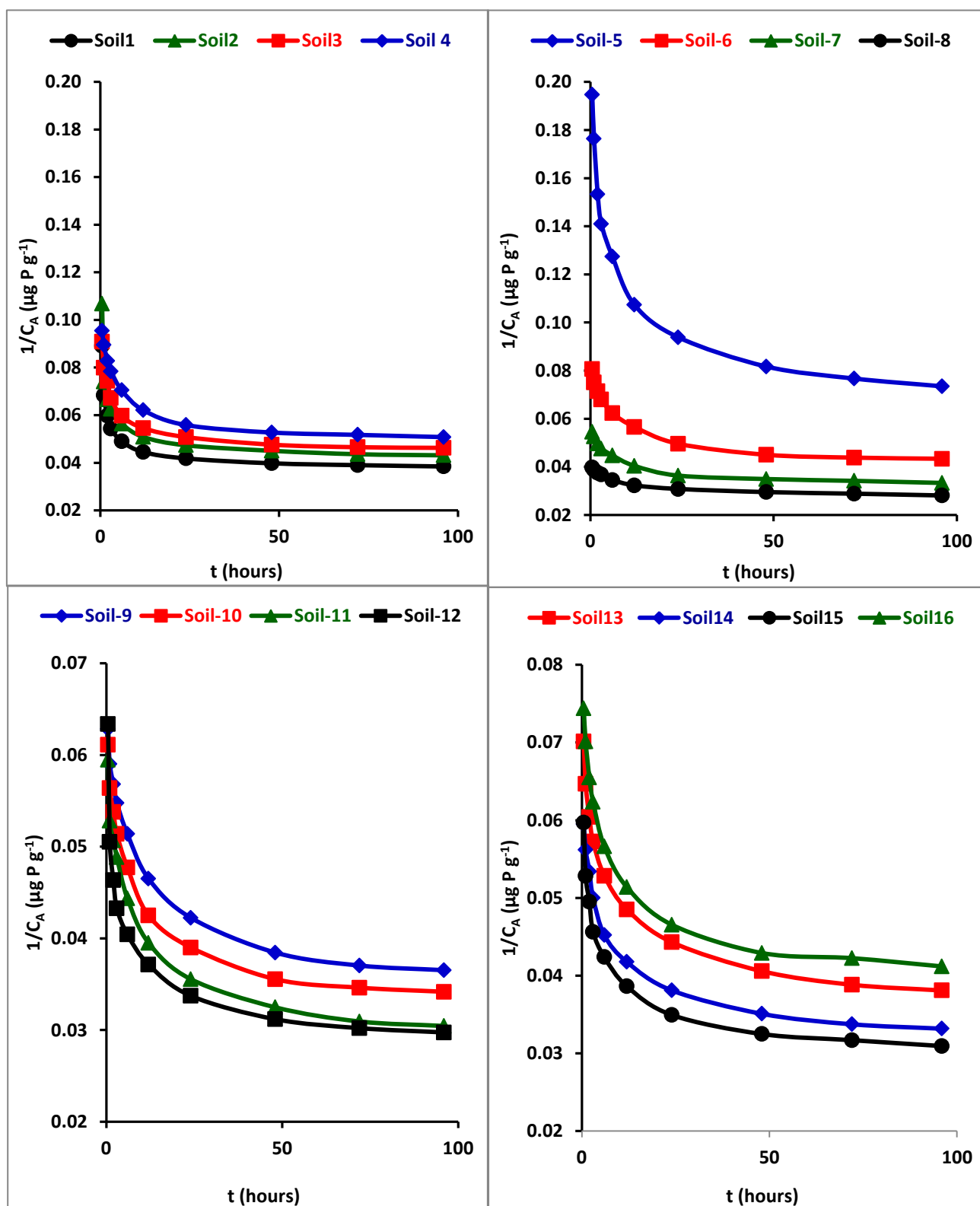


Fig 4.31 Kinetics of P release (Second order kinetics) in soils varying in physical and chemical properties [C_A =amount of P release, t =time, Soils 1-4: based on soil clay content, Soil-5-8: based on available P concentration, Soils 9-12: based on soil organic carbon concentration, Soils 13-16: based on calcium carbonate concentration]

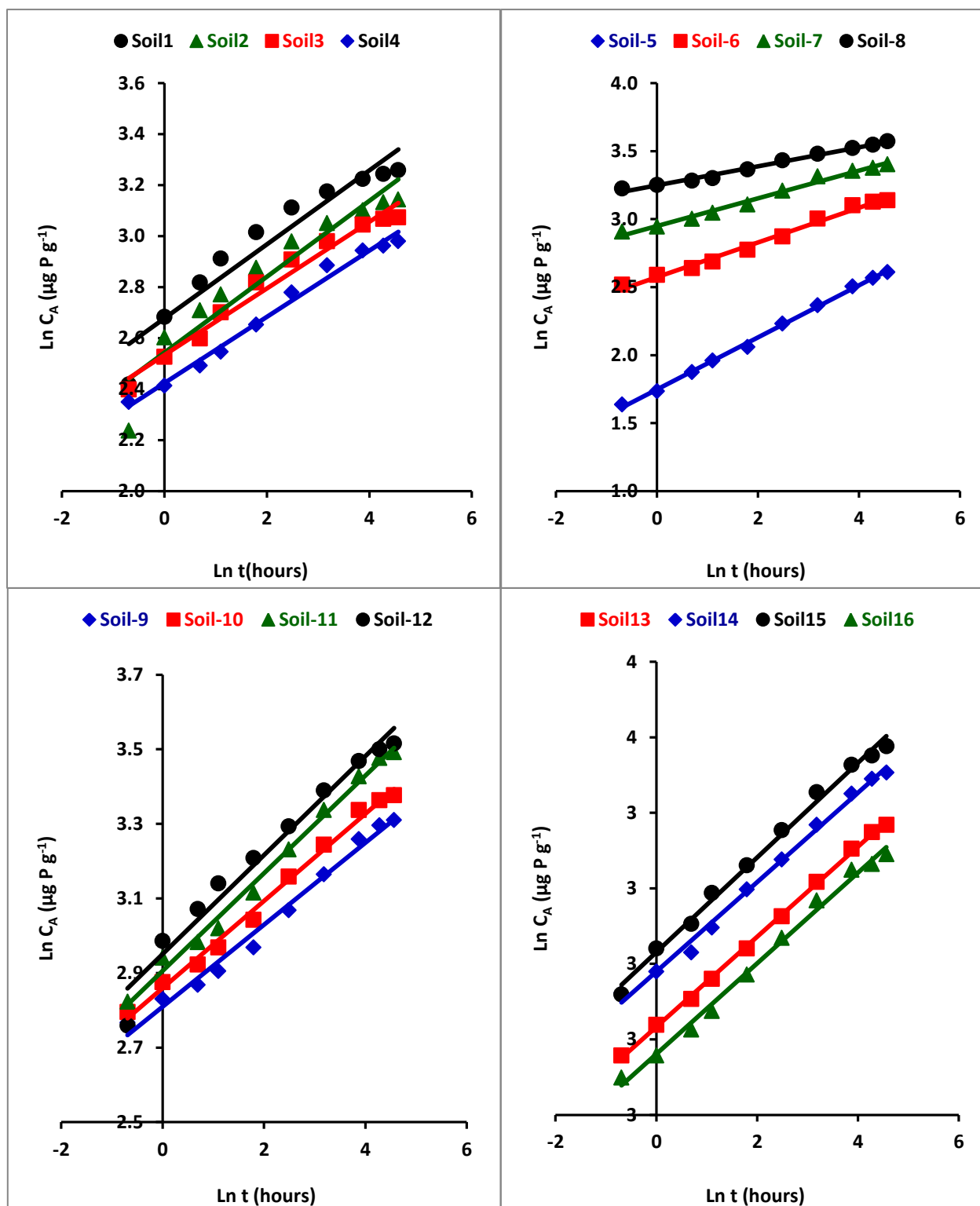


Fig 4.32 Kinetics of P release (Power function equation) in soils varying in physical and chemical properties [C_A =amount of P release, t =time, Soils 1-4: based on soil clay content, Soil-5-8: based on available P concentration, Soils 9-12: based on soil organic carbon concentration, Soils 13-16: based on calcium carbonate concentration]

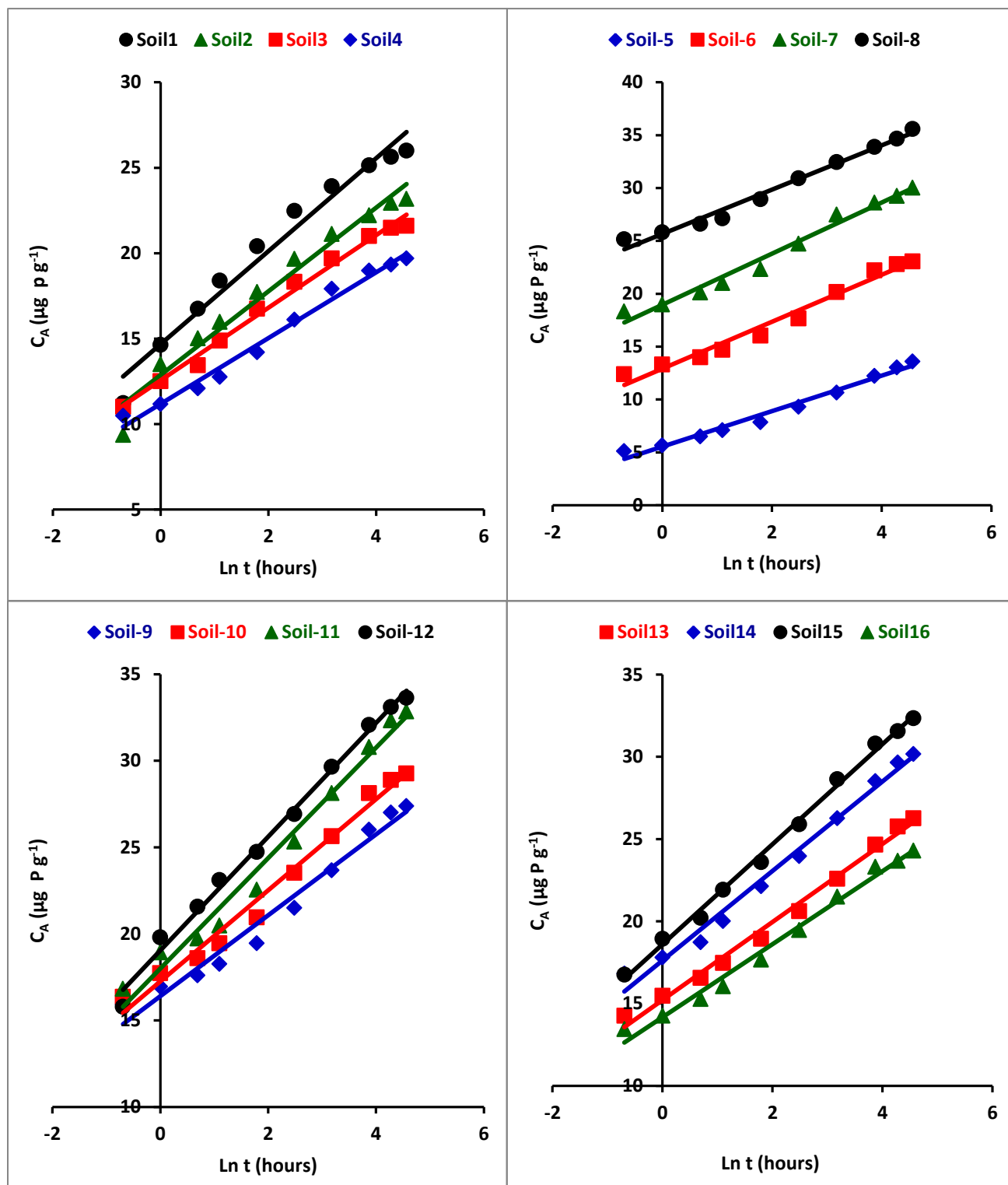


Fig 4.33 Kinetics of P release (Elovich equation) in soils varying in physical and chemical properties
 $[C_A$ =amount of P release, t =time, Soils 1-4: based on soil clay content, Soil-5-8: based on available P concentration, Soils 9-12: based on soil organic carbon concentration, Soils 13-16: based on calcium carbonate concentration]

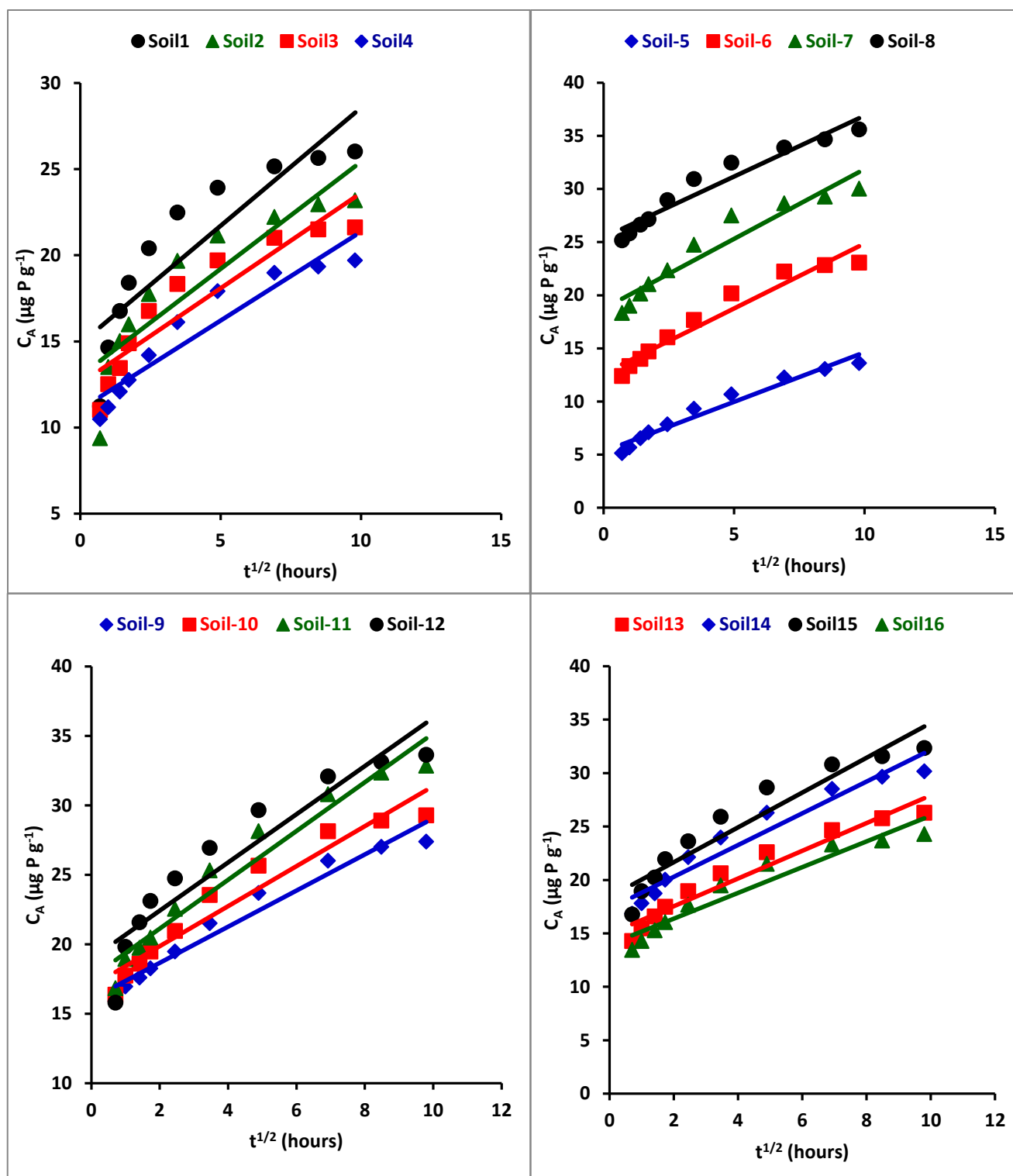


Fig 4.34 Kinetics of P release (Parabolic diffusion equation) in soils varying in physical and chemical properties [C_A =amount of P release, t =time, Soils 1-4: based on soil clay content, Soil-5-8: based on available P concentration, Soils 9-12: based on soil organic carbon concentration, Soils 13-16: based on calcium carbonate concentration]

Table 4.32 Statistical criteria for judging the suitability of different kinetic models fitted to describe the P release kinetics data for different soils varying in physical and chemical properties

Soil reference	ZOE [▼]			FOE [▲]			SOE [►]			PDE [◄]			PFE [◊]			EE [△]		
	S.E. _M [¶]	S.D. _M [†]	R ^{2‡}	S.E. _M	S.D. _M	R ²	S.E. _M	S.D. _M	R ²	S.E. _M	S.D. _M	R ²	S.E. _M	S.D. _M	R ²	S.E. _M	S.D. _M	R ²
Soil-1	1.13	3.57	0.60*	0.076	0.241	0.51	0.005	0.017	0.41	0.076	0.241	0.78**	1.13	3.57	0.92**	1.13	3.57	0.97**
Soil-2	1.25	3.94	0.62*	0.077	0.244	0.51	0.005	0.016	0.40	0.077	0.244	0.79**	1.25	3.94	0.90**	1.25	3.94	0.97**
Soil-3	1.45	4.59	0.68*	0.091	0.288	0.61*	0.006	0.020	0.55*	0.091	0.288	0.85**	1.45	4.59	0.98**	1.45	4.59	0.99**
Soil-4	1.61	5.09	0.74**	0.088	0.278	0.68*	0.005	0.016	0.63*	0.088	0.278	0.90**	1.61	5.09	0.99**	1.61	5.09	0.99**
Soil-5	0.99	3.13	0.92**	0.112	0.353	0.75**	0.014	0.043	0.65*	0.112	0.353	0.96**	0.99	3.13	0.99**	0.99	3.13	0.98**
Soil-6	1.31	4.14	0.73*	0.075	0.236	0.76**	0.004	0.014	0.70**	0.075	0.236	0.94**	1.31	4.14	0.99**	1.31	4.14	0.98**
Soil-7	1.42	4.50	0.58*	0.060	0.189	0.73**	0.003	0.008	0.69*	0.060	0.189	0.92**	1.42	4.50	0.99**	1.42	4.50	0.98**
Soil-8	1.23	3.89	0.41	0.041	0.129	0.68*	0.001	0.004	0.74**	0.041	0.129	0.94**	1.23	3.89	0.99**	1.23	3.89	0.98**
Soil-9	1.38	4.37	0.73**	0.064	0.204	0.79**	0.003	0.010	0.74**	0.064	0.204	0.96**	1.38	4.37	0.96**	1.38	4.37	0.97**
Soil-10	1.55	4.89	0.75**	0.068	0.216	0.75**	0.003	0.010	0.69*	0.068	0.216	0.94**	1.55	4.89	0.99**	1.55	4.89	0.98**
Soil-11	1.88	5.93	0.76**	0.077	0.242	0.76**	0.003	0.010	0.69*	0.077	0.242	0.95**	1.88	5.93	0.99**	1.88	5.93	0.98**
Soil-12	1.92	6.08	0.73**	0.079	0.248	0.64*	0.003	0.011	0.54*	0.079	0.248	0.88**	1.92	6.08	0.97**	1.92	6.08	0.99**
Soil-13	1.60	5.04	0.81**	0.069	0.219	0.75**	0.003	0.010	0.67*	0.069	0.219	0.95**	1.60	5.04	0.99**	1.60	5.04	0.99**
Soil-14	1.39	4.39	0.80**	0.069	0.220	0.74**	0.004	0.011	0.68*	0.069	0.220	0.98**	1.39	4.39	0.99**	1.39	4.39	0.99**
Soil-15	1.30	4.11	0.76**	0.070	0.222	0.69*	0.004	0.012	0.62*	0.070	0.222	0.91**	1.30	4.11	0.99**	1.30	4.11	0.99**
Soil-16	1.78	5.62	0.78**	0.073	0.232	0.72**	0.003	0.010	0.68*	0.073	0.232	0.93**	1.78	5.62	0.99**	1.78	5.62	0.99**

▼ZOE=Zero order equation, ▲FOE=First order equation, ►SOE=Second order equation, ◄PDE=Parabolic diffusion equation, ◊PFE=Power function equation,

△EE=Elovich equation

¶S.E._M=Standard error of mean, ‡R²=Coefficient of determination

*Relationship significant at $p < 0.05$

**Relationship significant at $p < 0.01$

Table 4.33 Phosphorus release constants of different kinetics models for sixteen surface (0-15 cm) soils varying in physical and chemical properties

Soil properties	Elovich	Parabolic diffusion		Power function		
	α ($\mu\text{g g}^{-1} \text{h}^{-1}$)	β ($\mu\text{g g}^{-1}$)	R ($\mu\text{g g}^{-1} \text{h}^{-1/2}$)	C ($\mu\text{g g}^{-1}$)	k_A ($\mu\text{g g}^{-1} \text{h}^{-1}$)	b ($\mu\text{g g}^{-1}$)
Soil-1	2.72	14.7	1.37	14.9	0.145	2.68
Soil-2	2.45	12.9	1.24	13.0	0.148	2.54
Soil-3	2.13	12.5	1.11	12.5	0.130	2.53
Soil-4	1.93	11.2	1.03	11.1	0.129	2.42
Average	2.31	12.8	1.19	12.9	0.138	2.54
Soil-5	1.68	5.5	0.93	5.3	0.191	1.75
Soil-6	2.22	12.9	1.22	12.6	0.127	2.57
Soil-7	2.42	19.0	1.31	18.7	0.101	2.95
Soil-8	2.10	25.7	1.15	25.4	0.069	3.25
Average	2.10	15.8	1.15	15.5	0.122	2.63
Soil-9	2.34	16.4	1.30	16.1	0.109	2.81
Soil-10	2.63	17.3	1.44	17.0	0.117	2.86
Soil-11	3.19	18.0	1.76	17.6	0.131	2.91
Soil-12	3.29	19.0	1.73	19.0	0.132	2.95
Average	2.86	17.7	1.56	17.4	0.122	2.88
Soil-13	2.37	15.2	1.30	15.0	0.119	2.73
Soil-14	2.72	17.6	1.49	17.3	0.118	2.88
Soil-15	3.04	18.6	1.63	18.4	0.125	2.93
Soil-16	2.22	14.2	1.20	14.0	0.119	2.66
Average	2.59	16.4	1.40	16.2	0.120	2.80

Table 4.34 Regression coefficients for modelled terms in a stepwise regression analysis relating P release constants to clay (%), soil organic carbon (%), available P (mg kg⁻¹) and calcium carbonate (%)

Equation	Dependent variable	Predictor (s) [#]	Constant	Clay	SOC	Available P	CaCO ₃	R ²
1	α	1,2,3	1.79	-0.03	2.58	0.01		0.55*
2		1,2,3,4	1.54	-0.25	2.91	0.01	-0.30	0.70**
3	β	1,2,3	3.94	-0.16	4.50	0.85		0.82**
4		1,2,3,4	2.01	-0.09	7.01	0.89	-2.29	0.90**
5	R	1,2,3	0.89	-0.02	1.34	0.01		0.58*
6		1,2,3,4	0.76	-0.01	1.52	0.01	-0.16	0.71**
7	C	1,2,3	4.09	-0.17	4.65	0.83		0.81**
8		1,2,3,4	2.15	-0.10	7.16	0.87	-2.29	0.89**
9	k_A	1,2,3	0.21	-0.00	0.06	-0.01		0.91**
10		1,2,3,4	0.21	-0.00	-0.06	-0.01	0.00	0.91**
11	b	1,2,3	1.71	0.00	0.36	0.06		0.76**
12		1,2,3,4	1.60	0.00	0.05	0.06	-0.14	0.81**

*Significance tested by *t*-test at $p < 0.05$.

** Significance tested by *t*-test at $p < 0.01$.

[#]1,2,3,4 represent clay, SOC, available P and CaCO₃.

Comparatively lower P sorption in soils of higher available P is due to the fact that active sorption sites are already occupied by P. Once the active sorption sites are occupied, P sorption is greatly reduced and a large amount of P remains in equilibrium solution. The comparison of soils in group-III showed higher P sorption in soil with lower concentration of SOC. Phosphorus sorption decreased as the SOC content increased (Figure 4.35). Soils with low SOC content tend to have higher P sorption because of high P affinity (Mashal *et al* 2014). Decreased P sorption in soils with high SOC content was because of the liberation of organic acids upon decomposition. Competitive sorption between low molecular weight organic acids produced during decomposition of organic matter (Hundal *et al* 1988) reduces P sorption on active surface sites of soil (Geelhoed *et al* 1999). It has also been observed that organic matter not only decreases P sorption on active sorption sites, but also delays P sorption (Singh and Jones 1976, Iyamureye *et al* 1996). Calcium carbonate also had pronounced influence on P sorption behavior (Figure 4.35). In general, P sorption was higher in calcareous soil (Soil-13, Soil-14 and Soil-16), compared to non-calcareous soil (Soil-15). In calcareous soils, the accumulation of CaCO_3 is believed to govern soil P reactions (Lindsay 1979) because of its adsorption and precipitation on the CaCO_3 surface (Cole *et al* 1953, Griffin and Jurinak 1973, Freeman and Rowell 1981, Amer *et al* 1985). Afif *et al* (1993) reported that the ratio of Olsen P to applied P was negatively correlated to CaCO_3 at high P application rates.

4.4.4 Langmuir and Freundlich sorption isotherms

When equilibrium solution P concentration was plotted against equilibrium P concentration/adsorbed P $\{c/(x/m)\}$, a linear relationship was obtained indicating that P adsorption in the soil could be defined by Langmuir equation. The Langmuir sorption isotherms (Figure 4.36) showed the formation of two adsorbed layers of higher and lower energy sites. Sorption maxima and bonding energy estimated from Langmuir isotherm for soils varying in physical and chemical properties are given in table 4.35. Langmuir sorption maxima ($A.M._1$ = Adsorption maxima for first sorbed layer and $A.M._2$ = Adsorption maxima for second sorbed layer) increased with clay and calcium carbonate content and decreased with available P and SOC content. Langmuir $A.M._1$ varied between 58.8-64.5, 66.7-77.5, 71.4-111.1 and 50.5-83.3 $\mu\text{g P g}^{-1}$, respectively in soil under group-I, II, III and IV, respectively. Likewise, $A.M._2$ varied between 200-333, 250-333, 243-351 and 250-323 $\mu\text{g P g}^{-1}$, respectively. Phosphorus sorption strength assessed through $B.E._1$ (Bonding energy for first sorbed layer) and $B.E._1$ ($B.E._2$ =Bonding energy for second sorbed layer) also showed trends similar to that observed for sorption maxima. Phosphorus sorption strength assessed through $B.E._1$ varied between 46-323, 42-239, 41-164 and 75-162 ml P g^{-1} , respectively in soils under group-I, II, III and IV, respectively. Similarly, $B.E._2$ varied between 8.0-12.7, 7.3-18.4, 7.0-16.8 and 9.0-17.7 ml P g^{-1} , respectively (Table 4.35).

A straight-line relationship was also obtained with Freundlich equation (Figure 4.37) and it explained the adsorption process as efficiently as the Langmuir sorption isotherm (Table 4.35). In soils of group-I, rate of P sorption (S.R.) varied between 32.6-72.8, 30.5-63.8, 28.8-33.4 and 38.2-54.5 g P ml^{-1} , respectively in soil under group-I, II, III and IV, respectively. Extent of P sorption (S.E.) varied between

3.82-14.69, 3.95-15.1, 3.99-8.95 and 5.79-12.79 $\mu\text{g P g}^{-1}$, respectively in soil under group-I, II, III and IV, respectively. Freundlich sorption constant (rate of P sorption and extent of P sorption) increased with increase in clay content (group-I soils) and CaCO_3 content (group-IV soils). The rate and extent of P sorption decreased with increase in available P (group-II soils) and SOC content (group-III soils). Soil clay content has been reported to be significantly related to the soil P sorption indices such as Langmuir constants (Samadi 2006). Wisawapipat *et al* (2009) reported that slightly greater portion of sorbed P was more readily available in the soil solution where soils were low in clay content. Presence of CaCO_3 and the large surface area of this mineral lead to more rapid P sorption and precipitation which reduced the P availability even in coarse textured (Vig *et al* 2000, Tisdale *et al* 2002, Amer *et al* 1985, Dunne *et al* 2011). Increase the values of Langmuir sorption constants with clay and calcium carbonate content leading to increase the P adsorption and decreasing the equilibrium P concentration in soil solution (Chaudhary 1990, Wani and Bhat 2010). During decomposition of organic matter, organic acids are produced which tends to cover colloidal sesquioxides surface, decrease P sorption (Stevenson *et al* 1982).

4.4.5 Effect of soil properties on phosphorus desorption

The soils used for P sorption were retained for P desorption studies. Phosphorus desorption data showed that the soils having high P sorption capacity had lower P desorption capacity. In group-I, highest P desorption occurred from soils having lower clay content and vice-versa (Table 4.36, Figure 4.38). In group-II, higher P desorption occurred from soils having high concentration of available P, compared to the soils with lower P concentration. Likewise, soils with high concentration of soil organic carbon had higher P desorption capacity. Higher P desorption, regardless of the level of P sorbed has occurred from non-calcareous soil than the calcareous soils. However, the soils with high concentration of calcium carbonate had lower P desorption capacity. P desorption data fitted to Langmuir type equation yielded desorption maxima (D.M._1 = desorption maxima for first sorbed layer and D.M._2 = desorption maxima for second sorbed layer and 'Kd' constants (Kd_1 = constant related to P mobility for first sorbed layer and Kd_2 = constant related to P mobility for second sorbed layer) also exhibited a change due to change in soil physical and chemical properties (Table 4.36, Figure 4.39). Decrease in P desorption with clay and CaCO_3 content may be due to their greater affinity to fix P, as the main phosphate-sorbing soil surfaces are those of edges of silicate clays and calcite (Matar *et al* 1992). Phosphorus is mainly precipitated as Ca phosphates or co-precipitates with carbonates. Ca-P minerals are stable and are barely desorbed once formed (Vepraskas *et al* 2001, Gustafsson *et al* 2008). Dhillon *et al* (2004) reported the increase in P desorption capacity of soil with SOC content. Soil organic C increases the soil aggregation and reduces the surface area of soil thereby increasing the surface P mobility (Saroa and Vig 1992, Messiga *et al* 2012, Benbi and Senapati 2010).

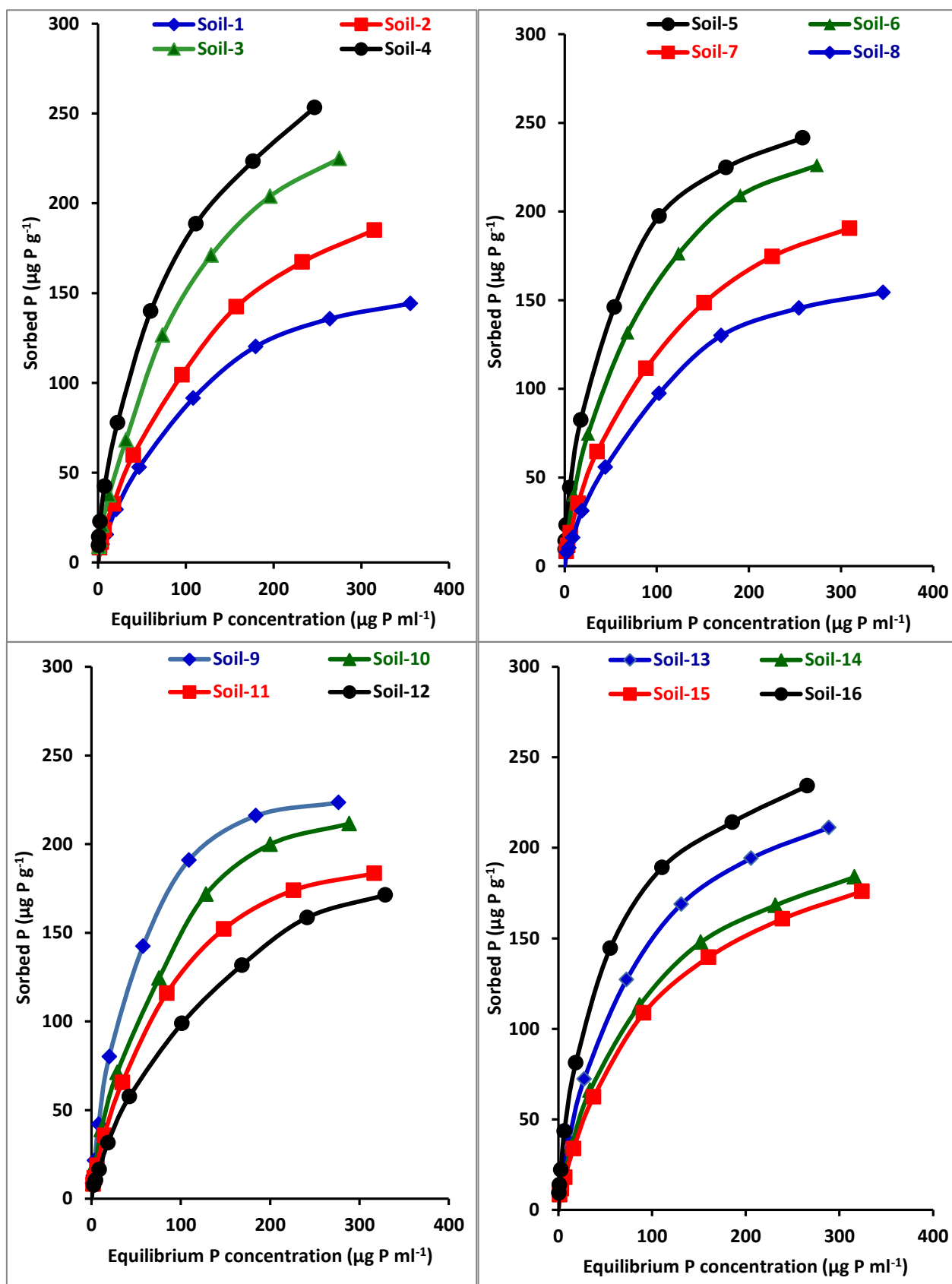


Fig 4.35 Effect of different physical and chemical properties of soils on phosphorus sorption behaviour [Soils 1-4: based on soil clay content, Soil-5-8: based on available P concentration, Soils 9-12: based on soil organic carbon concentration, Soils 13-16: based on calcium carbonate concentration]

Table 4.35 Langmuir and Freundlich phosphorus sorption constants for different group of soils

Soil reference	Langmuir sorption constants						Freundlich sorption constants		
	R_1^2	R_2^2	$A.M._1^\dagger$ ($\mu\text{g P g}^{-1}$)	$A.M._2^\ddagger$	$B.E._1^\heartsuit$ (ml P g^{-1})($\times 10^{-3}$)	$B.E._2^\spadesuit$	R^2	$S.R.^{\blacktriangle}$ (g ml^{-1})	$S.E.^{\blacktriangledown}$ ($\mu\text{g g}^{-1}$)
Group-I									
Soil-1	0.82**	0.99**	58.8	200.0	46.2	8.0	0.99**	32.6	3.82
Soil-2	0.94**	0.99**	60.6	256.4	69.9	7.3	0.99**	34.6	5.15
Soil-3	0.95**	0.99**	62.5	270.3	124.0	10.4	0.99**	39.8	7.96
Soil-4	0.98**	0.99**	64.5	333.3	322.9	12.7	0.99**	72.8	14.69
Group-II									
Soil-5	0.97**	0.99**	77.5	333.3	238.9	18.4	0.98**	63.8	15.14
Soil-6	0.92**	0.99**	76.3	320.5	101.6	11.6	0.99**	38.7	8.63
Soil-7	0.89**	0.99**	74.6	299.4	59.0	7.8	0.99**	34.2	5.68
Soil-8	0.76**	0.99**	66.7	250.0	42.4	7.3	0.99**	30.5	3.95
Group-III									
Soil-9	0.41	0.99**	111.1	350.9	163.6	16.8	0.98**	33.4	8.95
Soil-10	0.96**	0.99**	100.0	335.6	57.1	9.8	0.99**	33.3	7.03
Soil-11	0.93**	0.99**	83.3	257.1	52.2	10.6	0.99**	32.6	5.62
Soil-12	0.76**	0.99**	71.4	243.3	40.7	7.0	0.99**	28.8	3.99
Group-IV									
Soil-13	0.94**	0.99**	58.8	266.7	132.8	13.0	0.99**	42.3	8.38
Soil-14	0.89**	0.99**	53.8	257.1	85.0	10.1	0.99**	39.6	6.18
Soil-15	0.89**	0.99**	50.5	250.0	75.0	9.0	0.99**	38.2	5.79
Soil-16	0.86**	0.99**	83.3	322.6	162.2	17.7	0.98**	54.5	12.79

$^\dagger A.M._1$ =Adsorption maxima for first sorbed layer, $A.M._2^\ddagger$ =Adsorption maxima for second sorbed layer, $^\heartsuit B.E._1$ =Bonding energy for first sorbed layer, $^\spadesuit B.E._2$ =Bonding energy for second sorbed layer, $^{\blacktriangle} S.R.$ =Rate of P sorption, $^{\blacktriangledown} S.E.$ =Extent of P sorption

*Relationship significant at $p < 0.05$

**Relationship significant at $p < 0.01$

R^2 =Coefficient of determination

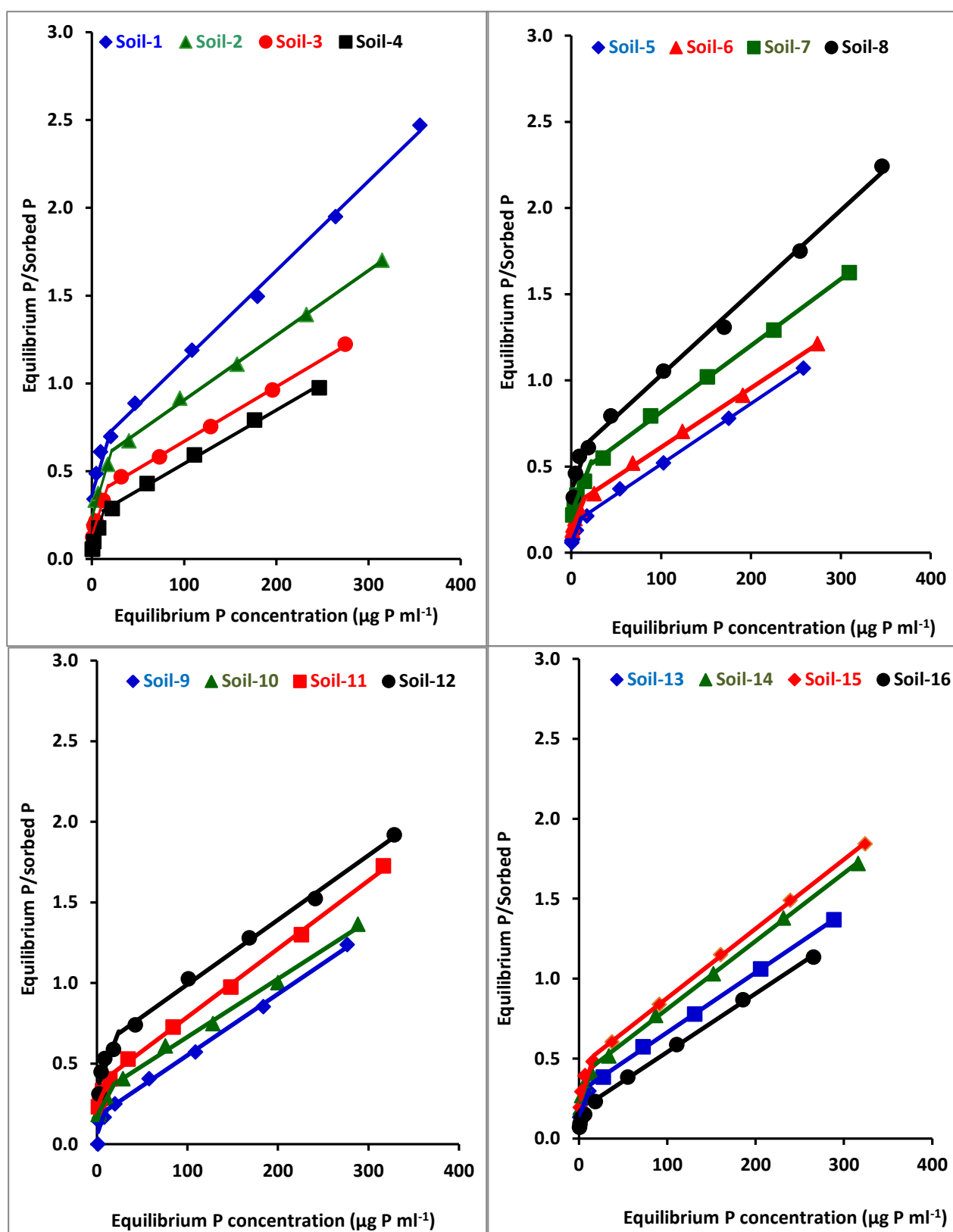


Fig 4.36 Langmuir sorption isotherms of soils varying in physical and chemical properties [Soils 1-4: based on soil clay content, Soil-5-8: based on available P concentration, Soils 9-12: based on soil organic carbon concentration, Soils 13-16: based on calcium carbonate concentration]

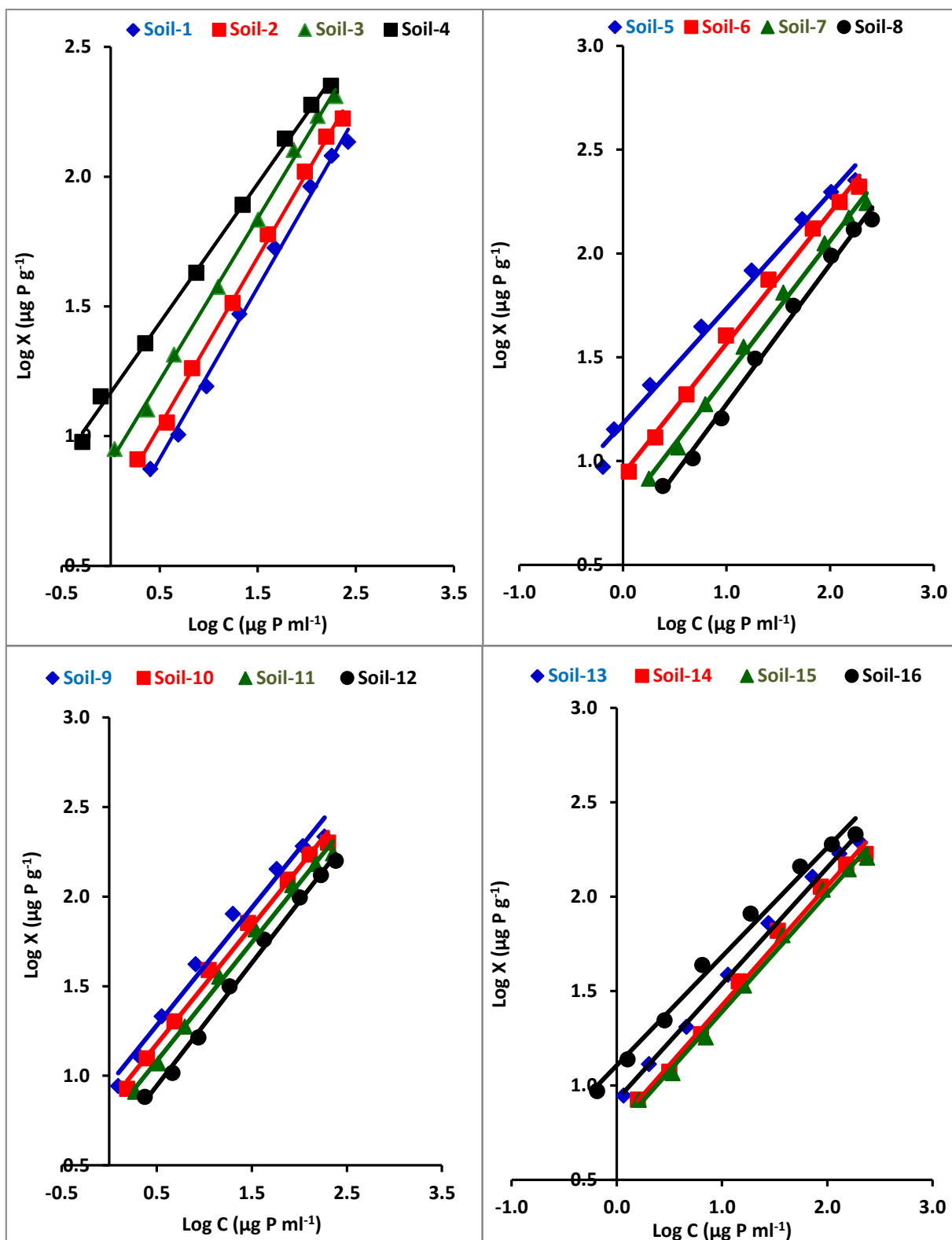


Fig 4.37 Freundlich sorption isotherms of soils varying in physical and chemical properties [Soils 1-4: based on soil clay content, Soils 5-8: based on available P concentration, Soils 9-12: based on soil organic carbon concentration, Soils 13-16: based on calcium carbonate concentration]

The soils used for P sorption were retained for P desorption studies. Desorption maxima for first sorbed layer (D.M.₁) and desorption maxima for second sorbed layer (D.M.₂) for soils of group-I, ranged between 19.2 to 25.0 $\mu\text{g P g}^{-1}$ and 250.0 to 400.0 $\mu\text{g P g}^{-1}$ (Table 4.36, Figure 4.39). For soils of group II, D.M.₁ and D.M.₂ ranged between 23.3 to 52.6 $\mu\text{g P g}^{-1}$ and 256 to 455 $\mu\text{g P g}^{-1}$. For soils of group-III, D.M.₁ and D.M.₂ ranged between 19.6 to 43.5 $\mu\text{g P g}^{-1}$ and 238 to 400 $\mu\text{g P g}^{-1}$. And for soils of group-IV, D.M.₁ and D.M.₂ ranged between 18.9 to 25.0 $\mu\text{g P g}^{-1}$ and 233 to 417 $\mu\text{g P g}^{-1}$. Constant related to P mobility for first sorbed layer (K_{d1}) and constant related to P mobility for first sorbed layer (K_{d2}) ranged between 8.67 to 20.0 and 0.143 to 0.250 ml P g^{-1} for soils of group-I. In soils of group-II, K_{d1} and K_{d2} ranged between 2.87 to 6.33 ml P g^{-1} and 0.126 to 0.183 ml P g^{-1} . In soils of group-III, K_{d1} and K_{d2} ranged between 2.32 to 4.60 ml P g^{-1} and 0.117 to 0.208 ml P g^{-1} . In soils of group-IV, K_{d1} and K_{d2} ranged between 13.3.9 to 26.7 ml P g^{-1} and 0.195 to 0.267 ml P g^{-1} .

A stepwise regression analysis showed that clay and SOC accounted for 46% variation in B.E.₁ ($R^2 = 0.46$, $n=16$) (Table 4.37). Inclusion of linear term for available P in the equation, as a soil property, improved the B.E.₁ predictability to 58 per cent ($R^2 = 0.58$, $n=16$). However, inclusion of linear term for CaCO_3 in the equation, improved the B.E.₁ predictability to 65 per cent ($R^2 = 0.65$). Stepwise inclusion of clay, SOC, available P and CaCO_3 accounted for 54% variation ($R^2 = 0.54$, $n=16$) in S.R and 58% variation ($R^2 = 0.58$, $n=16$) in extent of sorption (S.E.).

Soil properties viz. clay, SOC, available P and CaCO_3 strongly affect P release and sorption-desorption kinetics. Phosphorus release decreased with increase in clay and CaCO_3 content, but increased with increase in available P and SOC content suggesting that P availability will be higher in coarse-textured non-calcareous soil with relative higher levels of SOC and available P content. Phosphorus release constants are significantly related to available P and SOC contents. Langmuir and Freundlich sorption constants increased with clay and calcium carbonate content and decreased with available P and SOC content. Freundlich adsorption isotherms for estimating soil P adsorption capacities could predict effect of soil properties on soil P availability. The results showed that for efficient P management, it is important to take into account soil texture, the existing soil P level, SOC content and calcareousness of soil. Practices that increase SOC content and ameliorate CaCO_3 could lead to improved P use efficiency.

4.5 Effect of moisture and temperature regimes on changes in soil organic C, available Fe, Mn and P in texturally different soils

4.5.1 General soil properties

Effect of temperature and moisture on changes in SOC, available Fe, Mn and P was studied in three texturally different. The soils were loamy sand, clay loam and silty clay in texture. Soils were near neutral in reaction and were non-saline (Table 4.38).

Table 4.36 Langmuir desorption constants for surface soil (0-15 cm) sample varying in physical and chemical properties

Soil reference	Langmuir desorption constants					
	R_1^2	R_2^2	D.M. ₁ [†] ($\mu\text{g P g}^{-1}$)	D.M. ₂ [‡]	Kd ₁ [▼] (ml P g^{-1})	Kd ₂ [▲]
Group-I						
Soil-1	0.88**	0.99**	25.0	400.0	20.0	0.250
Soil-2	0.80**	0.98**	23.3	333.3	14.3	0.188
Soil-3	0.81**	0.99**	21.7	285.7	11.5	0.175
Soil-4	0.77**	0.97**	19.2	250.0	8.67	0.143
Group-II						
Soil-5	0.99**	0.96**	23.3	256.4	2.87	0.126
Soil-6	0.96**	0.98**	33.3	303.0	3.75	0.138
Soil-7	0.96**	0.99**	40.0	357.1	4.17	0.147
Soil-8	0.90**	0.99**	52.6	454.5	6.33	0.183
Group-III						
Soil-9	0.39	0.97**	19.6	238.1	2.32	0.117
Soil-10	0.85**	0.95**	22.2	277.8	3.21	0.138
Soil-11	0.73**	0.99**	30.3	312.5	4.07	0.160
Soil-12	0.94**	0.99**	43.5	400.0	4.60	0.208
Group-IV						
Soil-13	0.82**	0.99**	19.6	303.0	17.0	0.206
Soil-14	0.73**	0.99**	23.8	344.8	20.0	0.223
Soil-15	0.77**	0.99**	25.0	416.7	26.7	0.267
Soil-16	0.77**	0.99**	18.0	232.6	13.3	0.195

[†]D.M.₁=Desorption maxima for first sorbed layer, D.M.₂[‡]=Desorption maxima for second sorbed layer,

[▼]Kd₁=Constant related to P mobility for first sorbed layer,

[▲]Kd₂=Constant related to P mobility for second sorbed layer

*Relationship significant at $p < 0.05$

**Relationship significant at $p < 0.01$

R²=Coefficient of determination

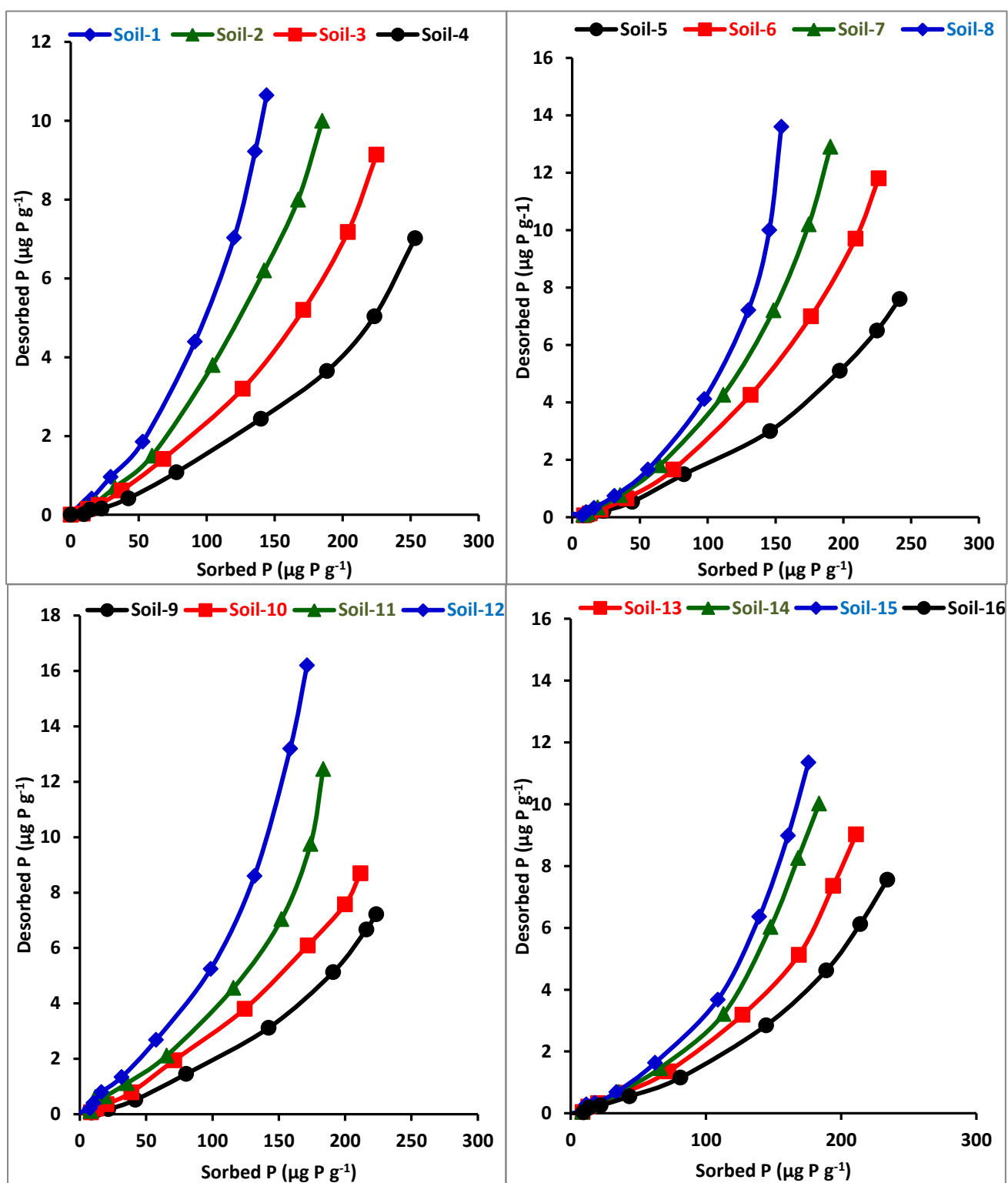


Fig 4.38 Effect of different physical and chemical properties of soils on phosphorus desorption behaviour (Soils 1-4: based on soil clay content, Soil-5-8: based on available P concentration, Soils 9-12: based on soil organic carbon concentration, Soils 13-16: based on calcium carbonate concentration)

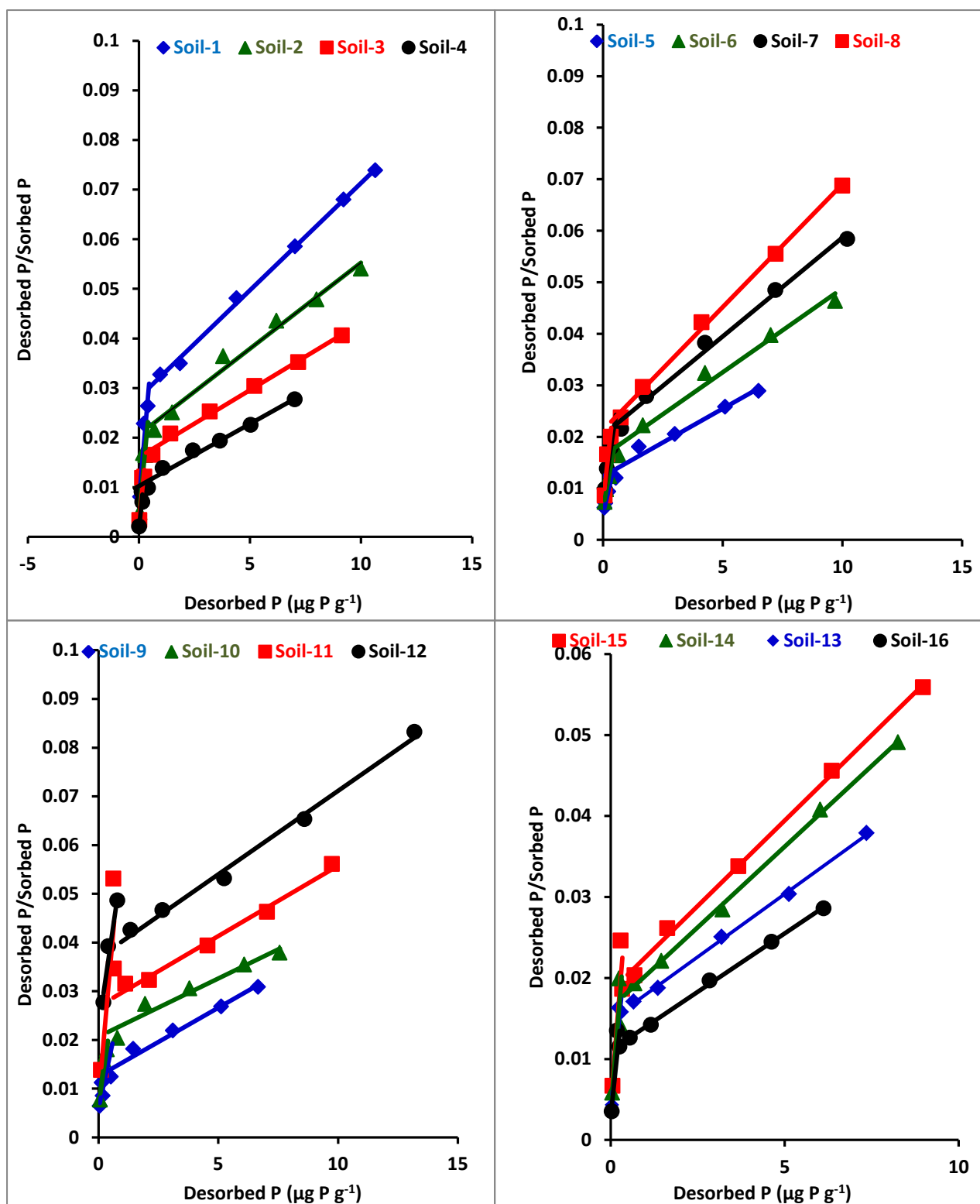


Fig 4.39 Langmuir desorption isotherms of soils varying in physical and chemical properties (Soils 1-4: based on soil clay content, Soil-5-8: based on available P concentration, Soils 9-12: based on soil organic carbon concentration, Soils 13-16: based on calcium carbonate concentration)

Table 4.37 Regression coefficients for modelled terms in a stepwise regression analysis relating P sorption constants to clay (%), soil organic carbon (%), available P (mg kg⁻¹) and calcium carbonate (%)

Dependent variable	Predictor (s)	Constant	Clay	SOC	Available P	CaCO ₃	R ²
A.M. ₁	Clay	75.0	-0.21				0.00
	Clay, SOC	79.5	0.23	-26.6			0.04
	Clay, SOC, Available P	67.4	0.39	-34.8	0.92		0.10
	Clay, SOC, Available P, CaCO ₃	66.7	0.42	-33.8	0.94	-0.84	0.10
A.M. ₂	Clay	233.1	3.76				0.07
	Clay, SOC	262.6	6.64	-172.8			0.31
	Clay, SOC, Available P	260.9	6.66	-173.9	0.13		0.31
	Clay, SOC, Available P, CaCO ₃	272.9	6.26	-189.5	-0.15	14.2	0.34
B.E. ₁	Clay	-0.06	0.01				0.22
	Clay, SOC	-0.01	0.02	-0.31			0.46*
	Clay, SOC, Available P	0.08	0.02	-0.25	-0.01		0.58*
	Clay, SOC, Available P, CaCO ₃	0.12	0.02	-0.30	-0.01	0.04	0.65*
B.E. ₂	Clay	0.01	0.0				0.04
	Clay, SOC	0.01	0.0	-0.01			0.11
	Clay, SOC, Available P	0.01	0.0	-0.01	0.0		0.16
	Clay, SOC, Available P, CaCO ₃	0.02	0.0	-0.01	0.0	0.01	0.47
S.R.	Clay	17.7	1.69				0.16
	Clay, SOC	23.0	2.21	-31.1			0.26
	Clay, SOC, Available P	38.6	2.00	-20.6	-1.19		0.43
	Clay, SOC, Available P, CaCO ₃	45.0	1.78	-28.9	-1.33	7.56	0.54*
S.E.	Clay	1.84	0.44				0.13
	Clay, SOC	3.75	0.62	-11.2			0.27
	Clay, SOC, Available P	7.72	0.57	-8.51	-0.30		0.41
	Clay, SOC, Available P, CaCO ₃	10.0	0.49	-11.5	-0.36	0.73	0.58*

*Significance tested by *t*-test at *p*<0.05.

#1,2,3,4 represent clay, SOC, available P and CaCO₃

R²=Coefficient of determination

The SOC concentration in the loamy sand, clay loam and silty clay soils was 3.6, 5.0 and 6.6 g kg⁻¹, respectively. Available P concentration in three soils ranged between 8.2 and 13.4 mg kg⁻¹ (Table 4.38), with the lowest in loamy sand and the highest in silty clay soil. Loamy sand soil was deficient in DTPA-Mn and Fe and the other two soils were sufficient in DTPA-Mn and Fe.

Table 4.38 Important physical and chemical properties of surface (0-15 cm) soils at the start of the incubation experiment

Soil property	Loamy sand	Clay loam	Silty clay
pH	7.43	7.36	7.25
EC (dSm ⁻¹)	0.26	0.29	0.24
Available P (mg kg ⁻¹)	8.2	11.1	13.4
SOC (g kg ⁻¹)	3.6	5.0	6.6
KMnO ₄ -C (mg kg ⁻¹)	259	425	742
DTPA-Fe (mg kg ⁻¹)	3.84	7.62	10.5
DTPA-Mn (mg kg ⁻¹)	3.12	4.46	5.62
Sand (%)	85.7	63.0	29.0
Silt (%)	4.7	11.0	30.5
Clay (%)	9.6	26.0	40.5
θ ^v (%)	20.4	29.3	32.2

θ^v = Volumetric moisture content

4.5.1.1 Change in soil organic carbon

The effect of incubation period on SOC concentration under different moisture and temperature regimes are shown in figure 4.40 and tables 4.39 and 4.40. At field capacity moisture regime, SOC concentration ranged between 3.60 to 4.37 (g kg⁻¹) in loamy sand soils, 5.00 to 6.34 (g kg⁻¹) in clay loam soils and 6.60 to 8.14 (g kg⁻¹) in silty claysoils. The SOC concentration increased significantly during initial 30 to 45 days of incubation and decreased sharply thereafter. The silty clay soils showed significantly higher SOC concentration followed by clay loam and loamy sand soils. Averaged across soils, SOC concentration was lowest (5.07 g kg⁻¹) at the start of incubation.

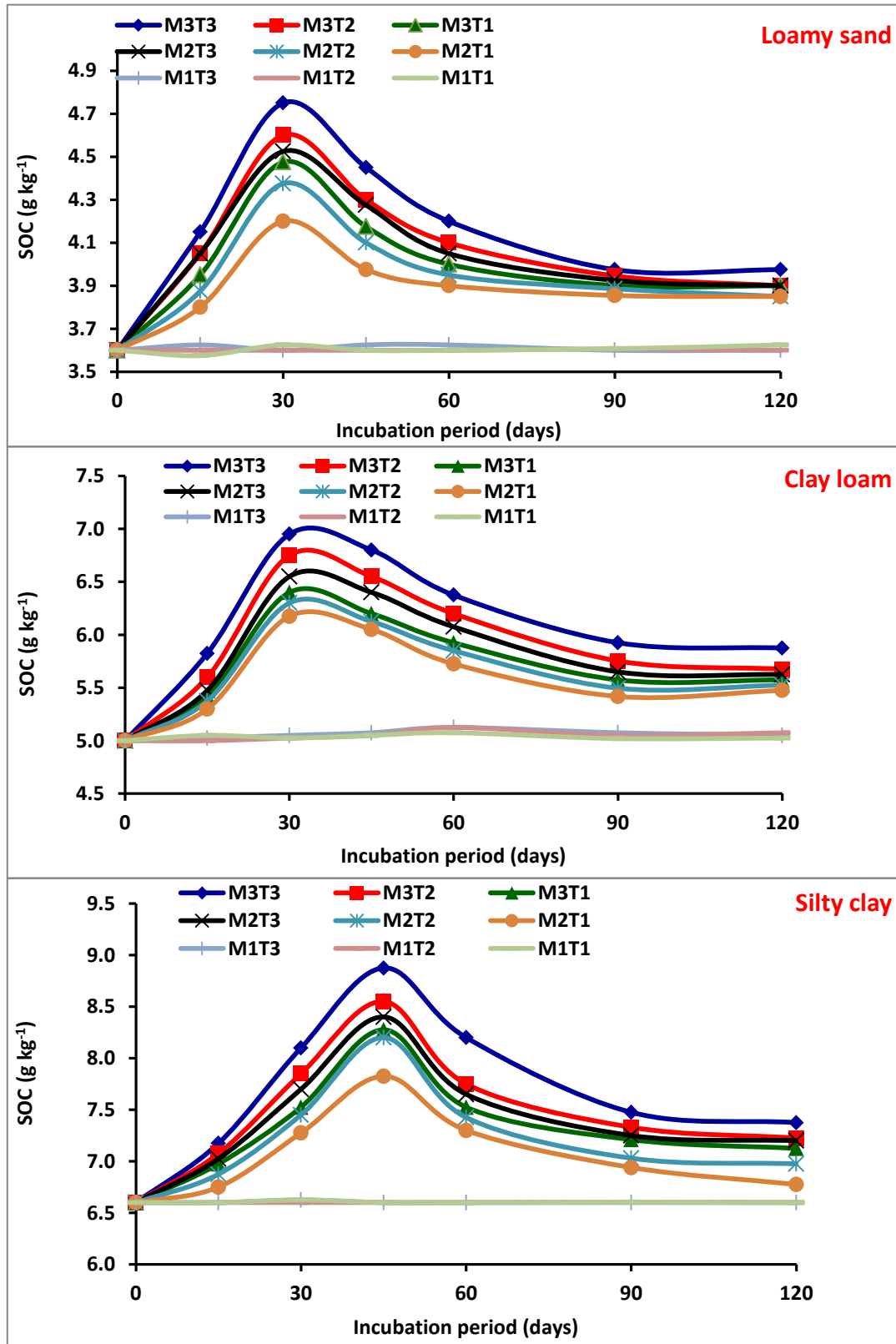


Fig 4.40 Effect of different moisture and temperature regimes on the concentration of soil organic carbon during 120 days incubation of three soils [M_1 , M_2 and M_3 represents air-dry, field capacity and submergence moisture regimes; T_1 , T_2 and T_3 represents 20, 30 and 40°C temperature regimes]

The SOC concentration was the highest (6.15 g kg^{-1}) at 45 days of incubation (Table 4.39, Figure 4.40). The SOC ranged between 3.60 to $4.61 \text{ (g kg}^{-1}\text{)}$ in loamy sand, 5.00 to $6.70 \text{ (g kg}^{-1}\text{)}$ in clay loam and 6.60 to $8.57 \text{ (g kg}^{-1}\text{)}$ in silty claysoils at submerged condition. The trends of SOC were similar to that observed at field capacity soil moisture. The silty clay soils showed higher SOC followed by clay loam and loamy sand soils. Averaged across the soils, SOC was the lowest (5.07 g kg^{-1}) at start than consecutive incubation periods. The SOC concentration was the highest (6.46 g kg^{-1}) at 45 days of incubation under submerged condition (Table 4.39, Figure 4.40). Averaged across the soil and incubation period SOC was significantly higher at submerged moisture regime than at field capacity moisture regime. At different temperature, SOC concentration ranged between 3.88 and 7.40 g kg^{-1} in different soils. The effect of moisture on the SOC concentration was more at higher temperature (40°C) than the other two temperatures (Table 4.40, Figure 4.40). The silty clay soils showed significantly higher SOC concentration followed by clay loam and loamy sand soils. The SOC concentration ranged between 4.00 to $4.16 \text{ (g kg}^{-1}\text{)}$ in loamy sand, 5.73 to $6.11 \text{ (g kg}^{-1}\text{)}$ in clay loam and 7.32 to $7.69 \text{ (g kg}^{-1}\text{)}$ in silty claysoils at submerged condition (Table 4.40). Averaged across the temperature, three soils showed higher SOC concentration at submerged condition than at field capacity moisture.

Table 4.39 Soil organic carbon concentration (g kg^{-1}) in three soils as affected by moisture regimes and incubation period

Incubation period	Loamy sand	Clay loam	Silty clay	Mean
Field capacity				
0	3.60	5.00	6.60	5.07
15	3.91	5.38	6.88	5.39
30	4.37	6.34	7.48	6.06
45	4.12	6.19	8.14	6.15
60	3.97	5.88	7.46	5.77
90	3.89	5.52	7.07	5.49
120	3.87	5.54	6.98	5.46
Mean	3.96	5.69	7.23	5.63
Submergence				
0	3.60	5.00	6.60	5.07
15	4.05	5.62	7.08	5.58
30	4.61	6.70	7.83	6.38
45	4.31	6.52	8.57	6.46
60	4.10	6.17	7.83	6.03
90	3.94	5.75	7.34	5.68
120	3.93	5.71	7.24	5.63
Mean	4.08	5.92	7.50	5.83
LSD ($p < 0.05$) Soils=0.16, Moisture=0.13, Incubation period=0.24, Moisture x Incubation period=0.062, Soil x Moisture=0.22, Soil x Incubation period=0.42, Soil x Incubation period x Moisture=NS				

Table 4.40 Soil organic carbon concentration (g kg⁻¹) in three texturally different soils as affected by moisture and temperature regimes

Temperature (°C)	Loamy sand	Clay loam	Silty clay	Mean
Field capacity				
20	3.88	5.59	7.07	5.51
30	3.95	5.67	7.22	5.61
40	4.05	5.83	7.40	5.76
Mean	3.96	5.69	7.23	5.63
Submergence				
20	4.00	5.73	7.32	5.68
30	4.07	5.93	7.48	5.83
40	4.16	6.11	7.69	5.98
Mean	4.08	5.92	7.50	5.83
LSD ($p < 0.05$) Soils=0.03, Temperature=0.03, Soil x Temperature=0.05, Moisture x Temperature=NS, Soil x Moisture x Temperature=NS				

4.5.1.2 Changes in potassium permanganate oxidizable carbon

The KMnO₄-C concentration in three soils incubated at air-dry conditions did not change throughout the incubation period (Figure 4.41). Averaged across soils, KMnO₄-C ranged between 475 to 565 (mg kg⁻¹) and increased significantly 30 days of incubation period (Figure 4.41). The KMnO₄-C varied between 259 to 333 (mg kg⁻¹) in loamy sand soils, 425 to 509 (mg kg⁻¹) in clay loam soils and 742 to 854 (mg kg⁻¹) in silty claysoils (Table 4.41). The KMnO₄-C in soils increased significantly during initial 30 days of incubation, and then gradually levelled-off as the incubation progressed. It may be due to the greater microbial activities during initial 30 days of incubation (Benbi *et al* 2014, Benbi and Khosa 2014). The silty clay soils showed significantly higher KMnO₄-C followed by clay loam and loamy sand soils. At submerged condition, KMnO₄-C varied between 259 to 315 (mg kg⁻¹) in loamy sand soils, 425 to 452 (mg kg⁻¹) in clay loam soils and 742 to 796 (mg kg⁻¹) in silty claysoils (Table 4.41). The trends of increase in KMnO₄-C with incubation period were similar to that observed at field capacity moisture regime. Averaged across the soils, KMnO₄-C ranged between 475 to 521 (mg kg⁻¹) and increased significantly 30 days of incubation period. At field capacity moisture regime, KMnO₄-C was significantly higher by 7.1% compared to submerged condition.

The soils incubated at field capacity moisture regime had significantly higher KMnO₄-C by 5.7-9.9% compared to soils at submerged conditions. It could possibly be due to the higher C mineralization under field capacity moisture regime than under submerged conditions (Dash *et al* 2014). The effect of moisture on KMnO₄-C was more conspicuous at higher temperature (40°C) and KMnO₄-C decreased with decrease the temperature (Table 4.42, Figure 4.41). Soils incubated at field capacity moisture and at 40°C had significantly higher KMnO₄-C than other two temperatures. At 40°C and submerged condition, clay loam and silty clay soils showed significantly higher KMnO₄-C compared to other temperatures. Benbi and Khosa (2014) also reported the higher C mineralization at 35°C compared to 15°C. Averaged across the temperature, the KMnO₄-C in soils was significantly

higher at field capacity moisture regime compared to submerged condition. Deficiency of oxygen and reduced microbial activity may be responsible of slower decomposition of organic matter in submerged soils than field capacity moisture regime soils (Sahrawat 2004).

Table 4.41 Potassium permanganate oxidizable carbon (KMnO₄-C) (mg kg⁻¹) in three texturally different soils as affected by moisture regime and incubation period

Incubation period	Loamy sand	Clay loam	Silty clay	Mean
Field capacity				
0	259 (2.4) [*]	425 (4.5)	742 (7.6)	475
15	305 (4.2)	475 (9.1)	809 (10.4)	530
30	322 (3.6)	496 (12.7)	834 (11.5)	551
45	328 (4.3)	499 (15.3)	842 (11.7)	556
60	330 (4.4)	503 (14.6)	844 (12.0)	559
90	333 (4.0)	507 (14.7)	849 (11.6)	563
120	333 (3.3)	509 (14.0)	854 (10.9)	565
Mean	316	488	825	543
Submergence				
0	259 (2.4)	425 (4.5)	742 (7.6)	475
15	286 (3.3)	437 (4.3)	766 (6.4)	496
30	303 (3.1)	444 (6.3)	777 (9.7)	508
45	308 (3.6)	448 (6.4)	783 (10.4)	513
60	311 (3.5)	452 (5.8)	784 (9.8)	515
90	313 (4.2)	452 (7.3)	788 (10.8)	517
120	315 (3.2)	452 (6.3)	796 (12.3)	521
Mean	299	444	776	507

LSD ($p<0.05$) Soils=2.77, Incubation period=4.24, Moisture=2.26, Moisture x Incubation period=6.00, Moisture x Soil=3.92, Soil x Moisture x Incubation period=10.4

^{*} Values in the parenthesis indicate standard error

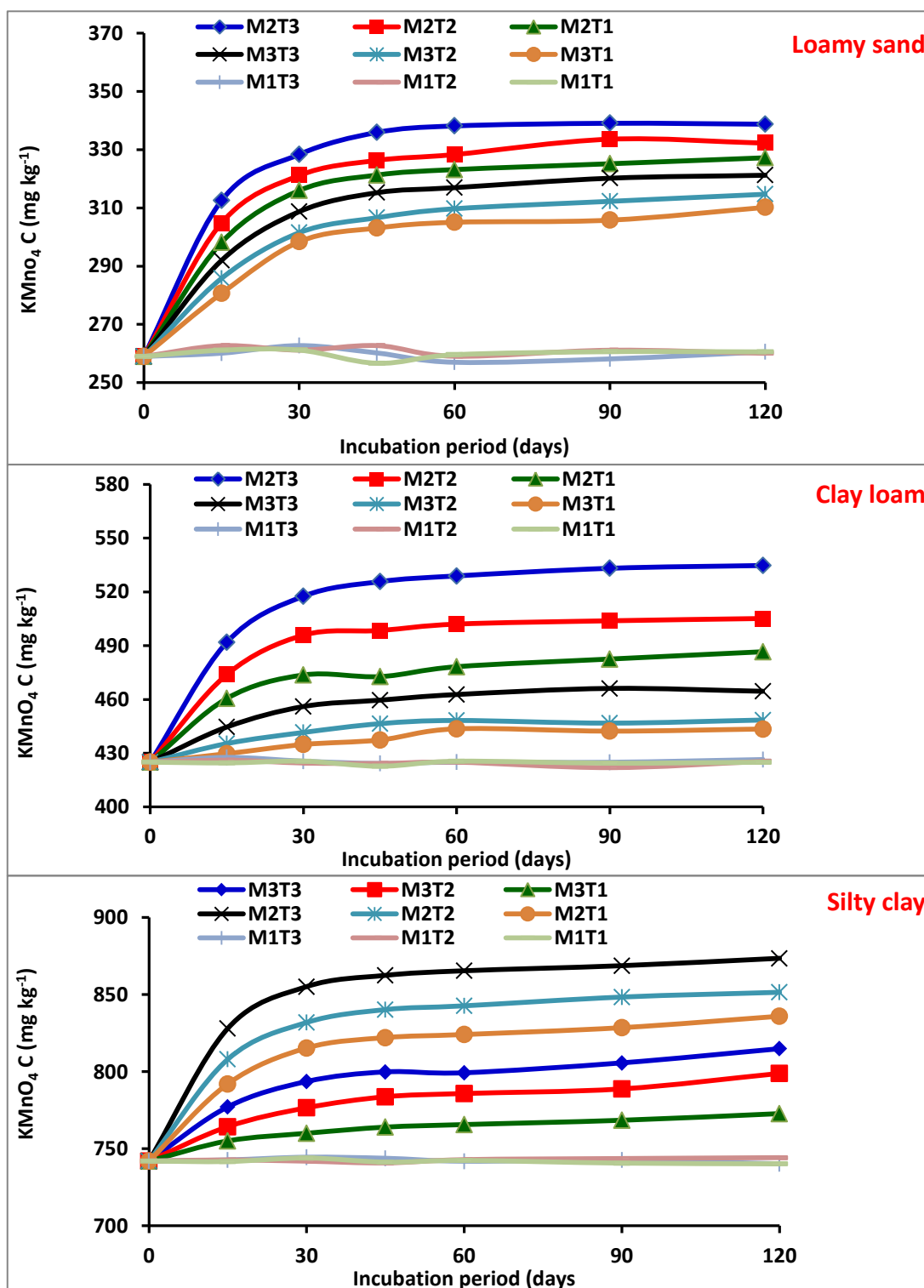


Fig 4.41 Effect of different moisture and temperature regimes on the concentration of potassium permanganate oxidizable carbon during 120 days incubation of three texturally different soils [M₁, M₂ and M₃ represents air-dry, field capacity and submergence moisture regimes; T₁, T₂ and T₃ represents 20, 30 and 40°C temperature regimes]

Table 4.42 Potassium permanganate oxidizable carbon (KMnO₄-C) (mg kg⁻¹) in three texturally different soils as affected by moisture and temperature regimes

Temperature (°C)	Loamy sand	Clay loam	Silty clay	Mean
Field capacity				
20	310 (9.3) [‡]	468 (7.9)	809 (12.3)	529
30	315 (10.0)	486 (11.0)	824 (14.6)	542
40	322 (11.0)	508 (14.9)	842 (17.6)	557
Mean	316	488	825	543
Submergence				
20	295 (6.9)	437 (2.7)	761 (3.9)	497
30	299 (7.5)	442 (3.3)	777 (7.1)	506
40	305 (8.5)	454 (5.6)	790 (9.2)	516
Mean	299	444	776	507
LSD ($p<0.05$) Soils=2.77, Temperature=2.77, Moisture=2.26, Moisture x Temperature=3.92, Moisture x Soil=3.92, Soil x Temperature=4.81, Soil x Moisture x Temperature=6.80				

[‡] Values in the parenthesis indicate standard error

4.5.1.3 Changes in DTPA-Fe in soils

The effect of incubation periods on the DTPA-Fe concentration under different moisture and temperature regimes are shown in figure 4.42 and tables 4.43 and 4.44. At field capacity moisture regime, DTPA-Fe varied between 3.8 and 21.2 (mg kg⁻¹) different soils. The DTPA-Fe increased in initial 30 days of incubation and decreased sharply thereafter upto 60 days, in soils. Averaged across the soils, DTPA-Fe was lowest (7.3 mg kg⁻¹) at start of incubation and the highest (14.8 mg kg⁻¹) at 30 days (Figure 4.42). The DTPA-Fe varied between 3.8 to 9.4 (mg kg⁻¹) in loamy sand soils, 7.6 to 16.4 (mg kg⁻¹) in clay loam soils and 10.5 to 23.2 (mg kg⁻¹) in silty claysoils at submerged condition. The trends of DTPA-Fe with incubation period were similar to that observed at field capacity moisture regime. Averaged across the soils, DTPA-Fe was lowest (7.3 mg kg⁻¹) at start and the highest (16.3 mg kg⁻¹) at 30 days of incubation period (Figure 4.42). Averaged across the soils and incubation period DTPA-Fe was higher at submerged moisture regime than at field capacity.

The effect of moisture on the DTPA-Fe was more at higher temperature (40°C) than other two temperatures (Table 4.44, Figure 4.42). At field capacity moisture, DTPA-Fe ranged between 5.7 to 6.5 (mg kg⁻¹) in loamy sand soils, 10.5 to 11.8 (mg kg⁻¹) in clay loam soils and 16.1 to 17.4 (mg kg⁻¹) in silty claysoils (Table 4.44). The DTPA-Fe concentration increased with temperature. The DTPA-Fe ranged between 6.2 to 7.1 (mg kg⁻¹) in loamy sand soils, 11.2 to 12.6 (mg kg⁻¹) in clay loam soils and 17.0 to 18.5 (mg kg⁻¹) in silty claysoils at submerged condition (Table 4.44). This increase in DTPA-Fe concentration with increase in temperature could be attributed to increase its diffusion in soils. The DTPA-Fe concentration was significantly higher at submerged condition by 8.0% compared to soils at field capacity moisture. This could be due to the reduction of iron from ferric (Fe³⁺) to ferrous (Fe²⁺) form under submerged conditions (Saha *et al* 1992). Submergence tends to decrease the redox potential and oxygen diffusion rate and increase the accumulation of CO₂, which are responsible in

increase concentration of Fe in the soils (Patrick and Mikkelsen 1971, Bandyopadhyay and Sen 1992). The drastic decrease in the concentration of DTPA-Fe after initial 30 days of incubation could be due to the formation of insoluble compounds of Fe in soils (Phillips 1998, Ponnampereuma 1977).

Table 4.43 Diethylene triamine pentaacetic acid extractable iron (DTPA-Fe) (mg kg⁻¹) in three soils as affected by moisture regime and incubation period

Incubation period	Loamy sand	Clay loam	Silty clay	Mean
Field capacity				
0	3.8 (0.05) [‡]	7.6 (0.06)	10.5 (0.09)	7.3
15	6.4 (0.20)	11.6 (0.65)	16.8 (0.26)	11.6
30	8.3 (0.39)	15.0 (0.70)	21.2 (0.68)	14.8
45	7.4 (0.38)	12.9 (0.58)	19.3 (0.36)	13.2
60	6.0 (0.31)	11.0 (0.30)	17.6 (0.48)	11.6
90	5.2 (0.27)	9.9 (0.28)	16.6 (0.46)	10.6
120	4.9 (0.15)	9.3 (0.36)	15.0 (0.33)	9.7
Mean	6.0	11.0	16.7	11.3
Submergence				
0	3.8 (0.05)	7.6 (0.06)	10.5 (0.09)	7.3
15	7.1 (0.33)	13.2 (0.60)	18.2 (0.66)	12.9
30	9.4 (0.29)	16.4 (0.59)	23.2 (0.96)	16.3
45	8.2 (0.32)	14.0 (0.69)	20.5 (0.43)	14.2
60	6.9 (0.34)	11.9 (0.34)	18.8 (0.38)	12.5
90	6.0 (0.36)	10.7 (0.39)	17.9 (0.46)	11.5
120	5.4 (0.19)	10.5 (0.37)	15.9 (0.33)	10.6
Mean	6.7	12.0	17.9	12.2

LSD ($p < 0.05$) Soils=0.64, Incubation period=0.98, Moisture=0.52, Moisture x Incubation period=NS, Soil x moisture=NS, Soil x Incubation period=1.70, Soil x Moisture x Incubation period=NS

[‡] Values in the parenthesis indicate standard error

4.5.1.4 Changes in DTPA-Mn in soils

The effect of incubation periods on the DTPA-Mn concentration at different moisture and temperature regimes are shown in figure 4.43, tables 4.45 and 4.46. At field capacity, DTPA-Mn varied between 3.24 to 5.52 (mg kg⁻¹) in loamy sand, 4.46 to 8.02 (mg kg⁻¹) in clay loam and 5.62 to 11.3 (mg kg⁻¹) in silty claysoils. The DTPA-Mn concentration increased during initial 30 days of incubation in soils and decreased sharply thereafter. The silty clay soils showed significantly higher DTPA-Mn followed by clay loam and loamy sand soils. Averaged across the soils, DTPA-Mn concentration was significantly lowest (4.44 mg kg⁻¹) at start than consecutive incubation periods. The DTPA-Mn concentration was highest (8.28 mg kg⁻¹) at 30 days of incubation (Figure 4.43). The DTPA-Mn varied

between 3.24 to 5.91 (mg kg⁻¹) in loamy sand, 4.46 to 8.63 (mg kg⁻¹) in clay loam and 5.62 to 12.2 (mg kg⁻¹) in silty claysoils at submerged condition. The DTPA-Mn concentration increased upto 15 days of incubation period. Unlike DTPA-Fe, the decrease in DTPA-Mn concentration in soils occurred earlier (at 15 days of incubation). It might be because of fast reduction of Mn compared to Fe (Mandal and Mitra 1982). The silty clay soils showed significantly higher DTPA-Mn concentration followed by clay loam and loamy sand soils. Averaged across the soils, DTPA-Mn concentration was lowest (4.44 mg kg⁻¹) at 0 day of incubation and the highest (8.91 mg kg⁻¹) at 15 days of incubation period (Figure 4.43). Averaged across the soils and incubation period DTPA-Mn was significantly higher at submerged moisture regime than at field capacity moisture regime. At different temperature, DTPA-Mn concentration ranged between 4.20 and 9.05 mg kg⁻¹ in different soils. The effect of moisture on the DTPA-Mn was more at higher temperature (40°C) than the other two temperatures (Table 4.46, Figure 4.43). The silty clay soils showed significantly higher DTPA-Mn followed by clay loam and loamy sand soils. The DTPA-Mn ranged between 4.36 to 4.73 (mg kg⁻¹) in loamy sand, 6.33 to 6.96 (mg kg⁻¹) in clay loam and 8.72 to 9.54 (mg kg⁻¹) in silty claysoils at submerged condition (Table 4.46). Averaged across the temperature, soils showed significantly higher DTPA-Mn at submerged condition than at field capacity moisture

Table 4.44 Diethylene triamine pentaacetic acid extractable iron (DTPA-Fe) (mg kg⁻¹) in three soils as affected by moisture and temperature regimes

Temperature (°C)	Loamy sand	Clay loam	Silty clay	Mean
Field capacity				
20	5.7 (0.51) [‡]	10.5 (0.79)	16.1 (1.16)	10.8
30	5.9 (0.56)	10.8 (0.89)	16.7 (1.27)	11.1
40	6.5 (0.67)	11.8 (1.08)	17.4 (1.41)	11.9
Mean	6.0	11.0	16.7	11.3
Submergence				
20	6.2 (0.63)	11.2 (0.92)	17.0 (1.32)	11.5
30	6.8 (0.71)	12.3 (1.12)	18.0 (1.52)	12.4
40	7.1 (0.74)	12.6 (1.17)	18.5 (1.66)	12.7
Mean	6.7	12.0	17.9	12.2
LSD (<i>p</i> <0.05) Soils=0.64, Temperature=0.64, Moisture=0.52, Soil x Moisture=NS, Soil x Temperature=NS, Moisture x Temperature=NS, Soil x Moisture x Temperature=NS				

[‡] Values in the parenthesis indicate standard error

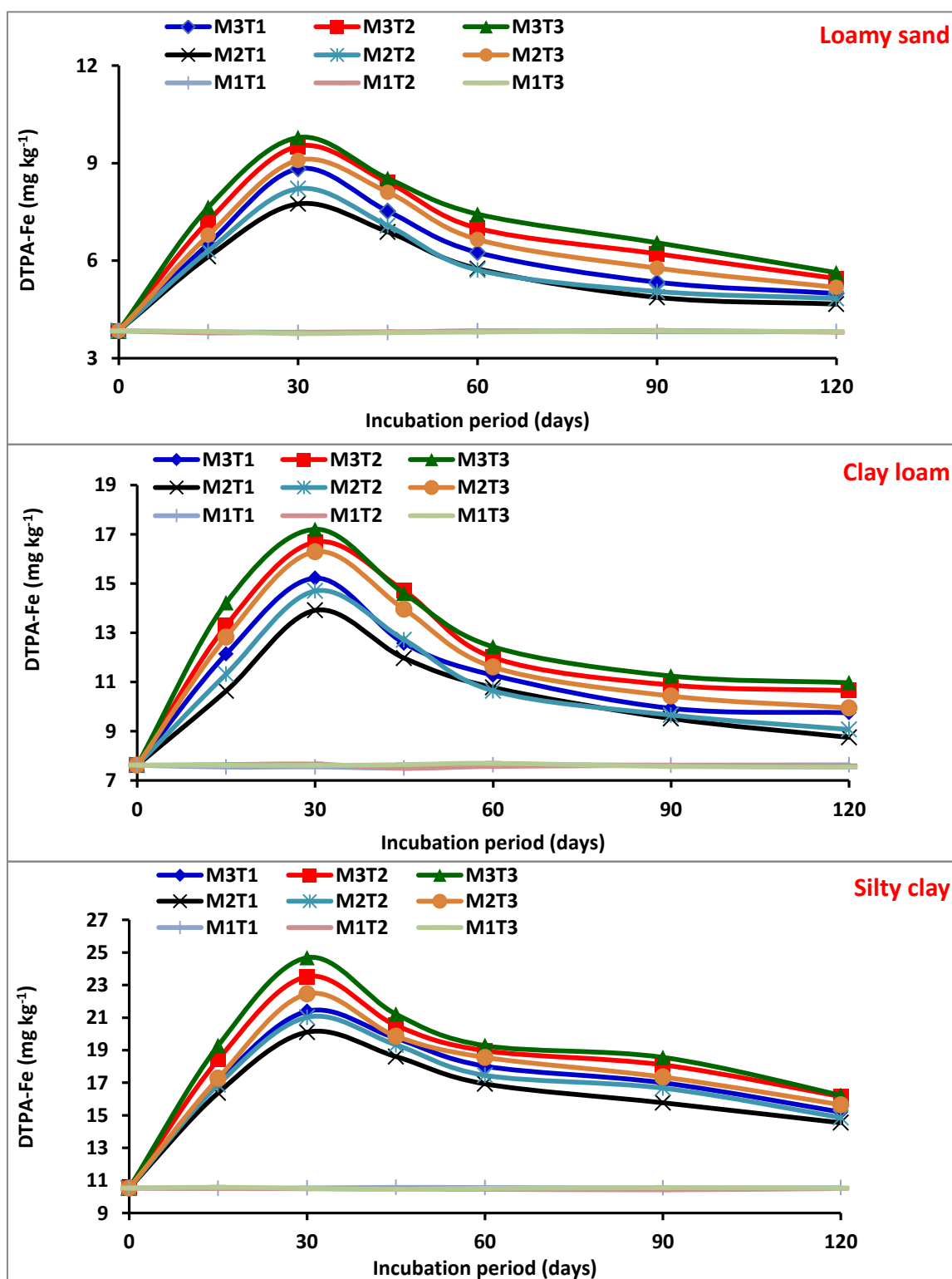


Fig 4.42 Effect of different moisture and temperature regimes on the concentration of DTPA-Fe during 120 days incubation of three texturally different soils [M₁, M₂ and M₃ represents air-dry, field capacity moisture regime and submergence moisture regimes; T₁, T₂ and T₃ represents 20, 30 and 40°C temperature regimes]

4.5.1.5 Changes in available phosphorus in soils

Available P concentration increased considerably as the incubation progressed in three soils except at air dry moisture regime (Figure 4.44). Available P varied between 8.2 to 11.5, 11.1 to 16.2 and 13.4 to 20.4 mg kg⁻¹ at field capacity moisture in loamy sand, clay loam and silty clay soils, respectively (Table 4.47). Averaged across the incubation period, clay loam and silty clay soils had 39.6 and 71.3% higher available P concentration than the loamy sand soil. Available P in soils under submerged condition varied between 8.2 to 12.5, 11.1 to 17.7 and 13.4 to 22.0 mg kg⁻¹ in loamy sand, clay loam and silty clay soils, respectively. Averaged across the soils, available P increased significantly with incubation period up to 90 days of incubation, at field capacity and submerged conditions.

Available P concentration increased with incubation period and was higher in soils incubated under submerged, than at field capacity. On an average, available P concentration was higher by 6.9 to 7.9% in loamy sand, clay loam and silty clay textured soils incubated under submerged compared to field capacity moisture (Table 4.47). Averaged across the soils and incubation period, available P increased by 6.47% in soils under submergence compared to soils at field capacity moisture (Table 4.47). Increase in the available P in equilibrium soil solution with the development of the reduced conditions has been reported by Hundal *et al* (1988). Significantly higher concentration of available P in soils under submerged than under field capacity moisture regime is due to the accumulation of carbon dioxide (CO₂) (Yadvinder-Singh *et al* 1988), reductive dissolution of mineral P (Patric and Mahapatra 1968, Kirk *et al* 1990, Huguenin-Eile *et al* 2003, Runyan and Dodorico 2012), and reduction of ferric phosphate. Moreover, submergence leads to the conversion of meta-stable calcium phosphate to less soluble forms (Wang *et al* 1967, Singh *et al* 2010). The effect of different temperature on the dynamics of available P in three texturally different soils is shown in table 4.48. The results revealed that available P varied between 9.7 to 10.6, 13.6 to 14.7 and 16.8 to 17.9 mg kg⁻¹, respectively in loamy sand, clay loam and silty clay soils at field capacity. Available P concentration increased with temperature at both moisture regimes. Available P concentration in soils was higher at 40°C than the soils incubated at 30 and 20°C (Table 4.48, Figure 4.44). Averaged across incubation period, silty clay soils showed highest (17.3 mg kg⁻¹) available P followed by clay loam and loamy sand soils. Averaged across the soils, available P in soils incubated at field capacity moisture was higher by 3.0 and 7.5% at 30 and 40°C compared to 20 °C. Adeli *et al* (2005) has earlier reported the higher available P concentration at 32°C than at 18°C. Available P varied between 10.5 to 11.2, 14.6 to 15.5 and 17.7 to 19.1 mg kg⁻¹, respectively in loamy sand, clay loam and silty clay soils under submergence. Similar to field capacity moisture regime, available P concentration increased with temperature in three soils. Silty clay soils showed the highest available P concentration followed by clay lom and loamy sand soils. Averaged across the soils, available P concentration was higher at 40°C than other two temperature regimes. Higher P release in soils incubated at 40°C compared with 20 and 30°C temperature could be due to accelerated diffusion of P from the soils at high temperature.

These results corroborates the earlier findings of Kabba and Aulakh (2004), who also reported higher P release from soils incubated at higher temperature, compared to the soils incubated at lower temperature conditions. They also have reported that the extent of P release from the soils at higher temperature was significantly increased when the soils were incubated under submerged, compared to field capacity moisture regime.

Table 4.45 Diethylene triamine pentaacetic acid extractable manganese (DTPA-Mn) (mg kg⁻¹) in three soils as affected by moisture regime and incubation period

Incubation period	Loamy sand	Clay loam	Silty clay	Mean
Field capacity				
0	3.24 (0.05) [‡]	4.46 (0.07)	5.62 (0.09)	4.44
15	5.17 (0.14)	7.33 (0.27)	9.87 (0.47)	7.45
30	5.52 (0.13)	8.02 (0.23)	11.3 (0.32)	8.28
45	4.45 (0.17)	6.63 (0.16)	9.17 (0.52)	6.75
60	4.25 (0.08)	6.15 (0.26)	8.28 (0.43)	6.23
90	4.01 (0.08)	5.67 (0.29)	7.54 (0.25)	5.74
120	3.82 (0.09)	5.38 (0.21)	7.23 (0.30)	5.48
Mean	4.35	6.23	8.43	6.34
Submergence				
0	3.24 (0.05)	4.46 (0.07)	5.62 (0.09)	4.44
15	5.91 (0.15)	8.63 (0.22)	12.2 (0.40)	8.91
30	5.54 (0.13)	7.87 (0.33)	11.0 (0.33)	8.14
45	4.74 (0.17)	6.94 (0.18)	9.85 (0.23)	7.18
60	4.42 (0.11)	6.86 (0.19)	9.10 (0.29)	6.79
90	4.15 (0.10)	6.20 (0.24)	8.33 (0.20)	6.22
120	4.04 (0.07)	5.94 (0.19)	7.96 (0.22)	5.98
Mean	4.57	6.70	9.16	6.81
LSD ($p<0.05$) Soils=0.16, Moisture=0.13, Incubation period=0.24, Moisture x Incubation period=0.34, Soil x Moisture=0.22, Soil x Incubation period=0.42, Soil x Incubation period x Moisture=NS				

[‡] Values in the parenthesis indicate standard error

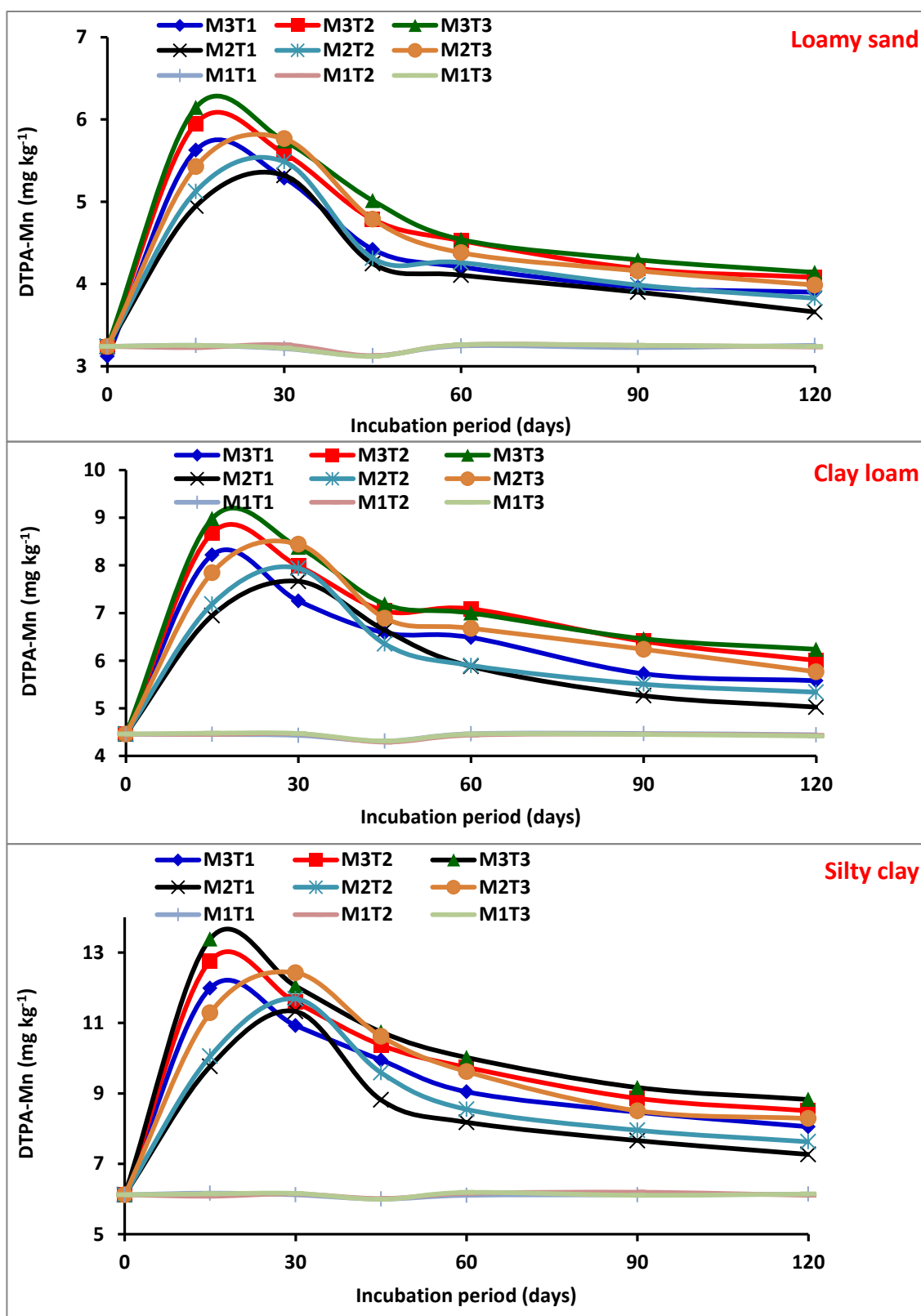


Fig 4.43 Effect of different moisture and temperature regimes on the concentration of DTPA-Mn during 120 days incubation of three texturally different soils [M₁, M₂ and M₃ represents air-dry, field capacity and submergence moisture regimes; T₁, T₂ and T₃ represents 20, 30 and 40°C temperature regimes]

Table 4.46 Diethylene triamine pentaacetic acid extractable manganese (DTPA-Mn) (mg kg⁻¹) in three soils as affected by moisture and temperature regimes

Temperature (°C)	Loamy sand	Clay loam	Silty clay	Mean
Field capacity				
20	4.20 (0.27) [‡]	5.98 (0.44)	7.95 (0.65)	6.04
30	4.32 (0.29)	6.10 (0.44)	8.30 (0.69)	6.24
40	4.53 (0.33)	6.62 (0.50)	9.05 (0.80)	6.73
Mean	4.35	6.23	8.43	6.34
Submergence				
20	4.36 (0.32)	6.33 (0.46)	8.72 (0.73)	6.47
30	4.62 (0.35)	6.81 (0.52)	9.21 (0.82)	6.88
40	4.73 (0.37)	6.96 (0.56)	9.54 (0.89)	7.08
Mean	4.57	6.70	9.16	6.81
LSD ($p<0.05$) Soils=0.16, Moisture=0.13, Temperature=0.16, Soil x Temperature=0.27, Moisture x Temperature NS, Soil x Moisture=0.22, Soil x Moisture x Temperature=NS				

[‡] Values in the parenthesis indicate standard error

Table 4.47 Available P concentration (mg kg⁻¹) in three texturally different soils as affected by moisture regime and incubation period

Incubation period	Loamy sand	Clay loam	Silty clay	Mean
Field capacity				
0	8.2 (0.03) [‡]	11.1 (0.05)	13.4 (0.06)	10.9
15	9.0 (0.12)	12.4 (0.12)	14.7 (0.09)	12.0
30	9.8 (0.20)	13.5 (0.23)	16.1 (0.17)	13.1
45	10.4 (0.29)	14.5 (0.37)	17.7 (0.39)	14.2
60	10.8 (0.35)	15.2 (0.37)	18.7 (0.45)	14.9
90	11.2 (0.36)	16.2 (0.53)	19.9 (0.54)	15.8
120	11.5 (0.43)	16.2 (0.51)	20.4 (0.57)	16.0
Mean	10.1	14.1	17.3	13.9
Submergence				
0	8.2 (0.03)	11.1 (0.05)	13.4 (0.06)	10.9
15	9.6 (0.17)	13.0 (0.22)	15.6 (0.20)	12.7
30	10.6 (0.22)	14.5 (0.20)	17.7 (0.44)	14.3
45	11.2 (0.29)	15.5 (0.28)	19.1 (0.45)	15.3
60	11.8 (0.32)	16.3 (0.28)	20.0 (0.51)	16.0
90	12.3 (0.29)	17.4 (0.38)	21.6 (0.70)	17.1
120	12.5 (0.25)	17.7 (0.41)	22.0 (0.62)	17.4
Mean	10.9	15.1	18.5	14.8
LSD ($p<0.05$) Soils=0.21, Incubation period=0.33, Moisture=0.17, Soil x Moisture=NS, Soil x Incubation period=0.58, Moisture x Incubation period=0.47, Soil x Moisture x Incubation period=NS				

[‡] Values in the parenthesis indicate standard error

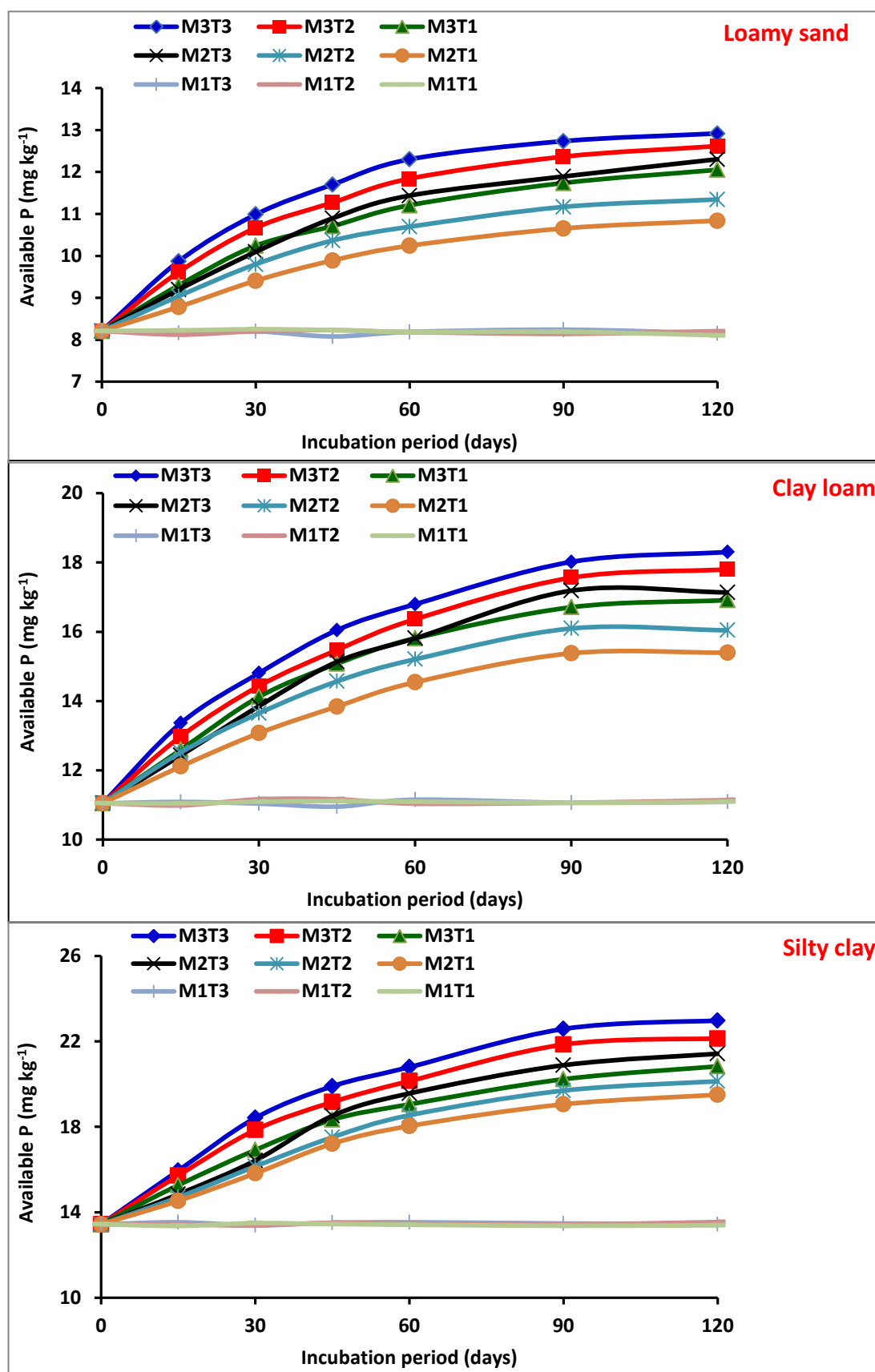


Fig 4.44 Effect of different moisture and temperature regimes on the concentration of available P during 120 days incubation of three texturally different soils [M₁, M₂ and M₃ represents air-dry, field capacity and submergence moisture regimes; T₁, T₂ and T₃ represents 20, 30 and 40°C temperature regimes]

Table 4.48 Available P concentration (mg kg⁻¹) in three texturally different soils as affected by moisture and thermal regimes

Temperature (°C)	Loamy sand	Clay loam	Silty clay	Mean
Field capacity				
20	9.7 (0.37) [‡]	13.6 (0.62)	16.8 (0.87)	13.4
30	10.1 (0.43)	14.2 (0.71)	17.2 (0.95)	13.8
40	10.6 (0.56)	14.7 (0.88)	17.9 (1.15)	14.4
Mean	10.1	14.1	17.3	13.9
Submergence				
20	10.5 (0.52)	14.6 (0.82)	17.7 (1.01)	14.3
30	10.9 (0.60)	15.1 (0.93)	18.6 (1.21)	14.9
40	11.2 (0.65)	15.5 (0.99)	19.1 (1.32)	15.3
Mean	10.9	15.1	18.5	14.8
LSD (<i>p</i> <0.05) Soils=0.21, Moisture=0.17, Temperature=0.21, Moisture x temperature=NS, Soil x Moisture=NS, Soil x Temperature=NS, Soil X Moisture x Temperature=NS				

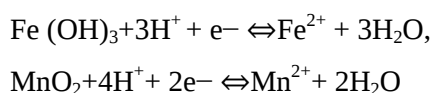
[‡] Values in the parenthesis indicate standard error

4.5.2 Relationship of SOC with DTPA extractable Fe and Mn

At field capacity and submerged conditions, DTPA-Fe concentration in soils increased with incubation period and was highest at 30 days of incubation (Figure 4.42, Table 4.43). The DTPA-Mn concentration in soils increased with incubation period and was highest between 15-30 days of incubation period (Figure 4.43 and Table 4.45). The SOC concentration also increased with incubation period and was highest between 30-45 days of incubation period.

At both soil moisture regimes, increase in the concentration of SOC, DTPA-Fe and DTPA-Mn were positively related to the incubation period (Figure 4.45). Soil organic C exhibited significant (*p*<0.05) correlation with DTPA-Fe (*r*=0.95**) and Mn (*r*=0.86**) (Figure 4.46).

The reduction of Fe³⁺ to Fe²⁺ and Mn⁴⁺ to Mn²⁺ is expressed by following equation (Ponnamperuma 1977):



Because potassium dichromate (K₂Cr₂O₇) is used as an oxidation agent in Walkley and Black (1934) method. Which may oxidized the the reduced forms of Fe and Mn. Therefore, the increase in the concentration of Fe and Mn in puddle soils may be responsible for sharp increase in the SOC. Consequently, the determination of SOC in puddled rice soils may give the higher values of SOC. It

could be possible due to the presence of reduced forms of Mn and Fe (Jackson 1967). This may not be actual increase in SOC. Therefore, it needs further investigation.

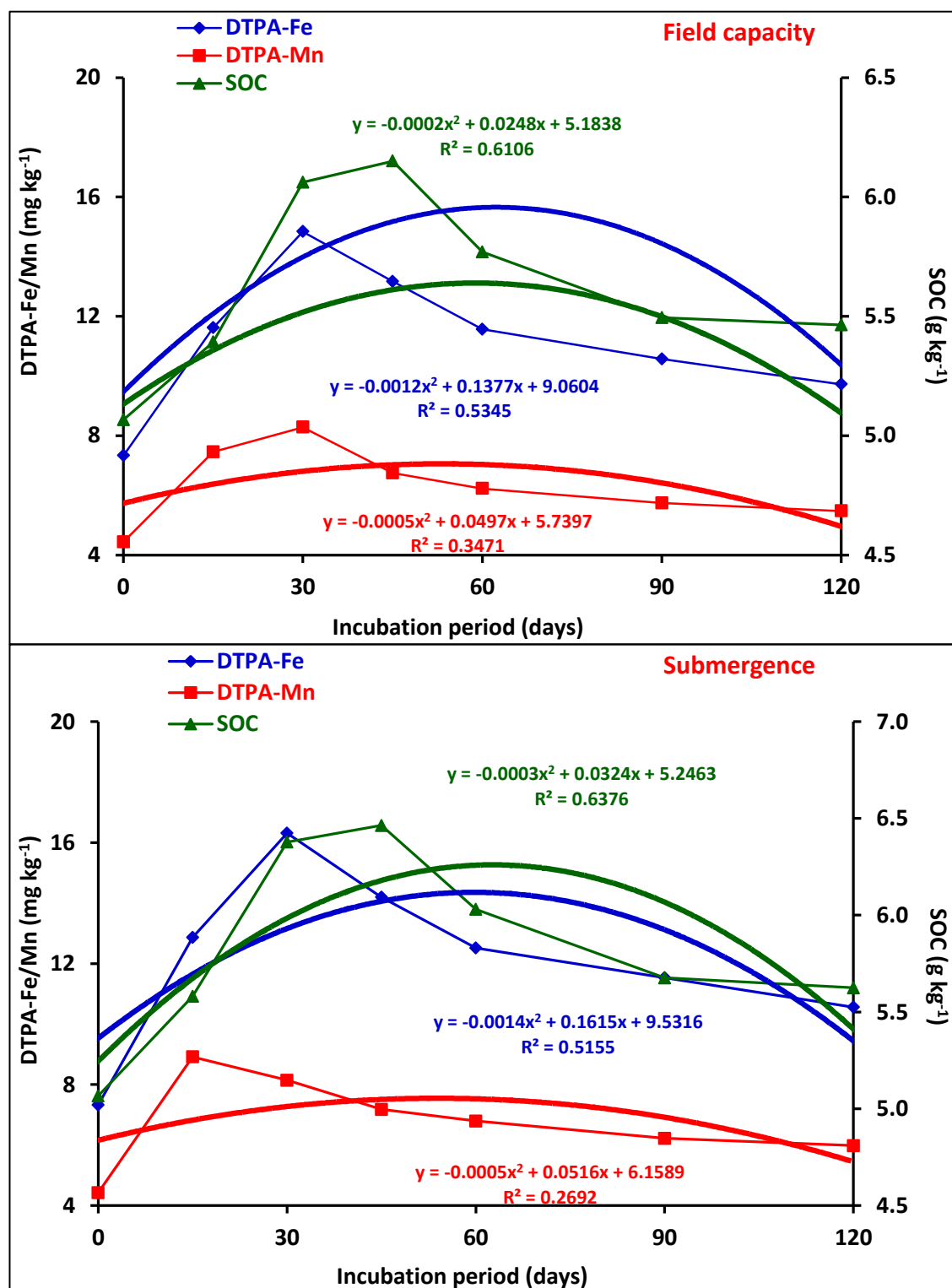


Fig 4.45 Scatter plot of DTPA-Fe, Mn and SOC versus incubation period under field capacity and submerged condition (Data pooled for soils)

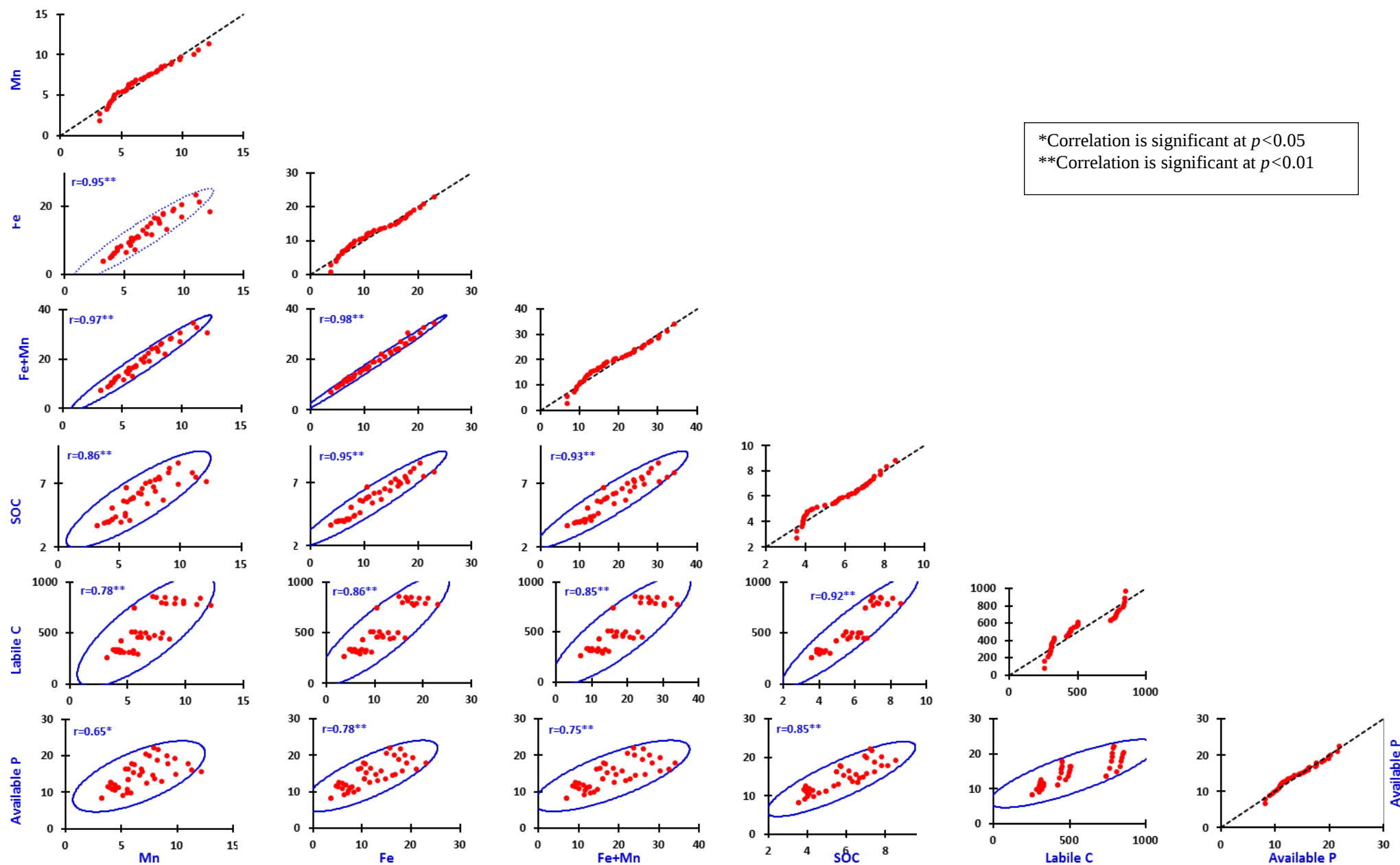


Fig 4.46 Correlation between different soil properties (Data pooled for soils and moisture regimes)

CHAPTER V

SUMMARY

Phosphorus (P) is one of the major nutrients required for plant growth. More than 5.7 billion hectares cropland across the world had insufficient P concentration to achieve an optimal crop production. Phosphorus dynamics in soil depend on soil properties such as texture, organic carbon (SOC), calcium carbonate content (CaCO_3) and available P content. Nutrient management, choice of cropping system and land-use profoundly influence P availability and its dynamics in soils. Soil management practices that increase organic matter level influence P availability through reduction in sorption and conversion of non-labile P to labile-P. Soil organic carbon and labile C pools respond to agricultural management practices, which had significance in P cycling. Therefore, it is important to study dynamics of P in relation to SOC under different land-use and nutrient management practices.

5.1 Effect of rate and source of P application on soil properties and phosphorus fractions

Soil samples from an ongoing field experiment were collected after 7 cycles of rice-wheat cropping from 0-7.5, 7.5-15, 15-30 and 30-60 cm soil depths. Irrespective of the treatment, soil pH increased and electrical conductivity (EC) decreased with depth. Fertilizer-P or farmyard manure applications showed positive influence on soil properties. Compared to unamended control (CK), farmyard manure either alone or in combination with rock phosphate (RP) applications significantly lowered the soil bulk density. The soil bulk density was lower in surface (0-7.5 cm) soil and increased with depth. Compared to CK, the greatest amount of available nutrients, SOC and labile C pools were observed under farmyard manure and RP treated plots in surface (0-7.5 cm) soil. Beneficial effects of fertilizer-P application through RP were relatively less than with single superphosphate (SSP) application. However, conjoint application of RP and FYM showed greater increase in available nutrients and organic carbon compared to application of SSP alone. Farmyard manure and RP applications increased SOC and available P over CK by 98% and 72%, respectively in surface soil. Effect of different treatments on soil properties was more in surface soil and decreased with depth. Below plough layer, different treatments did not influence available P, available K and soil bulk density significantly. The KMnO_4 -oxidizable C was the largest labile C pool and constituted 13.8% of SOC. Water-extractable organic C was the smallest pool and constituted 0.51% of SOC. Carbon mineralization in laboratory incubation studies was higher at 35 °C than at 25 °C, but the magnitude varied with the field treatment. Cumulative amount of CO_2 -C evolved in soil at both the incubation temperatures followed the order $\text{F}_1\text{P}_{30\text{RP}} > \text{F}_1\text{P}_0 > \text{F}_0\text{P}_{30\text{SSP}} > \text{F}_0\text{P}_{30\text{RP}} > \text{F}_0\text{P}_0 > \text{CK}$. Carbon management index (CMI) ranged between 122-261 in surface (0-7.5 cm) soil and 116-227 in subsurface (7.5-15 cm) soil. Carbon management index improved considerably with fertilizer-P and FYM applications in surface and subsurface soils, indicating greater C stabilization in soil.

Applications of fertilizer either alone or in combination with manure increased the concentrations of inorganic, organic and total P in surface soil. Applications of single super phosphate

to both crops in rice-wheat sequence increased organic P compared with RP application. Farmyard manure and rock phosphate applications significantly increased all the soil P fractions, compared to single super phosphate or RP applications. Inorganic P constituted the largest proportion (88.1-92.0%) of total P and organic P constituted the smallest proportion (7.2-10.2 %) of total P at different soil depths. Relative preponderance of different inorganic P fractions in these soils followed the order calcium-aluminium associated inorganic P > iron associated inorganic P > humic bound inorganic P > water soluble inorganic P. The organic P followed the order humic bound organic P > calcium-aluminium associated organic P > sugar bound organic P > acid soluble organic P > iron associated organic P > nucleic acid organic P and polyphosphate > water soluble organic P. The maximum P enrichment among different soil inorganic and organic P fractions occurred with FYM and fertilizer-P, compared to their sole application. Organic P showed higher P enrichment than total P and inorganic P.

Phosphorus release increased rapidly with increase in shaking time. The release of P in soils proceeded in two phases: an initial rapid release phase followed by a slow release after 12-24 hours of shaking. Amount of cumulative P released from soils nearly levelled-off after 48 hours of shaking. Cumulative P release increased with fertilizers P and manure application either alone or in combination and followed the order of $F_1P_{30RP} > F_1P_0 > F_0P_{30SSP} > F_0P_{30RP} > F_0P_0 > CK$. Phosphorus release was best described by Elovich and power function equations as judged by higher coefficient of determination ($R^2 \geq 0.98$) closely followed by parabolic diffusion equation.

All the P fractions, except humic bound inorganic P were significantly and positively correlated with soil C pools. This indicates that several P containing organic compounds after mineralization could increase P availability to crops.

5.2 Effect of nutrient management practices on soil phosphorus and organic carbon fractions

Soil samples from an ongoing field experiments were collected after harvest of wheat crop in basmati-wheat cropping. The samples were collected from 0-7.5, 7.5-15, 15-30 and 30-60 cm soil depths. The experiment involved application of farmyard manure (FYM), rice straw compost (RSC) and vermicompost (VC) to supply 400 kg N ha⁻¹ and recommended rates of fertilizer N, P and K. Irrespective of the treatment, soil pH increased and EC decreased with depth. Compared to CK, soil bulk density (D_b) significantly decreased in plots amended with farmyard manure (FYM) and vermicompost (VC) in surface (0-7.5 cm) soil. Soil D_b increased with depth and all the treatment showed similar soil D_b in lower soil layer. The effect of different treatments was in reverse trend for soil porosity.

Compared to CK, mineral N, available P and K significantly increased with fertilizer and manure applications in 0-7.5 cm and 7.5-15 cm soil. In surface (0-7.5 cm) soil, mineral N significantly increased in plots amended with organic sources viz. FYM, RSC and VC compared to plots amended with NPK. In surface (0-7.5 cm) soil, application of recommended rates of NPK and adoption of INM

improved available P in soil over unamended control by 75 and 100%, respectively. Integrated nutrient management improved available K by 25.6% over NPK treatment. Plots amended with RSC showed significant higher available K compared to FYM amended plots. Adoption of INM showed increase in mineral N and available K, compared to organically amended soils. The comparison of three organic manure treated plots revealed that mineral N and available P was higher in soil receiving 400 kg N ha⁻¹ through FYM, followed by RSC and lowest in VC.

Compared to CK, fertilizer and manure applications increased TOC, labile C pools including WEOC, HWSC, MBC and KMnO₄-C in surface (0-7.5 cm) soil. Compared to TOC, labile C pools for example WEOC, HWSC and KMnO₄-C respond promptly to nutrient management practices. Farmyard manure application significantly increased WEOC, HWSC and KMnO₄-C compared to INM treatments. Adoption of INM significantly increased TOC and all the labile C pools compared to NPK application. Adoption of INM and organic manure application alone (FYM, RSC and VC) showed significant increase in MBC concentration compared to NPK. C mineralization was considerably lower in the CK plots and increased with inorganic and organic fertilizers applications. Adoption of INM increased KMnO₄-C by 14% compared to NPK application. Farmyard manure, RSC and VC applications increased KMnO₄-C concentration by 29, 8 and 13% compared to INM treatments. Regardless of the incubation temperature, amount of cumulative evolved C from the soils, followed the order FYM>VC>RSC>INM>NPK>CK. Carbon management index (CMI) improved considerably with fertilizer and manure applications and followed the order FYM>VC>RSC>INM>NPK>CK. Water extracted organic C comprised the smallest pool (0.53-0.60% of TOC) and KMnO₄-C comprised the largest pool (11.5-17.4% of TOC) at different depth of soil. Hot water soluble C was relatively larger in size (4.37-4.69% of TOC) than MBC (2.53-3.05% of TOC) at different soil depth.

In surface soil (0-7.5 cm), application of RSC, VC and NPK with or without FYM, significantly increased the inorganic, organic and total P compared to unfertilized soils. Compared to NPK applications, INM increased inorganic, organic and total P by 77, 82 and 78%, respectively. Plots amended with organic manure alone showed significantly higher inorganic, organic and total P, compared to INM treatments. Application of FYM, RSC and VC exhibited similar inorganic and total P concentration while organic P concentration was significantly higher in plots amended with VC followed by RSC and FYM. Calcium-aluminium associated inorganic P fraction represented the largest proportion (72.9-75.4 %) of inorganic P. Water soluble inorganic P represented the smallest proportion (0.23-0.35%) of inorganic P. Humic bound organic P constituted major proportion (39.5-49.5%) of organic P. Water soluble organic P represented the smallest proportion (0.83-2.5%) of organic P. Inorganic P constituted the largest proportion (75.2-90.4%) and organic P constituted smallest proportion (8.0 to 23.4 %) of total P. Application of inorganic fertilizers increased total P stock by 14% compared to unfertilized plots. Further, adoption of INM showed significantly higher (72%) total P stock compared to NPK treated plots. Plots amended with manure viz. FYM, RSC and

VC exhibited significant increase in total P stock compared to INM plots. Effect of different treatments on inorganic P stocks was similar to that observed in for total P stocks. Organic P stock was significantly higher in VC amended plots followed by RSC and FYM amended plots. Influences of different treatment on P fractions and stocks were higher in surface (0-7.5 cm) soil and decreased with depth. Adoption of INM increased % enrichment in P fractions compared with NPK applications. Application of manure showed highest % P enrichment than other treatments. The percent P enrichment was highest in organic P and source of organic manure followed the order VC>RSC>FYM.

Beneficial effects of different treatment on soil properties were higher in surface (0-7.5 cm) soil and decreased with soil depth.

Regardless of the shaking time, cumulative P release was higher in soils involving INM, followed by FYM>RSC>VC>NPK>CK. The comparison of three organic sources revealed that higher P release occurred from soils amended with FYM (10.4-22.9 $\mu\text{g P g}^{-1}$) and lowest from VC (9.9-21.9 $\mu\text{g P g}^{-1}$) amended soil. Release of P with time was best described by power followed by Elovich and parabolic diffusion equations.

Highly significant positive correlation was observed among the soil C pools. Except calcium-aluminium and iron associated organic P, all the P fractions were significantly correlated with TOC. Except iron associated organic P, all the P fractions showed significant positive correlation with WEOC. Mostly P fractions were significantly positively correlated with MBC, except calcium-aluminium, iron and humic bound organic P. Except water soluble inorganic P, all P fraction showed significant and positive correlation with $\text{KMnO}_4\text{-C}$. Organic and total P were significantly and positively correlated with TOC and labile C pools. Inorganic P was significantly correlated with WEOC.

5.3 Effect of land-use on phosphorus and organic carbon fractions in soil

Ninety six surface soil samples (0-15 cm) were collected from farmers' fields, which were under rice-wheat, maize-wheat, cotton-wheat cropping and agroforestry systems. Soil samples were characterized for P fractions and extractable pools of SOC. Total P concentration was the highest under agroforestry (569 mg P kg^{-1}) followed by rice-wheat (517 mg P kg^{-1}), cotton-wheat (462 mg P kg^{-1}), and the lowest under maize-wheat (449 mg P kg^{-1}) system. Soils under rice-wheat had significantly greater total P concentration than the soils under cotton-wheat and maize-wheat cropping systems. Inorganic P was the dominant fraction and accounted for 92.3, 94.0 and 94.6% of total P in soils under rice-wheat, maize-wheat and cotton-wheat cropping systems, respectively. However, soils under agroforestry had relatively smaller proportion (72.9%) of total P occurring as inorganic P. Therefore, agroforestry systems had relatively higher proportion of organic P (27%) compared to the other land-uses (6-7.7%).

Water soluble inorganic P fraction represented the smallest proportion (0.13-0.26%) of total inorganic P in soils. Calcium-aluminium associated inorganic P represented the largest proportion

(73.5-75%) of total inorganic P in soils under different land-uses. Among the organic P fractions, water soluble organic P fraction was the least in amount and represented the smallest proportion (0.70-3.2%) of organic P under different land-uses. Humic-bound organic P comprised the largest proportion (38.4-53.4%) of organic P in soils under different land-uses. Irrespective of the land-use, the relative abundance of different inorganic P fractions followed the order calcium-aluminium associated inorganic P > iron associated inorganic P > humic bound inorganic P > water soluble inorganic P.

Concentrations of SOC and $\text{KMnO}_4\text{-C}$ were the highest under agroforestry and the lowest under cotton-wheat cropping system. Maize-wheat and cotton-wheat cropping systems exhibited similar SOC concentration. The concentration of hot water soluble C (HWSC) was significantly higher in soils under agroforestry and rice-wheat than the other systems. Significant positive correlation between SOC and labile C fractions was observed with silt and clay content under different land-uses. Available P in soil was positively correlated with clay content in soils under rice-wheat, maize-wheat and cotton-wheat cropping systems. Total and inorganic P showed significant correlation with clay content. Soil organic C, HWSC and $\text{KMnO}_4\text{-C}$ showed highly significant positive correlation with soil P fractions.

5.4 Effect of soil physical and chemical properties on P sorption kinetics

Sixteen soil samples varying in clay, SOC, available P and CaCO_3 content were selected to study P release and sorption-desorption kinetics. Phosphorus release from soils proceeded in two phases- an initially faster phase followed by a slower phase as equilibration progressed. Cumulative amount of P released in 96 h was greater in soils with lower clay content and higher available P and SOC concentration. Elovich equation ($R^2 \geq 0.97^{**}$), Power function ($R^2 \geq 0.90^{**}$) and parabolic diffusion equation ($R^2 \geq 0.78^{**}$) described well the P release versus time data. Phosphorus release coefficients for power function were significantly ($p < 0.01$) correlated with available-P and SOC. Stepwise inclusion of clay, SOC, available P and CaCO_3 significantly improved the predictability of various release constants. The equilibrium solution P concentration continued to increase with increasing amount of P added. Langmuir sorption isotherms suggested the formation of two adsorbed layers of high and low energy sites. Langmuir and Freundlich sorption constant (S.R.= rate of P sorption and S.E.= extent of sorption) increased with increase in clay and CaCO_3 content. Increase in SOC content and available P concentration in the soils, there had been a substantial reduction in the rate and extent of P sorption. Freundlich adsorption isotherms for estimating soil P adsorption capacities can be used to predict effect of soil properties on soil P availability. For efficient P management it is important to take into account soil texture, the existing soil P level, SOC content and calcareousness of soil.

5.5 Effect of temperature and moisture on changes in soil organic C and available Fe, Mn and P in soils

To study weather increase in SOC under submerged condition is reality or myth. Three bulk soil samples (0-15 cm soil depth) were collected from Hoshiarpur (loamy sand soil), Rupnagar (clay loam soil) and Patiala (silty clay soil) under rice-wheat cropping system. An incubation study was conducted for 120d. Soil organic C increased with incubation period and showed highest value at 30-45 d and decreased sharply thereafter. Concentration of DTPA-Fe was highest at 30 d and decreased sharply thereafter. However, DTPA-Mn concentration was highest at 15 and at 30 d of incubation, under submerged and field capacity soil moisture regimes. Concentration of $\text{KMnO}_4\text{-C}$ increased rapidly upto 30 d of incubation period and thereafter did not change. Available P concentration continuously increased with incubation period. Submerged conditions showed higher SOC, DTPA-Fe, DTPA-Mn and available P than the soils incubated at field capacity. Regardless of soils, soil organic C, DTPA-Fe, Mn, and available P were higher under submerged conditions at 40°C followed by 30°C and 20°C temperature. Regardless of the soil and temperature, values of these variables did not change at air dry soil moisture regime. The concentration of DTPA-Fe and Mn showed positive relationship with SOC concentration at submerged and field capacity soil moisture regimes. Therefore, increase in SOC with moisture may be due to the increase in DTPA-Fe and Mn.

Farmyard manure and RP application improved soil properties to a greater extent than their individual applications, indicating the need for combined use of FYM and RP in these alluvial soils.

Integrated nutrient management resulted in higher increase in mineral N, available P and available K, compared to FYM applications. Effect of different treatments on TOC, labile C fractions and C mineralization followed the order $\text{FYM} > \text{VC} > \text{RSC} > \text{INM} > \text{NPK} > \text{CK}$. Compared to INM, farmyard manure, RSC and VC applications showed significant increase in inorganic, organic and total P pools in soil. Therefore, integrated nutrient management practice is important to enhance P availability in soil. However, manure applications build-up the soil P pools and organic C pools as well.

Soil P fractions showed significant correlation with SOC. However, inorganic and the available P concentrations were lower in soils under agroforestry, compared with other land-uses, suggesting that P cycling depends on the land-use and their nutrient management practices. Therefore, fertilizer P application may be required for intercrop under agroforestry systems.

For efficient P management, it is important to take into account soil texture, the existing soil P level, SOC content and calcareousness of soil. Practices that increase SOC content and ameliorate CaCO_3 could lead to improved P use efficiency.

The concentration of DTPA-Fe and Mn showed positive relationship with SOC concentration at submerged and field capacity soil moisture regimes. Therefore, increase in SOC with moisture may be due to the increase in DTPA-Fe and Mn.

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SUBMITTED/ACCEPTED/PUBLISHED RESEARCH ARTICLES

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3	Effect of Rates and Source of Phosphorus Application on Soil Properties under Rice-Wheat Cropping System	Pedosphere	7.38	Submitted



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Land-use effects on phosphorus fractions in Indo-Gangetic alluvial soils

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Abstract:	Phosphorus (P) in soil exists both in organic and inorganic forms and their relative abundance could determine P supplying capacity of soil. Differential input of exogenous and plant-mediated phosphorus and carbon in soil under different land-uses could influence P availability and fertilizer P management. While the effect of land-use on soil organic carbon (SOC) is fairly well-documented, its effect on soil P fractions is relatively less known. We investigated the effect of different land-uses including rice-wheat, maize-wheat, cotton-wheat cropping systems and poplar-based agroforestry systems on soil P fractions and organic carbon accrual in soils. Total P concentration was the highest under agroforestry (569 mg P kg⁻¹) and the lowest under maize-wheat (449 mg P kg⁻¹) cropping systems. On the contrary, soils under rice-wheat had significantly higher available P concentration than the agroforestry systems, probably because of higher fertilizer P application in rice-wheat and prevailing wetland conditions during rice growth. In soils under sole cropping systems viz. rice-wheat, maize-wheat and cotton-wheat, inorganic P was the dominant fraction and accounted for 92.3 to 94.6% of total P. However, the soils under agroforestry had smaller proportion (72.9%) of total P existing as inorganic P. Among soil P fractions, water soluble inorganic P (0.13-0.26%) represented the smallest proportion inorganic P in soils under different land-uses. Agroforestry showed significantly ($p < 0.05$) higher concentrations of SOC than the other land-uses. Soil organic C was significantly correlated with soil P fractions. It was concluded that poplar-based agroforestry systems besides leading to C accrual in soil result in build-up of organic P and the P supplying capacity of soil.

Land-use effects on phosphorus fractions in Indo-Gangetic alluvial soils

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Abstract

Phosphorus (P) in soil exists both in organic and inorganic forms and their relative abundance could determine P supplying capacity of soil. Differential input of exogenous and plant-mediated phosphorus and carbon in soil under different land-uses could influence P availability and fertilizer P management. While the effect of land-use on soil organic carbon (SOC) is fairly well-documented, its effect on soil P fractions is relatively less known. We investigated the effect of different land-uses including rice-wheat, maize-wheat, cotton-wheat cropping systems and poplar-based agroforestry systems on soil P fractions and organic carbon accrual in soils. Total P concentration was the highest under agroforestry (569 mg P kg⁻¹) and the lowest under maize-wheat (449 mg P kg⁻¹) cropping systems. On the contrary, soils under rice-wheat had significantly higher available P concentration than the agroforestry systems, probably because of higher fertilizer P application in rice-wheat and prevailing wetland conditions during rice growth. In soils under sole cropping systems viz. rice-wheat, maize-wheat and cotton-wheat, inorganic P was the dominant fraction and accounted for 92.3 to 94.6% of total P. However, the soils under agroforestry had smaller proportion (72.9%) of total P existing as inorganic P. Among soil P fractions, water soluble inorganic P (0.13-0.26%) represented the smallest proportion inorganic P in soils under different land-uses. Agroforestry showed significantly ($p < 0.05$) higher concentrations of SOC than the other land-uses. Soil organic C was significantly correlated with soil P fractions. It was concluded that poplar-based agroforestry systems besides leading to C accrual in soil result in build-up of organic P and the P supplying capacity of soil.

Keywords Land-use. Agroforestry. Available P. Soil P fractions. Soil organic carbon. Organic P. Inorganic P.

Introduction

Phosphorus (P) is an essential nutrient required for normal plant growth. It plays an important role in maintaining soil fertility and sustaining productivity. Although most soils in the world contain sufficient amounts of total P (~200-3,000 mg P kg⁻¹ soil), but only a small proportion (<1%) is available to plants, because of its physico-chemical behaviour and interaction at the soil mineral interface (Stewart and Tiessen, 1987; Richardson et al. 2005). While some soils have low P availability due to a small amount of total P, the others are deficient in plant-available P despite the presence of a considerable amount of total P (Muhammad et al. 2008). In India, despite the presence of sufficient amounts of total P, about 42% soils are deficient and 38% are medium in plant available P (FAI, 2012).

Phosphorus is immobile in soil and exists in organic and inorganic forms. Applied P in soil is either taken up by the crop or becomes physically/chemically adsorbed onto calcium, aluminium and iron or incorporated into organic P (McLaughlin et al. 1988). Although, inorganic P is considered a major source of available P in soils, but mineralization of organic P has also been shown to be important in both low and high fertility soils (Stewart and Tiessen, 1987). Phosphorus dynamics in soil are controlled by combinations of dissolution-precipitation, sorption-desorption and mineralization-immobilization reactions that respond to agricultural management and land-use change (Frossard et al. 2000; Aguiar et al. 2013). Among different agricultural management practices, nutrient management, cropping system and land-use change greatly influence P dynamics in soil (Chen et al. 2003; Aguiar et al. 2013). Soil organic carbon (SOC) plays an important role in supply of nutrient and provides energy for soil organisms. An improvement in SOC with organic manure application enhances soil microbial activity and thereby alters P availability through mineralization-immobilization processes (Chen et al. 2003). Soil P transformations are primarily mediated by microbial activity, which is influenced by a combination of factors including land-use, soil type and nutrient management (Chen et al. 2008; Wright 2009). Inorganic P released from soil microbial biomass and mineralization of soluble organic P contributes to plant available P pool. Therefore, land-use, which influences SOC accumulation in soil, may also impact plant P availability. It has been reported that soils under grassland had a significantly higher concentration of total P, microbial biomass P and organic P than the croplands (Chen et al. 2003). Agroforestry has been advocated as an important strategy for C sequestration in soil (Benbi et al. 2012). It has been shown that soils under agroforestry systems have greater C stocks and C rehabilitation capacity than the croplands because of greater addition of leaf and root biomass to soil (Benbi et al. 2015). While several studies have documented the influence of land-use including cropland and agroforestry systems on SOC, the effect of such land-uses on soil P fractions and P availability is relatively less known. Knowledge about soil P fractions under different land-uses can increase our understanding of sinks and sources of P in the soil for efficient P management. We hypothesized that agroforestry and rice-wheat, maize-wheat and cotton-wheat cropping systems with different nutrient requirement and residue return to soil will

differently influence soil P reactions and its stabilization in different fractions. Further, wetland condition during rice and upland conditions during maize and cotton will also influence P reactions in soil. The specific aim of this study was to investigate the effect of poplar-based agroforestry, rice-wheat, maize-wheat and cotton-wheat cropping systems on soil P fractions and P availability in Indo-Gangetic alluvial soils.

Materials and methods

Soil sampling sites and sample collection

Punjab state is located in North-Western India and lies between latitudes 29.30° N to 32.32° N and longitudes 73.55° E to 76.50° E. Punjab climate comprises of three seasons viz. summer from mid April to the end of June, the rainy season from early July to end of September and the winter season from early December to end of February. The region falls in the agro-ecological sub-region 4.1 of India and is characterized as semiarid subtropical with monsoonal climate. Annual rainfall ranges between 700 and 800 mm and more than 70% of it occurs during the monsoon months of July–September. The temperature ranges from minimum of 4 °C in winter to 45 °C in summer. The mean monthly minimum and maximum air temperature respectively average 18 and 35°C during rice/maize growth season (June–October) and 7 and 23°C during wheat season (November–April).

Surface soil samples (0–15 cm) were collected from 96 sites representing four different land-uses viz. rice-wheat, maize-wheat, cotton-wheat and under agroforestry systems for 15 years or more. Soil samples were collected from different districts of Punjab (India) (Fig. 1). For every land-use, 24 samples, each composite of three spots within a field were taken with a core sampler, after the harvest of wheat crop in April/May 2013. In the agroforestry systems, samples were collected between tree rows. Between the trees row, farmers were growing intercrops viz. moong (*Vigna radiata*), black gram (*Vigna mungo*) in summer and wheat (*Triticum aestivum*) during winter for 3–4 yr of each succession. In agroforestry, fertilizers are applied to wheat only. Wheat under agroforestry and sole cropping system is fertilized at 120–135 kg N, 50–60 kg P₂O₅, 20–30 kg K₂O. Rice, maize and cotton are fertilized at 115–125 kg N, 15–25 kg P₂O₅, 15–20 kg K₂O. Farmyard manure (FYM) at 8–9 Mg ha⁻¹ is applied to rice, 5–6 Mg ha⁻¹ to both maize and cotton. All the land-use systems were irrigated with the canal or groundwater. Rice fields were kept submerged during first month after transplanting and thereafter flood-irrigated and all the other crops received an irrigation of 7.5 cm as and when required.

Sample analyses

Samples were air-dried and ground to pass 2 mm sieve before analysis. The soil samples were analyzed for pH (1:2 soil: water suspension) using glass electrode, electrical conductivity (EC, 1:2

soil: water supernatant) using conductivity meter and particle size distribution by pipette method (USDA, 1930). Available P was determined by extracting the soil samples with 0.5 M NaHCO_3 , pH 8.5 (Olsen et al. 1954) and measuring the P content in the extract colorimetrically using ascorbic acid method (Murphy and Riley 1962). Available K was determined by extracting with 1N ammonium acetate (pH 7.0). Potassium concentration in the extract was determined with a flame photometer (Jackson 1967). Calcium Carbonate was determined by titrating soil suspension (soil, water, calcium sulphate powdered and aluminium chloride) with 0.5N H_2SO_4 in presence of bromothymol blue and bromocresol green indicators (Puri 1950). Soil organic carbon was determined by wet digestion method (Walkley and Black's 1934).

Phosphorus fractionation

The chemical speciation of P in soil samples was achieved by using a sequential extraction scheme proposed by Golterman (1996) and Golterman et al. (1998) (Fig. 2). Briefly, 0.5 g soil was sequentially extracted by shaking with 30 ml deionized water for 2 hours. This was followed by 2 hours shaking with 0.05M Ca-EDTA (+1% Na-dithionite, pH=7.8). Then same soil was shaken for 16 hours with 0.1M Na-EDTA (pH=4.5). After this same soil was shaken for 2 hours with 0.5M H_2SO_4 , and 2 hours with cold 0.5M tri-chloroacetic acid (TCA; 0 °C,) followed by the shaking of same soil with hot 0.5M TCA (95°C) for 30 minutes. Then, in the same soil 2M NaOH (90°C) was added and shaken for 1 hour. Finally, the same soil was shaken for 2 hours with persulphate ($\text{K}_2\text{S}_2\text{O}_8$)+ H_2SO_4 which is believed to remove the residual P_i . These fractions represent in sequential order: water soluble or soil solution P ($\text{H}_2\text{O-P}$), Fe associated P, Ca associated P, acid soluble organic P (ASOP), sugar bound P after digestion with $\text{K}_2\text{S}_2\text{O}_8$ (cold TCA), nucleic acid and polyphosphate P after digestion with $\text{K}_2\text{S}_2\text{O}_8$ (hot TCA; Golterman 1960), humic bound P and phytate (NaOH P_i and NaOH P_o), and residual P. Following extraction, each soil-suspension was centrifuged at 3500 rpm for 15 min, decanted, and an aliquot was taken for P determination. For $\text{H}_2\text{O-P}$, Fe-P, Ca-P, and NaOH fractions, the organic P (P_o) fraction was defined as the difference between P detectable before and after digestion with $\text{K}_2\text{S}_2\text{O}_8$. Phosphorus in extracts was determined colorimetrically with the molybdate-ascorbic acid method (Murphy and Riley 1962).

Statistical analyses

Results were subjected to analysis of variance (ANOVA) using a completely randomized block design. Mean separation for different treatments was evaluated at 95% confidence interval using the Duncan's multiple range test (DMRT). The statistical analyses were performed with SPSS 16.0 for Windows (SPSS Inc., Chicago, U.S.A.).

Results and discussions

General soil properties

The soils under all the land-uses were non-saline and near-neutral to alkaline in reaction though the soils under agroforestry had significantly lower pH than the other land-uses that did not differ significantly (Table 1). The electrical conductivity (EC) was significantly lower in soils under cotton-wheat than the other land-uses. Soils under all the land-uses were sandy loam in texture with sand content ranging between 60 and 64.6% and silt content between 21.8 and 25.1%. Soils under all the land-uses were medium to high (9.8 to 16.0 mg P kg⁻¹) in available P and high in available K (83 to 100 mg K kg⁻¹). Available K concentration was significantly higher in soils under agroforestry compared with other land-uses. Contrarily, available P concentration was significantly lower in soils under agroforestry, compared to the other land-uses. Lower concentration of available P in soils under agroforestry may be due to wide C : P ratio. Wide C : P ratio reduces P mineralization leading to decrease in available P concentration in soil (Broder et al. 2012). The relatively greater P concentration under sole cropping systems may be attributed to regular use of organic manure (FYM) and fertilizer-P during crop production. CaCO₃ concentration in soils under different land-uses did not differ significantly and ranged between 0 and 19.5 g kg⁻¹ soil.

Soil phosphorus fractions

Total P concentration was significantly higher in soils under agroforestry (569 mg P kg⁻¹) than the other land-uses. Among the sole cropping systems, rice-wheat exhibited significantly greater total P concentration than maize-wheat and cotton-wheat cropping systems (Fig. 3). Under sole cropping systems, inorganic P was the dominant fraction that represented 92.3, 94.0 and 94.6% of total P in soils under rice-wheat, maize-wheat and cotton-wheat systems, respectively. However, soils under agroforestry had relatively lower proportion (72.9%) of inorganic P and greater proportion of organic P (27%) compared to other land-uses. Significantly lower proportion of inorganic P in soils under agroforestry may be ascribed to relatively lower fertilizer P application than the other land-uses, higher uptake of P by poplar trees and wide C: P ratio of soil. Further, higher organic P concentration in soils under agroforestry may be attributed to the greater addition of organic P through plant biomass (roots and leaves) in agroforestry systems than the other land-uses. Another reason for lower inorganic P under agroforestry soils could be immobilization of P by microorganisms in their structural development to mineralize the organic residues added into the soil (Xavier et al. 2011). Immobilization-mineralization of microbial P are the major processes regulating P cycling and availability from organic material in the soil (Oberson and Joner 2005).

Higher proportion of organic P relative to total P in the soils under agroforestry compared with conventional cropping has been attributed to the effect of agroforestry on the dynamics of P in the soils, through the conversion of inorganic P into organic P (Cardoso et al. 2001) and the reduced tillage and higher deposition of root and leaf litters on the surface (Lobato et al. 2014). Perrot et al.

(1992) reported that greater root biomass and increase in SOC under agroforestry favour microbial growth and microbial P immobilization and thus increase organic P accumulation (Beck and Sanchez 1994). Greater accumulation of organic, inorganic and total P in soils under rice-wheat compared with maize-wheat and cotton-wheat cropping systems may be attributed to the application of higher amount of organic manure ($8\text{--}9 \text{ Mg ha}^{-1} \text{ yr}^{-1}$) coupled with greater addition of plant biomass (roots and leaves) under rice-wheat system.

Water soluble inorganic P was the smallest fraction, which represented 0.13 to 0.26% of inorganic P in soils under different land-uses (Table 2). Calcium-aluminium associated inorganic P was the most dominant inorganic P fraction and represented 73.5 to 75.0% of inorganic P in soils under different land-uses. Iron associated inorganic P represented 14.3 to 17.6% of inorganic P and humic bound fraction comprised 8.5 to 10.9% of inorganic P in soils under different land-uses.

The water soluble organic P fraction represented 0.71 to 3.17 % of organic P in soils under different land-uses. Iron associated organic P comprised 3.8 to 7.7% of organic P in soils. Calcium-aluminium associated organic P comprised 14.6 to 18.9% of organic P in soils under various land-uses. Humic bound organic P, acid soluble P, and sugar bound organic P represented 38.4 to 53.4%, 9.73 to 14.4%, 10.4 to 11.8% of organic P, respectively, in soils under different land-uses. Nucleic acid organic P and polyphosphate varied from 2.8 to 9.0% of organic P in soils under different land-uses.

Water soluble inorganic P concentration was significantly lower in soils under cotton-wheat, compared to other land-uses (Table 2). It was higher by 44.6, 87.5 and 91.1% in soils under maize-wheat, rice-wheat and agroforestry systems compared to cotton-wheat system. Water soluble organic P was significantly higher in soils under agroforestry, compared to other land-uses. Soils under rice-wheat showed significantly higher water soluble organic P concentration than the other two cropping systems. Iron associated inorganic P concentration did not differ significantly among different land-uses (Table 2). However, the concentration of iron associated organic P was significantly lower in soils under cotton-wheat cropping system, and was 81.5, 32.2 and 292.5% higher in soils under rice-wheat, maize-wheat and agroforestry compared to cotton-wheat cropping system. The concentration of calcium-aluminium associated inorganic P was significantly higher in soils under rice-wheat cropping system compared to other land-use. Irrespective of the land-use, the relative abundance of different inorganic P fractions followed the order calcium-aluminium associated inorganic P > iron associated inorganic P > humic bound inorganic P > water soluble inorganic P. Several studies (Aulakh et al. 2003; Jalali and Matin 2013) have reported similar trends of Ca-P, Al-P and Fe-P fractions in soils.

The calcium-aluminium associated inorganic P fraction represented 69.1, 69.7, 75.0 and 53.6% of total P in soils under rice-wheat, maize-wheat, cotton-wheat and agroforestry systems, respectively. This could be attributed to the formation of insoluble Ca-P compounds in these soils having calcareous nature as Ca^{2+} activity in the liquid phase is mainly responsible for formation of

insoluble Ca-phosphate mineral in calcareous soil (Tunési et al. 1999). In calcareous soils, the accumulation of CaCO_3 is believed to govern soil P reactions because of its adsorption and precipitation on the CaCO_3 surface (Lindsey 1979; Freeman and Rowell 1981). Relatively lower proportion of calcium-aluminium associated inorganic P in soils under agroforestry may be attributed to the effect of organic matter returned to the soil through litter fall and root biomass that has the ability to solubilize the native soil P (Gaume et al. 2001; Boschetti et al. 2009). Apatite is the primary mineral of P which represents the calcium associated P in soils, P from this mineral is not readily available to plants (Williams et al. 1980). Organic acids such as oxalic and citric acids are released during the decomposition of soil organic matter and ectomycorrhizal fungi, may increase calcium phosphate dissolution. Excretion of carboxylate, enzymes, and protons by roots and fungi participate in ligand exchange reactions with sesquioxides thereby increases the P molecules into soil solution (Gaume et al. 2001). Several studies (Aulakh and Pasricha 1991; Guo et al. 2000) have reported that in less weathered and subtropical soils, the excess P from fertilizer tends to accumulate as calcium associated inorganic P with fertilizer P and organic manure application. After that unused P tends to transform into iron and aluminium P in non calcareous and non-calcareous soils (McLaughlin et al. 2011). In slightly weathered soils calcium associated inorganic P can be gradually convert into available P (Guo et al. 2000). Humic bound P pools acts as a P sink when the system is fertilized and as a source when available P is being depleted (Beck and Sanchez 1994).

Concentration of organic P fractions viz. calcium associated organic P, acid soluble organic P, sugar bound organic P, nucleic acid organic P and polyphosphate, and humic bound organic P was significantly higher in soils under agroforestry than other land-uses. Except nucleic acid organic P and polyphosphate, all the organic P fractions were significantly higher under rice-wheat compared to other two cropping systems (Table 2). Hedley et al. (1982) has reported that organic P compounds are mainly associated with rapidly to slowly decomposable organic molecules, such as nucleic acids, phospholipids, sugar phosphates, inositol phosphates, and recalcitrant humic substances.

Soil organic carbon

Averaged across sites, SOC concentration was the highest under agroforestry and the lowest under cotton-wheat system (Table 1). While maize-wheat and cotton-wheat cropping systems exhibited similar SOC concentration. The rice-wheat system had significantly higher SOC concentration than two cropping systems but significantly lower than agroforestry systems. Significantly higher concentration of SOC in soils under agroforestry compared to sole cropping systems could be attributed to the effect of large return of plant biomass C through leaf litter and reduced tillage practices under agroforestry. Bene et al. (2011) has reported that soil organic matter is closely related to the amount of above and below ground organic matter inputs. Lobato et al. (2014) has reported that reduced tillage and its duration tends to build-up SOC under agroforestry than the

sole cropping systems. In many long-term experiments, researchers have shown a significant relationship between C input through plant biomass and organic manures with SOC sequestration (Tong et al. 2009; Benbi et al. 2012; Huang et al. 2014). The results of the present investigation corroborates the findings of Benbi et al. (2012), who also reported higher SOC concentration under agroforestry than in soils under rice-wheat cropping system. The comparison of three cropping systems revealed significantly higher SOC concentration in the soils under rice-wheat than the maize-wheat and cotton-wheat cropping systems. This could be attributed to retarded rate of soil organic matter decomposition due to prevailing anaerobic conditions during rice cultivation (Manlay et al. 2002). Since rice-wheat cropping involves cultivation of wetland and upland crops in sequence, it experiences alternate wetting and drying and thus differential stabilization of soil organic matter, compared to the other two cropping systems which are grown under upland conditions.

Correlation analysis

The correlation matrix depicting relationship among soil organic C and P pools is given in Table 3. In all the land-uses except for agroforestry, SOC, exhibited highly significant positive correlation with soil P fractions, indicating the role of on SOC in determining P dynamics in soils. The probable reason for relatively lower values of correlation coefficient (r) in soils under agroforestry is the entirely different soil management system, compared with the other cropping systems. Under agroforestry, soils are least disturbed because of restricted soil tillage, which affects the oxidative losses of SOC. The differences in soil management results in differential stabilization of soil organic matter (Benbi et al. 2012), which affects the mineralization-immobilization processes in the soil system (Cardoso et al. 2001).

SOC was significantly correlated to soil P fractions. Water soluble inorganic and organic P showed significant correlation (0.53^{**} and 0.58^{**} , $p < 0.01$) with soil clay content, indicating that the soils with higher clay content had higher concentration of water soluble inorganic and organic P (Table 4). Iron and calcium-aluminium associated inorganic P also showed significantly linear relationship with soil clay content. The humic bound inorganic P exhibited a significant positive correlation with soil clay content, indicating the formation of clay-humus complexes in the soils affecting P availability in the soils. On the contrary, these soil P pools had negative significant relationship with sand content. Data pooled for different land-use systems further, revealed the significance of SOC and its labile pools in dictating the dynamics of soil P among different pools (Table 4). All the inorganic P fractions were positively correlated with available P ($p < 0.01$). Gou et al. (2000) reported that in less weathered soils, calcium associated and residual P were depleted by plant uptake. Organic P fractions were negatively correlated with available P concentration indicating the important role of organic P pools in P availability. The proportional increase in humic bound organic P is an important fraction in the replenishment of available P on medium-term (Zhang et al.

2006). Therefore, soil organic and inorganic P fractions can play a different role in P availability on different soils which could reduce fertilizer P requirement.

Conclusions

Total P concentration was the highest under agroforestry followed by rice-wheat, cotton-wheat, and the lowest under maize-wheat systems. Inorganic P was the dominant fraction, which accounted for more than 92% of total P in soils under sole cropping systems. However, soils under agroforestry had relatively smaller proportion (72.9%) of total P occurring as inorganic P. Therefore, agroforestry systems had relatively higher proportion of organic P (27%) than the other land-uses (6-7.7%). Water soluble inorganic P represented the smallest proportion (0.13-0.26%) of inorganic P in soils. Calcium-aluminium associated inorganic P represented the largest proportion (73.5-75%) of total inorganic P in soils under different land-uses. Humic-bound organic P represented the largest proportion (38.4-53.4%) of organic P in soils under rice-wheat, maize-wheat, cotton-wheat and agroforestry systems, respectively. Irrespective of the land-use, the relative abundance of different inorganic P fractions followed the order calcium-aluminium associated inorganic P > iron associated inorganic P > humic bound inorganic P > water soluble inorganic P. Available P in soil was positively correlated with clay content in soils under rice-wheat, maize-wheat and cotton-wheat cropping systems. Soil P fractions showed significant correlation with SOC. However, inorganic and available P were lower in soils under agroforestry, compared to other land-uses, suggesting that P cycling depends on the land-use and their nutrient management practices. Therefore, fertilizer-P application may be required for intercrop under agroforestry systems.

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Table 1 Soil properties of the surface (0-15 cm) soils under different land-use in Punjab, India. Numbers in parenthesis indicate standard error

Property	Land-use			
	Rice-wheat	Maize-wheat	Cotton-wheat	Agroforestry
pH	7.76 ^b (0.05)	7.73 ^b (0.06)	7.72 ^b (0.06)	7.29 ^a (0.03)
Electrical Conductivity (dS m ⁻¹)	0.31 ^{ab} (0.01)	0.34 ^b (0.01)	0.28 ^a (0.01)	0.33 ^b (0.01)
Sand (%)	60.0 ^a (1.4)	63.0 ^{ab} (1.1)	63.3 ^{ab} (1.2)	64.6 ^b (1.2)
Silt (%)	25.1 ^b (0.72)	23.1 ^{ab} (0.62)	23.3 ^{ab} (0.70)	21.8 ^a (0.63)
Clay (%)	14.1 ^a (0.79)	13.1 ^a (0.58)	13.5 ^a (0.64)	13.6 ^a (0.69)
SOC (g C kg ⁻¹)	4.74 ^b (0.02)	3.98 ^a (0.02)	3.94 ^a (0.02)	5.78 ^c (0.02)
Available P (mg kg ⁻¹)	16.0 ^b (1.2)	14.1 ^b (0.74)	14.9 ^b (0.81)	9.8 ^a (0.91)
Available K (mg kg ⁻¹)	87a ^b (4.3)	87 ^{ab} (3.9)	83 ^a (4.6)	100 ^b (6.0)
CaCO ₃ (g kg ⁻¹)	1.41 ^a (0.08)	2.53 ^a (0.12)	1.22 ^a (0.08)	1.73 ^a (0.10)

^aMean values for a soil property in a row followed by different letter are significantly ($p < 0.05$) different by Duncan's multiple range test (DMRT).

Table 2 Concentration (mg P kg⁻¹) of organic, inorganic and total P pools in surface (0-15 cm) soils under different land-use in Punjab, India. Numbers in parenthesis represent standard error.

Property	Land-use			
	Rice-wheat	Maize-wheat	Cotton-wheat	Agroforestry
H ₂ O-Pi [*]	1.05 ^c (0.04)	0.81 ^b (0.03)	0.56 ^a (0.03)	1.07 ^c (0.03)
Ca-EDTA-Pi [†]	68 ^a (2.6)	69 ^a (2.3)	71 ^a (2.4)	73 ^a (2.3)
Na-EDTA-Pi [‡]	357 ^b (13.0)	313 ^a (10.8)	328 ^{ab} (10.9)	305 ^a (9.5)
NaOH-Pi [►]	52 ^b (1.9)	39 ^a (1.4)	37 ^a (1.2)	37 ^a (1.1)
H ₂ O-Po [*]	0.92 ^b (0.04)	0.72 ^a (0.03)	0.73 ^a (0.03)	1.07 ^c (0.03)
Ca-EDTA-Po [†]	2.65 ^c (0.09)	1.93 ^b (0.07)	1.46 ^a (0.05)	5.73 ^d (0.18)
Na-EDTA-Po [‡]	7.18 ^b (0.24)	4.54 ^a (0.16)	3.36 ^a (0.09)	26.6 ^c (0.87)
H ₂ SO ₄ -Po [‡]	3.82 ^b (0.14)	2.79 ^a (0.10)	3.31 ^a (0.11)	14.7 ^c (0.46)
_c TCA-Po [▲]	3.94 ^b (0.14)	2.82 ^a (0.10)	2.56 ^a (0.08)	17.8 ^c (0.55)
_H TCA-Po [▼]	2.33 ^b (0.08)	2.26 ^b (0.07)	2.00 ^a (0.06)	4.23 ^c (0.13)
NaOH-Po [►]	17.10 ^b (0.65)	9.60 ^a (0.44)	9.50 ^a (0.39)	80.6 ^c (2.2)
Res-P [◄]	2.23 ^b (0.09)	1.82 ^a (0.08)	2.12 ^b (0.09)	2.52 ^c (0.09)

^{*}H₂O-Pi/Po=Water soluble inorganic and organic P, [†]Ca-EDTA-Pi/Po=Iron associated inorganic and organic P, [‡]Na-EDTA-Pi/Po=Calcium-aluminium associated inorganic and organic P, [‡]H₂SO₄-Po=Acid soluble organic P, [▲]_cTCA-Po=Sugar bound organic P, [▼]_HTCA-Po=Nucleic acid organic P and polyphosphate, [►]NaOH-Pi/Po=Humic bound inorganic and organic P, [◄]Res-P=Residual P, ^{*}TPo=Organic P, [▼]TPi=Inorganic P.

◊ Mean values for a given P fraction in a row followed by different letters differ significantly ($p<0.05$) by Duncan's multiple range test (DMRT).

Table 3 Correlation of soil organic carbon with various soil P pools for soils under different land-uses

Soil organic carbon	Inorganic P					Organic P										
	Ca-		Na-		▼TPi	Ca-		Na-		H ₂ SO ₄ - Po [‡]	cTCA- Po [▲]	hTCA -Po [▼]	NaOH- Po [►]	▲TPo	Res-P◄	Total P
	H ₂ O	EDTA-	EDT	NaOH-		H ₂ O-	EDTA	EDTA-								
	-Pi [*]	Pi [†]	A-Pi [¶]	Pi [►]		-Po [†]	Po [¶]	Po [‡]								
Rice-wheat	0.74**	0.66**	0.68**	0.64**	0.68**	0.64**	0.68**	0.60**	0.66**	0.67**	0.65**	0.74**	0.71**	0.68**	0.68**	
Maize-wheat	0.58**	0.67**	0.68**	0.68**	0.68**	0.57**	0.69**	0.68**	0.71**	0.67**	0.65**	0.61**	0.68**	0.71**	0.69**	
Cotton-wheat	0.53**	0.62**	0.60**	0.62**	0.61**	0.46*	0.58**	0.51*	0.59**	0.66**	0.55**	0.45*	0.53**	0.54**	0.61**	
Agroforestry	0.21	0.36	0.30	0.34	0.31	0.38	0.32	0.35	0.33	0.33	0.33	0.32	0.33	0.26	0.32	

^{*}H₂O-Pi/Po=Water soluble inorganic and organic P, [†]Ca-EDTA-Pi/Po=Iron associated inorganic and organic P, [¶]Na-EDTA-Pi/Po=Calcium-aluminium associated inorganic and organic P, [‡]H₂SO₄-Po=Acid soluble organic P, [▲]cTCA-Po=Sugar bound organic P, [▼]hTCA-Po=Nucleic acid organic P and polyphosphate, [►]NaOH-Pi/Po=Humic bound inorganic and organic P, [◄]Res-P=Residual P, [♥]TPo=Organic P, [♥]TPi=Inorganic P

*Correlation is significant at $p < 0.05$ level (2-tailed)

**Correlation is significant at $p < 0.01$ level (2-tailed)

Table 4 Correlation matrix depicting relationship among soil physical and chemical properties of soils and various soil phosphorus pools (*Data pooled for different land-use*)

Soil P pools	Sand	Silt	Clay	SOC	Av. P
H ₂ O-Pi [*]	-0.45**	0.29**	0.53**	0.63**	0.25*
H ₂ O-Po [*]	-0.48**	0.31**	0.58**	0.70**	0.22*
Ca-EDTA-Pi [†]	-0.66**	0.46**	0.76**	0.49**	0.57**
Ca-EDTA-Po [†]	-0.07	-0.06	0.19	0.67**	-0.22*
Na-EDTA-Pi [‡]	-0.75**	0.59**	0.79**	0.37**	0.74**
Na-EDTA-Po [‡]	0.03	-0.14	0.09	0.63**	-0.31**
H ₂ SO ₄ -Po [‡]	0.03	-0.14	0.09	0.62**	-0.30**
cTCA-Po [▲]	0.05	-0.16	0.07	0.62**	-0.32**
_H TCA-Po [▼]	-0.16	0.001	0.29**	0.68**	-0.12
NaOH-Pi [►]	-0.69**	0.58**	0.70**	0.34**	0.65**
NaOH-Po [►]	0.06	-0.17	0.06	0.62**	-0.33**
Res-P [◄]	-0.51**	0.33**	0.61**	0.64**	0.33**
TPo [◆]	0.04	-0.15	0.08	0.63**	-0.32**
TPi [♥]	-0.75**	0.59**	0.80**	0.40**	0.73**
Total P	-0.59**	0.39**	0.69**	0.69**	0.40**

^{*}H₂O-Pi/Po=Water soluble inorganic and organic P, [†]Ca-EDTA-Pi/Po=Iron associated inorganic and organic P, [‡]Na-EDTA-Pi/Po=Calcium-aluminium associated inorganic and organic P, [‡]H₂SO₄-Po=Acid soluble organic P, [▲]cTCA-Po=Sugar bound organic P, [▼]_HTCA-Po=Nucleic acid organic P and polyphosphate, [►]NaOH-Pi/Po=Humic bound inorganic and organic P, [◄]Res-P=Residual P, [◆]TPo=Organic P, [♥]TPi=Inorganic P

*Correlation is significant at $p < 0.05$ level (2-tailed)

**Correlation is significant at $p < 0.01$ level (2-tailed)

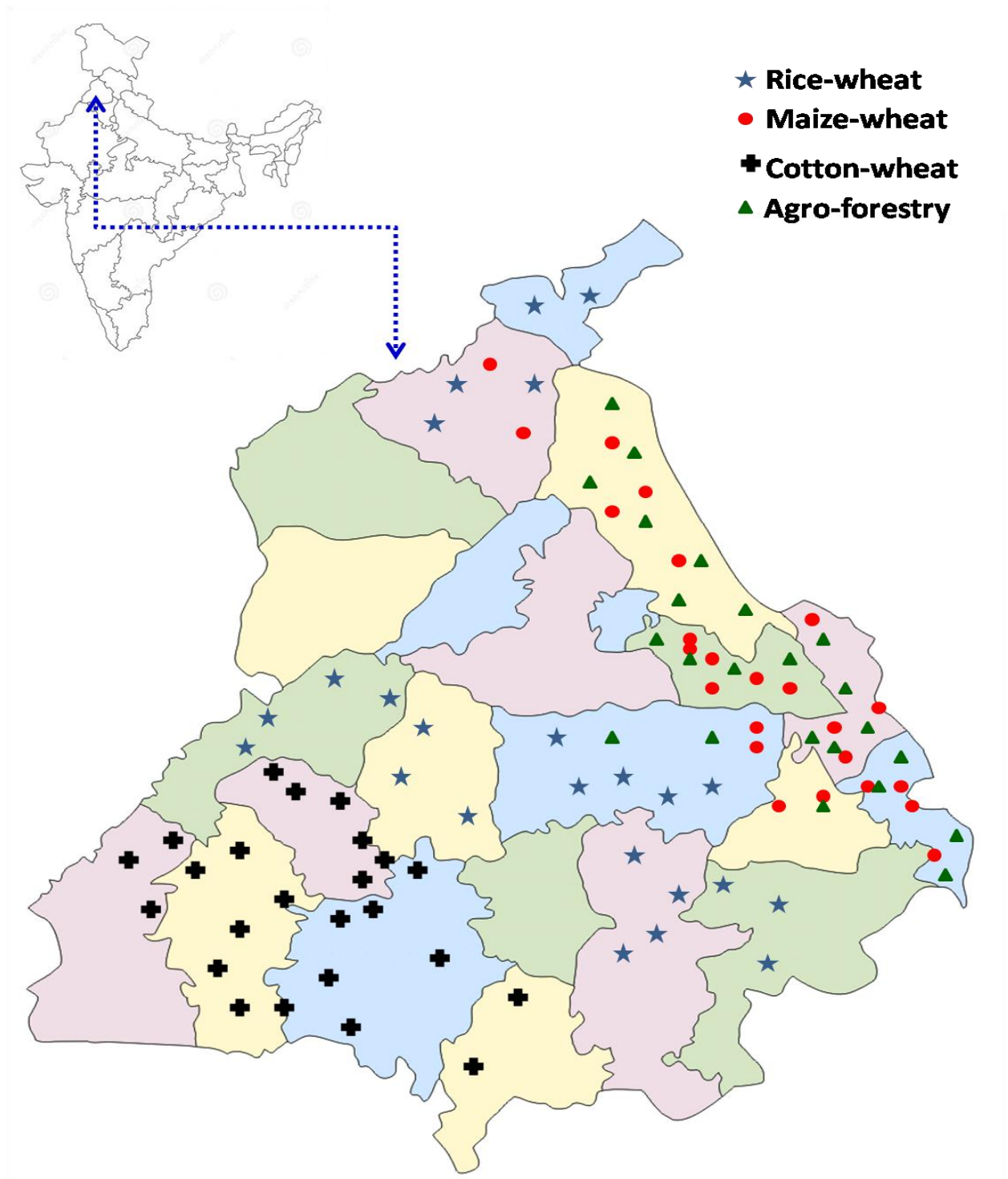


Fig. 1 Soil sampling sites in different districts of Punjab (India)

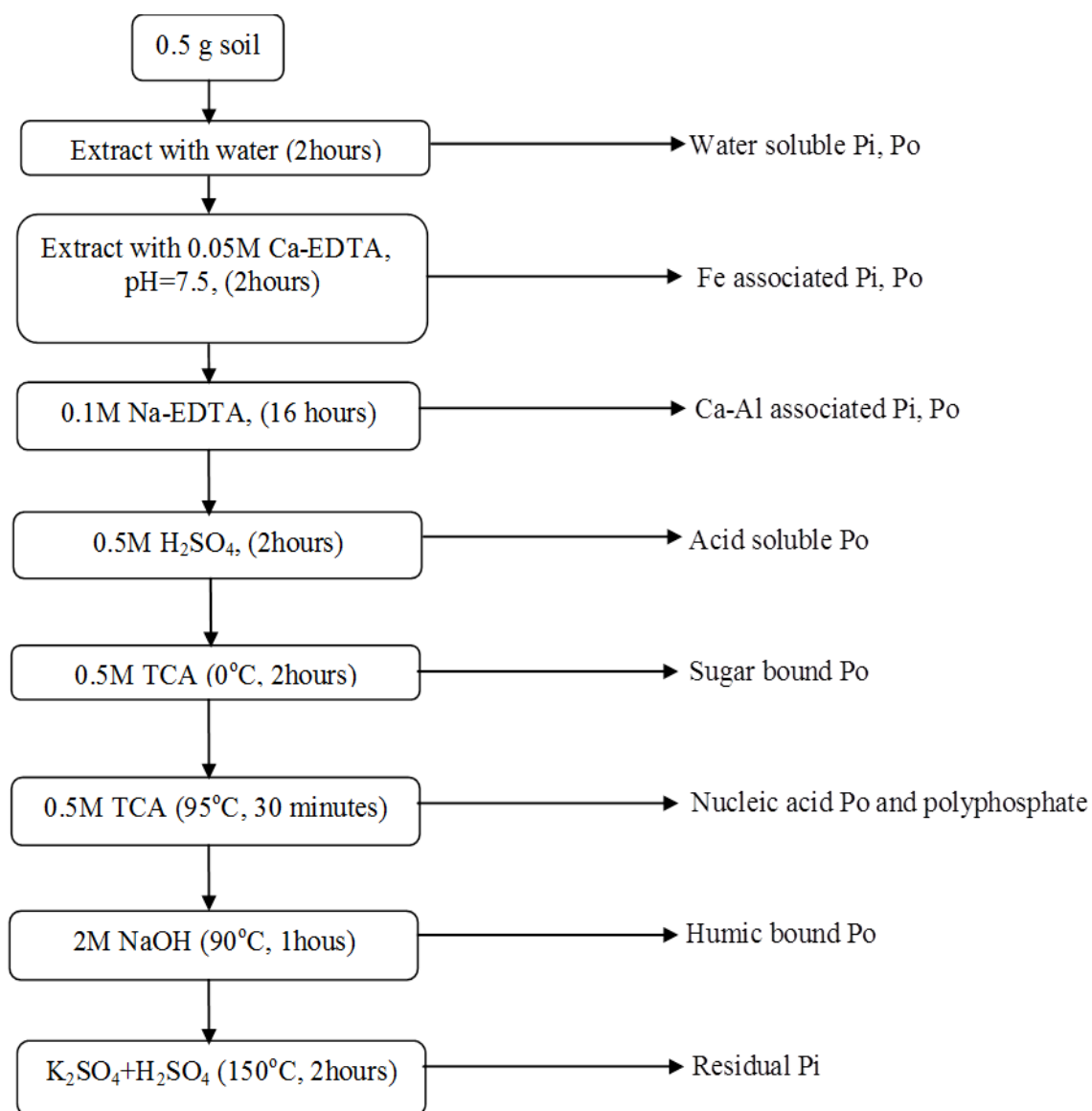


Fig. 2 Flow chart of the sequential P fractionation scheme proposed by Golterman (1996) and Golterman *et al* (1998)

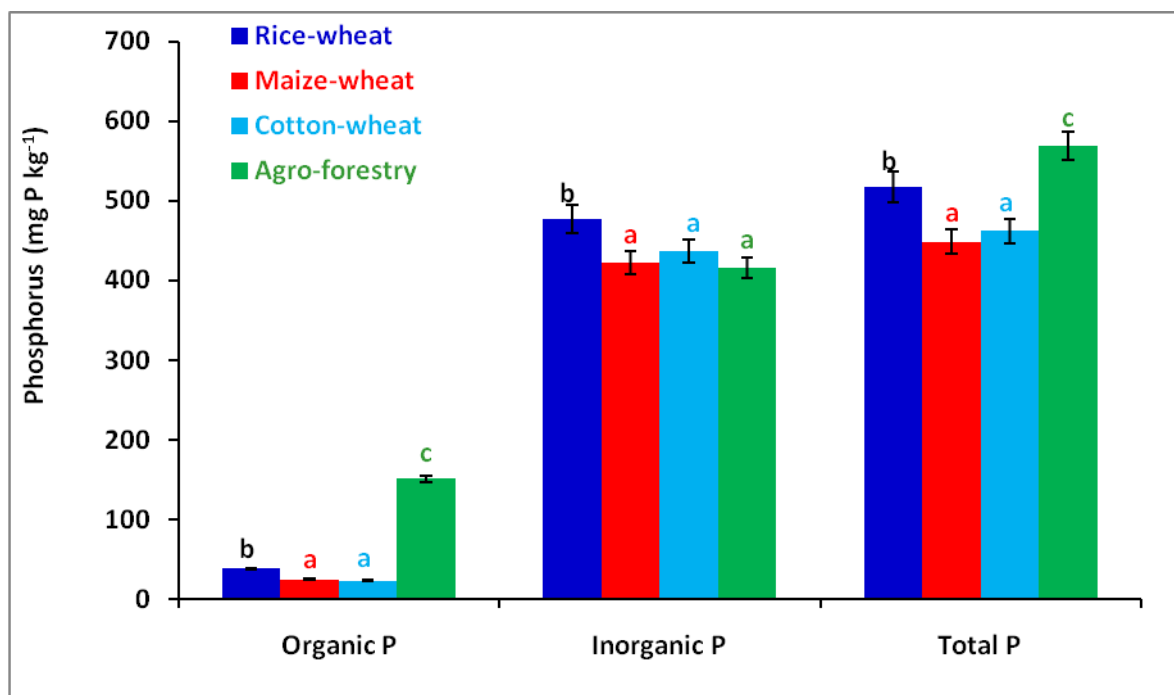


Fig. 3 Distribution of organic, inorganic and total P pools in surface (0-15 cm) soils under rice-wheat, maize-wheat, cotton-wheat and agroforestry systems. Line bars represent standard error of mean. Mean values for a given soil phosphorus pool for different land-uses followed by different letters differ significantly ($p < 0.05$) by Duncan's multiple range test (DMRT)



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Clay, Organic Carbon, Available P and Calcium Carbonate Effects on Phosphorus Release and Sorption-Desorption Kinetics in Alluvial Soils

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Abstract

Information on phosphorus release kinetics and sorption-desorption in soils is important for understanding how quickly reaction approaches equilibrium and replenishes the depleted soil solution. Laboratory experiments were conducted to study the P release and sorption-desorption kinetics in soils differing in clay, organic carbon (SOC), available P and calcium carbonate (CaCO₃) contents. Phosphorus release from soils proceeded in two phases- initially faster phase followed by slower phase as equilibration progressed. Elovich equation ($R^2 \geq 0.97^{**}$) described well the P release versus time data. Phosphorous release coefficients for power function were significantly correlated with available P and SOC. Freundlich sorption constants increased with increase in clay and CaCO₃ content. With increase in SOC content and available P concentration in soils, substantial reduction in sorption constants was observed. It was concluded that for efficient P management, it is important to take into account soil texture, the existing soil P level, SOC content and soil calcareousness.

Keywords: P availability, Calcium carbonate, Elovich equation, P release, Parabolic diffusion equation, Power function equation, Soil organic carbon, P sorption

Introduction

Phosphorus (P) is one of the major nutrients required for plant growth, but its low availability is a major constraint to crop production. Phosphorus availability in soils is governed by a combination of physical and chemical processes involving mineralization-immobilization, dissolution-precipitation and sorption-desorption (Frossard et al. 2000). The rate of P uptake by plant roots depends on P concentration in soil solution. The sorbed-P as such cannot be taken-up by plant roots unless it is released into the soil solution. The rate at which sorbed P is released from soil colloidal complex and its replenishment in soil solution, to maintain critical solution P concentration ($0.2 \mu\text{g P ml}^{-1}$), is influenced by soil properties (Fox and Kamprath, 1970) such as clay, soil organic C (SOC) content, available P concentration and calcium carbonate (CaCO_3) content (Serrano et al. 2014, Trivedi et al. 2010, Mashal et al. 2014, Hadgu et al. 2014). Replenishment of P concentration in soil solution occurs predominately through the release of P from clay and organic matter (Goh et al. 1986, Jalali and Ranjbar 2010). This controls short- and long-term P availability in soils (Messiga et al. 2012).

Clay tends to sorb P because of the existence of a large number of positively charged functional groups attached to colloidal matrix that interact and bind the negatively charged phosphate (PO_4^-) ions in soil (Singh and Gilkes 1991). Phosphorus sorption capacity has been found to be closely related to the content of fine particles (Zhang et al. 2012). Significant relationship between clay content and sorption coefficients estimated from Langmuir and Freundlich isotherms have been reported emphasizing the role of clay in influencing P availability in soils (Solis and Torrent 1989, Samadi 2006,). Besides clay content per se, the concentration of plant available P in soil influences the effect of clay on P availability in soil. In soils with higher amount of available P, most of the active sorption sites on colloidal matrix are occupied resulting in greater concentration of P in soil solution (McDowell and Sharpley 2001, Shafquat and Pierzynski 2010). Soil organic matter being a source of organic P, influences availability of P by (i) converting insoluble phosphates to soluble forms, (ii) producing humate ions that compete with phosphate ions for sorption sites (iii) releasing carbon dioxide, which increases solubility of Ca-P and (iv) producing

organic acids that cover colloidal sesquioxides surface (Stevenson 1982). In calcareous soils, large surface area of CaCO_3 results in rapid precipitation of P, which affects its release for plant growth (Tisdale et al. 2002). The effect of CaCO_3 in influencing P sorption is greater in coarse-textured than the fine-textured soils (Vig et al. 2000). Decreased P release due to the presence of CaCO_3 has been reported in several studies (Dunne et al. 2011, Pizzeghello et al. 2011). Borrero et al. (1988) reported that in calcareous soil both the total apparent surface area and P sorption by CaCO_3 are relatively lower than clay but play a dominant role in P sorption. Time-dependent P release from soil requires understanding of mechanisms involved in reaction by the use of empirical models. Different kinetic equations such as first order, second order, Elovich, power function and parabolic diffusion equations have been proposed to quantify P release from soil (Toor and Bahl, 1999, Abdu, 2013).

Several researchers have reported the effect of soil properties on P release and sorption-desorption kinetics in soils (Saroa et al. 1990, Gaston et al. 2003, Azeez and Averbek 2011, Gorgin et al. 2011). Most of these studies on P release and sorption-desorption focussed mainly on the effect of one soil property (such as clay, SOC or available P concentration) with little consideration for variation in other soil properties. To circumvent the effect of variation in soil properties other than the one under study, some researchers artificially created variation in a given property, for example by adding organic matter, CaCO_3 or fertilizer P (Vig et al. 2000, Tisdale et al. 2002, Shafquat and Pierzynski 2010, Dunne et al. 2011, Hadgu et al. 2014). However, artificially created changes do not mimic the soil properties that have stabilized over years. We studied the effect of variation in clay, SOC, available P and CaCO_3 content at almost constant level of other soil properties in Indo-Gangetic alluvial soils. Our hypothesis was that the effect of soil properties on P release and P sorption-desorption could be better understood by selecting soils with variation in one soil property at similar level of other soil properties. The present study was therefore, conducted (i) to study the effect of clay, SOC, available P and CaCO_3 on P release kinetics in soils, (ii) to examine factors that control P sorption-desorption in soils varying in physical-chemical properties under semi-arid and subtropical conditions, and (ii) to study the relationships between soil

physical-chemical characteristics and P release constants estimated from Langmuir and Freundlich sorption isotherms.

Materials and Methods

Physical and chemical properties of soils

Sixteen surface soil samples (0-15 cm) were collected from farmers' field in different districts of Punjab, India (Figure 1). Each sample was a composite of 3 sites within a field. The samples were selected on the basis of variation in clay (8-20%), available P (5-25 mg P kg⁻¹), soil organic carbon (2.2-7.2 g kg⁻¹), and calcium carbonate (0-2%) content (Table 1). The samples were grouped into four classes depending on variation in one of the selected soil property and similar values for other properties. Samples were air dried in shade, ground to pass 2 mm sieve for laboratory analysis. Particle size distribution was determined by international pipette method (Piper 1968), soil pH and EC were determined (1:2 soil : water) using pH meter and solubridge, respectively. Soil organic carbon was determined using wet oxidation method (Walkley and Black 1934). Available P was determined by extraction with 0.5 M NaHCO₃ (pH 8.5) (Olsen et al. 1954). Phosphorus in the extract was determined using ammonium molybdate-ascorbic acid method (Murphy and Riley 1962). Calcium carbonate was determined by the method proposed by Puri (1930).

Kinetics of P release

Phosphorus release kinetics were studied by equilibrating each soil with 0.5M NaHCO₃ (pH 8.5) in 1:5 soil : solution ratio for 0.5, 1, 2, 3, 6, 12, 24, 48, 72 and 96 h. The supernatant solution was analyzed for P concentration using ascorbic acid method (Watanabe and Olsen 1965). Amount of P released (C_A) was determined for different equilibration periods (t) and P release data were fitted to six different models (Table 2).

Phosphorus sorption and desorption studies

Three gram of each soil sample was equilibrated with 15 ml KH_2PO_4 (1:5) in 0.01M CaCl_2 solution containing 0, 2, 3, 5, 10, 20, 40, 60, 80 and 100 $\mu\text{g P ml}^{-1}$. Two drops of toluene were added to each sample to check microbial activity. The centrifuge tubes containing soil suspension were intermittently shaken on an end to end shaker for 24 hours and thereafter centrifuged at 3500 rpm for 15 minutes. Phosphorus in the equilibrium solution was determined colorimetrically using ascorbic acid method (Watanabe and Olsen 1965). Sorbed P was calculated from the difference between P added and that remained in equilibrium solution (Eq. 1)

$$x/m = \frac{V}{G} (C_0 - C) \tag{1}$$

Where, x/m = amount of P sorbed ($\mu\text{g P g}^{-1}$ soil), V = volume of equilibrium solution (ml), G = weight of soil taken (g), C_0 = P concentration in added solution ($\mu\text{g ml}^{-1}$), C = P concentration in equilibrium solution ($\mu\text{g ml}^{-1}$)

Phosphorus sorption data were fitted to Langmuir (Eq. 2) and Freundlich (Eq. 3) sorption isotherms.

$$\frac{C}{x/m} = \frac{1}{k.b} + \frac{C}{b} \tag{2}$$

Where, x/m = Amount of P sorbed ($\mu\text{g g}^{-1}$ soil), C = Concentration of P in equilibrium solution ($\mu\text{g ml}^{-1}$), b = Langmuir adsorption maxima ($\mu\text{g g}^{-1}$ soil), k = Langmuir bonding energy constant (ml g^{-1}). A plot of ' $C/x/m$ ' versus ' C ' gives a straight line. The slope and intercept were used to obtain the constant k (slope/intercept) and b (1/slope), respectively.

$$x/m = aC^{1/b} \tag{3}$$

Where, x/m = Amount of P adsorbed ($\mu\text{g g}^{-1}$ soil), C = Concentration of P in the equilibrium solution ($\mu\text{g ml}^{-1}$), A plot of ' $\log x/m$ ' versus ' $\log C$ ' gives a straight-line. The intercept and slope were used to obtain constants ' a ' ($\mu\text{g g}^{-1}$) and ' b ', (g ml^{-1} , 1/slope), respectively. Antilog of ' a ' and ' b ' of Freundlich adsorption isotherm were taken as measures of the extent and rate of sorption, respectively.

Phosphorus desorption

Phosphorus desorption was carried out on the residual soils previously used for P sorption as described above. The residual soils were equilibrated with 15 ml of 0.01M CaCl₂ for 6 hours (Singh and Jones 1976) and P was measured in equilibrium solution by ascorbic acid method (Watanabe and Olsen 1965). The data on P desorption were fitted to the following equation (Eq. 4)

$$De/x/m = 1/Kd \cdot Dm + De/Dm \quad (4)$$

where x/m is the amount of pre-sorbed P ($\mu\text{g g}^{-1}$), De is the amount of P desorbed ($\mu\text{g ml}^{-1}$), Dm is desorption maxima ($\mu\text{g g}^{-1}$ soil), and Kd is desorption constant related to P mobility in soils (ml g^{-1}) is a constant related to the mobility of P in soil. The desorption maxima (Dm) and constant (Kd) were calculated from the slope and intercept of the linear plot of De/S versus De respectively.

Statistical analysis

Phosphorus release data were fitted to six different kinetic models with SPSS 16.0 for Windows (SPSS Inc., Chicago, U.S.A.). A stepwise regression analysis for predicting release constants was performed by adding linear term for different soil properties. All the statistical and regression analysis were performed using SPSS 16.0 for Windows (SPSS Inc., Chicago, U.S.A.).

Results and Discussion

General soil properties

The soils under all the groups were non-saline ($\text{EC } 0.22\text{--}0.37 \text{ dS m}^{-1}$) and near neutral to slightly alkaline in reaction ($\text{pH } 7.2\text{--}7.8$) (Table 1). Soils under group-I had clay content varying between 8.2 and 20.1 percent with similar level of pH, EC, SOC and available P. The soils in this group were free from CaCO₃. Soils under group-II varied in available P content only (5.1 to 25.1 mg kg^{-1}), with similar values for all other properties analysed. Soils in group-III varied in organic carbon (2.2 and 7.2 g kg^{-1}) and those in group-IV varied in CaCO₃ content (0-2%), with similar level of other properties. The soils under different groups were classified as Typic Udorthents and Udic Haplustepts (USDA, 1999).

Phosphorus release from soils

Phosphorus release in all the 16 soils increased as the shaking time progressed and the highest amount of P was released after 96 h of equilibration (Figure 2). The increase in P release was faster during initial period of shaking, which gradually levelled-off as the shaking time progressed. Apparently P release from soils proceeded in two phases: an initial rapid phase followed by a period of slow release (Abdu 2009, Jalali and Ranjbar 2011, Abdu 2013). Initial fast phase occurred due to the release of P from the labile P pools and the subsequent slower P phase occurred because of conversion of non-labile or semi-labile P to labile P (Hundal et al. 1988, Jalali and Ranjbar 2011). Phosphorus bound to reactive surfaces is released rapidly, while slow P release is due to dissolution or diffusion from interior sites inside soil aggregates (Lookman et al. 1995). Initial fast reaction corresponds to rapid dissolution of poorly crystalline and amorphous phosphates in the soil (Griffin and Jurinak 1974).

The amount of P released from soils under group-I followed the order: Soil-1> Soil-2 >Soil-3 >Soil-4 showing decrease in P release with increasing clay content (Figure 2). Lower P release from fine-textured soils has been related to their higher P sorption capacity (Mozaffari and Sims 1994, Zhang et al., 2012, Hadgu et al. 2014). Higher P sorption and consequently lower release from clay is because of their greater surface area than sand (Singh and Gilkes 1991). Diaz et al. (2006) reported that sandy soils had small sorption but higher P release capacity. Among soils under group-II, maximum amount of P was released from Soil-8 having the highest concentration of available P (Figure 2). In general, amount of P released was higher from soils having higher available P concentration and vice versa (Soil-8> Soil-7> Soil-6> Soil-5). Higher P release from soils with high available P concentration has also been reported earlier (McDowell and Sharpley 2001, Shafquat and Pierzynski 2010). Hadgu et al. (2014) observed a negative relationship between available P and P adsorption maxima showing that P sorption decreased with increase in available P content in soils. Because of greater amount of available P in soils most of the active sorption sites on soil colloidal complex are occupied and contribute towards greater P release in soil (McDowell and Sharpley 2001, Shafquat and Pierzynski 2010).

Cumulative P release from soils under group-III was the highest from soils with the greater organic C content (Soil-12) and it decreased as the SOC declined from Soil 12 to Soil 9 (Figure 2). Improvement in SOC enhances soil microbial biomass and thereby alters P availability through mineralization-immobilization processes (Chen et al. 2003, Sigua et al. 2009). Zhang et al. (2012) observed that the amount of P released from the soil was positively correlated with the organic P content. Hadgu et al. (2014) observed that P sorption at low concentrations of added P was negatively correlated with SOC suggesting that organic matter competes with P for adsorption sites.

Among soils under group-IV, the cumulative P release was the highest from the non-calcareous soil (Soil-15) and the lowest from calcareous soil with 2% CaCO_3 content (Soil-16, Figure 2). Accumulation of CaCO_3 is believed to govern soil P reactions in calcareous soils because of P adsorption and precipitation on CaCO_3 surface (Griffin and Jurinak 1974, Amer et al. 1985, Dunne et al. 2011). High amounts of CaCO_3 and its large surface area lead to rapid precipitation of P (Tisdale et al., 2002). Castro and Torrent (1998) showed that in calcareous soils, reaction between Ca and P results in precipitation as Ca-phosphates. Calcium ion activity in liquid phase is responsible for formation of insoluble Ca-phosphate minerals in calcareous soil (Tunesi et al. 1999). A greater contribution of exchangeable Ca ions to P precipitation than that of CaCO_3 has been reported (Akinremi and Cho 1991, McDowell and Sharpley 2003). Borrero et al. (1988) reported that in calcareous soil both the total apparent surface area of CaCO_3 and P-sorption by CaCO_3 are relatively lower than clay but play a dominant role in P sorption and subsequent release.

Modelling P release kinetics

Phosphorus release was best described by Elovich and power function equations as judged by higher coefficient of determination ($R^2=0.97^{**}$ for Elovich and $R^2=0.90^{**}$ for power equation) followed by parabolic diffusion equation ($R^2=0.78^{**}$) (Table 3). Chien and Clayton (1980) also reported the superiority of Elovich equation over other models in describing P release kinetics.

Within each group of soils, value of Elovich constants ‘ α ’ and ‘ β ’ were dependent on the property of soil under study (Table 4). For example, in group-I soils these constant varied with clay content, in group-II with available P, in group-III with SOC and in group-IV with CaCO_3 . Similarly, the release constants for parabolic diffusion equation (R and C) and power function (k_A and b), varied with distinguishing soil property.

Release coefficients were significantly ($p<0.01$) correlated with available P and SOC concentration (Figure 3). Elovich constant ‘ β ’, parabolic diffusion constant ‘C’ and power function constant ‘b’ showed linear increase with increase in available P (mg kg^{-1}) concentration in soil (Eq. 5-7).

$$\beta \text{ (}\mu\text{g g}^{-1}\text{)} = 0.88* \text{ available P} + 3.12, \quad R^2=0.803^{**} \text{ (}p<0.01\text{)} \quad \text{Eq. (5)}$$

$$C \text{ (}\mu\text{g g}^{-1}\text{)} = 0.86* \text{ available P} + 3.21, \quad R^2=0.787^{**} \text{ (}p<0.01\text{)} \quad \text{Eq. (6)}$$

$$b \text{ (}\mu\text{g g}^{-1}\text{)} = 0.06* \text{ available P} + 1.82, \quad R^2=0.740^{**} \text{ (}p<0.01\text{)} \quad \text{Eq. (7)}$$

Similarly, a linear relationship between SOC (%) and Elovich constant ‘ α ’ and parabolic diffusion constant ‘R’ was observed by Eq. 8 and 9.

$$\alpha \text{ (}\mu\text{g g}^{-1} \text{h}^{-1}\text{)} = 2.36* \text{ SOC} + 1.53, \quad R^2=0.501* \text{ (}p<0.05\text{)} \quad \text{Eq. (8)}$$

$$R \text{ (}\mu\text{g g}^{-1} \text{h}^{-1/2}\text{)} = 1.28* \text{ SOC} + 0.82, \quad R^2=0.520* \text{ (}p<0.05\text{)} \quad \text{Eq. (9)}$$

A stepwise regression analysis for Elovich coefficient ‘ α ’ showed that inclusion of terms for clay, SOC and available P accounted for 55% variability in data ($R^2=0.55*$, $n=16$) (Eq. 10, Table 5). Inclusion of a term for CaCO_3 in the equation improved the predictability to 70% ($R^2=0.70^{**}$, Eq. 11). The Elovich constant ‘ β ’ showed higher relationship with soil properties than ‘ α ’. Clay, SOC and available P accounted for 82% variation in β ($R^2=0.82^{**}$) and inclusion of CaCO_3 in equation improved the predictability to 90% ($R^2=0.90^{**}$). Parabolic diffusion constant ‘R’ was relatively weakly correlated to

soil properties. Clay, SOC and available P together accounted for 58% variation in Parabolic diffusion constant 'R' ($R^2=0.58^*$; Eq. 14) and inclusion of a term for CaCO_3 improved the predictability to 71% ($R^2=0.71^{**}$, $p<0.01$). The predictability of Power function constant ' k_A ' did not change with the inclusion of CaCO_3 in the regression involving clay, SOC and available P ($R^2=0.91^{**}$, Eq. 18, and 19). However, the predictability of Power function constant 'b' improved by about 5% with the inclusion of CaCO_3 in the equation ($R^2=0.81^{**}$, Eq. 21, Table 5).

These results suggest that soil clay content, available P, SOC and calcium carbonate content govern the availability of P in Indo-Gangetic alluvial soils.

Phosphorus sorption characteristics of soils

Soils showed wide variation in P adsorption behaviour. The equilibrium solution P concentration increased with increasing amount of P added. Among soils under group-I, higher P sorption (at each applied P level) in soil occurred in soils with having higher clay content (Figure 4). Amount of added P sorbed on soil followed the order (Soil-4<Soil-3>Soil-2>Soil-1) of increasing clay content. Higher P sorption in soils of greater clay content was because of higher active surface area of clay Wang et al. (2011). Sorption being a surface phenomenon is directly related to surface area of the adsorbate.

Among soils under group-II, P sorption decreased as the available P content in soils increased (Figure 4). Lower P sorption in soils of higher available P is due to lesser availability of active sorption sites. Once the active sorption sites are occupied, P sorption is greatly reduced and a large amount of P remains in equilibrium solution. Phosphorus sorption behavior in group-III showed higher P sorption in soil with lower SOC concentration (Figure 4). Soils with low SOC content tends to have higher P sorption because of high P affinity (Mashal et al. 2014). Decreased P sorption in soils with high SOC content is because of the liberation of organic acids upon decomposition. Competitive sorption between low molecular weight organic acids produced during decomposition of organic matter reduces P sorption on active surface sites of soil (Hundal et al. 1988, Geelhoed et al. 1999). It has also been observed that organic matter not only decreases P sorption on active sorption sites, but also delays P sorption (Singh and

Jones 1976, Iyamuremye and Dick 1996). Calcium carbonate also had pronounced influence on P sorption behavior (Figure 4). In general, P sorption was higher in calcareous soil (Soil-13, Soil-14 and Soil-16), than the non-calcareous soil (Soil-15). In calcareous soils, the accumulation of CaCO_3 is believed to govern soil P reactions because of its adsorption and precipitation on the CaCO_3 surface (Lindsey 1979, Cole et al. 1953, Griffin and Jurinak 1973, Amer et al. 1985). Afif et al. (1993) reported that the ratio of available P to applied P was negatively correlated to CaCO_3 at high P application rates.

When equilibrium solution P concentration was plotted against equilibrium P concentration/adsorbed P $\{C/(x/m)\}$, a linear relationship was obtained indicating that P adsorption in the soil followed Langmuir equation. The Langmuir sorption isotherms showed the formation of two adsorbed layers of high and low energy (Table 6). Langmuir sorption maxima ($A.M._1$ = Adsorption maxima for first sorbed layer and $A.M._2$ = Adsorption maxima for second sorbed layer) increased with clay and calcium carbonate content and decreased with available P and SOC content. (Table 6). Phosphorus sorption strength assessed through $B.E._1$ (Bonding energy for first sorbed layer) and $B.E._2$ ($B.E._2$ =Bonding energy for second sorbed layer) also showed trends similar to that observed for sorption maxima.

A straight-line relationship was also obtained with Freundlich equation and it explained the adsorption process as efficiently as the Langmuir sorption isotherm (Table 6). Freundlich sorption constant S.R. (rate of P sorption) and S.E. (extent of P sorption) increased with increase in clay content (group-I soils) and CaCO_3 content (group-IV soils). The rate and extent of P sorption decreased with increase in available P (group-II soils) and SOC content (group-III soils). Soil clay content has been reported to be significantly related to the soil P sorption indices such as Langmuir constants (Samadi 2006). Wisawapipat *et al.* (2009) reported that slightly greater portion of sorbed P was more readily available in the soil solution where soils were low in clay content. Presence of CaCO_3 and the large surface area of this mineral lead to more rapid P sorption and precipitation which reduced the P availability even in coarse textured (Vig et al. 2000, Tisdale et al. 2002, Amer et al. 1985, Dunne et al. 2011). Increase the values of Langmuir sorption constants with clay and calcium carbonate content leading to increase the P adsorption and

decreasing the equilibrium P concentration in soil solution (Chaudhary 1990, Wani and Bhat 2010). During decomposition of organic matter, organic acids are produced which tends to cover colloidal sesquioxides surface, decrease P sorption (Stevenson et al. 1982).

P desorption in relation to soil properties

Phosphorus desorption data showed that the soils having high P sorption capacity had lower P desorption capacity. In group-I, highest P desorption occurred from soils having lower clay content and vice-versa (Table 7). In group-II, higher P desorption occurred from soils having high concentration of available P, compared to the soils with lower P concentration. Likewise, soils with high concentration of soil organic carbon had higher P desorption capacity. Higher P desorption, regardless of the level of P sorbed has occurred from non-calcareous soil than the calcareous soils. However, the soils with high concentration of calcium carbonate had lower P desorption capacity. P desorption data fitted to Langmuir equation yielded desorption maxima ($D.M._1$ = desorption maxima for first sorbed layer and $D.M._2$ = desorption maxima for second sorbed layer and 'Kd' constants (Kd_1 = constant related to P mobility for first sorbed layer and Kd_2 = constant related to P mobility for second sorbed layer) also exhibited a change due to change in soil physical and chemical properties (Table 7). Decrease in P desorption with clay and $CaCO_3$ content may be due to their greater affinity to fix P, as the main phosphate-sorbing soil surfaces are those of edges of silicate clays and calcite (Matar et al. 1992). Phosphorus is mainly precipitated as Ca phosphates or co-precipitates with carbonates. Ca-P minerals are stable and are barely desorbed once formed (Vepraskas et al. 2001, Gustafsson et al. 2008). Dhillon et al. (2004) reported the increase in P desorption capacity of soil with SOC content. Soil organic C increases the soil aggregation and reduces the surface area of soil thereby increasing the surface P mobility (Saroa and Vig 1992, Messiga et al. 2012, Benbi and Senapati 2010).

A stepwise regression analysis showed that clay, SOC, available P and $CaCO_3$ accounted for 65% variation in $B.E._1$ ($R^2 = 0.65^*$, Eq. 22, $n=16$), 54% variation in S.R. ($R^2 = 0.54^*$, Eq. 23, $n=16$) and 58% variation in S.E. ($R^2 = 0.58^*$, Eq. 24, $n=16$) (Table 8).

Conclusions

Soil properties viz. clay, SOC, available P and CaCO_3 strongly affect P release and sorption-desorption kinetics. Phosphorus release decreased with increase in clay and CaCO_3 content, but increased with increase in available P and SOC content suggesting that P availability will be higher in coarse-textured non-calcareous soil with relative higher levels of SOC and available P content. Phosphorus release constants are significantly related to available P and SOC contents. Langmuir and Freundlich sorption constants increased with clay and calcium carbonate content and decreased with available P and SOC content. Freundlich adsorption isotherms for estimating soil P adsorption capacities could predict effect of soil properties on soil P availability. The results showed that for efficient P management it is important to take into account soil texture, the existing soil P level, SOC content and calcareousness of soil. Practices that increase SOC content and ameliorate CaCO_3 could lead to improved P use efficiency.

Review Only

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Table 1 Important physical and chemical properties of the surface (0-15 cm) soil samples selected for phosphorus sorption-desorption and release kinetics studies

Soil /Group	pH	EC [†]	SOC [‡]	Available P (mg kg ⁻¹)	Calcium carbonate (%)	Soil texture		
		(dS m ⁻¹)	(g kg ⁻¹)			Sand (%)	Silt (%)	Clay (%)
Group-I								
Soil-1	7.6	0.30	3.05	10.4	0	71.5	20.3	8.2
Soil-2	7.4	0.36	3.13	11.0	0	58.5	29.0	12.6
Soil-3	7.8	0.37	3.13	9.4	0	59.6	24.1	16.2
Soil-4	7.6	0.24	3.43	11.2	0	56.3	23.7	20.1
Mean	7.6	0.32	3.18	10.5	0	61.5	24.3	14.3
Group-II								
Soil-5	7.7	0.26	2.98	5.11	0	67.2	22.6	10.2
Soil-6	7.7	0.31	2.83	12.4	0.1	64.6	25.0	10.4
Soil-7	7.5	0.24	3.13	18.3	0	65.9	23.6	10.6
Soil-8	7.6	0.31	3.05	25.1	0	68.4	21.0	10.6
Mean	7.6	0.28	2.99	15.2	0	66.5	23.1	10.4
Group-III								
Soil-9	7.8	0.28	2.15	15.9	0	62.8	23.0	14.3
Soil-10	7.6	0.34	3.95	16.3	0	65.2	20.3	14.4
Soil-11	7.3	0.26	5.68	16.8	0	69.4	16.4	14.2
Soil-12	7.2	0.29	7.18	15.7	0	66.1	19.2	14.7
Mean	7.5	0.29	4.74	16.2	0	65.9	19.7	14.4
Group-IV								
Soil-13	7.3	0.33	4.93	16.8	1.5	66.8	18.0	15.3
Soil-14	7.5	0.22	4.85	14.2	0.6	68.1	16.7	15.2
Soil-15	7.2	0.37	5.00	13.4	0	64.8	20.0	15.2
Soil-16	7.3	0.25	5.08	16.6	2.0	67.2	17.7	15.1
Mean	7.3	0.29	4.96	15.2	1.0	66.7	18.1	15.2

[†]EC=Electrical conductivity, [‡]SOC=Soil organic carbon

Table 2 Kinetics models fitted to P sorption versus time data

Model	Equation	Parameter
Zero-order	$C_A = C_{A0} + k_A t$	k_A is rate coefficient
First-order	$\ln C_A = \ln C_{A0} + k_A t$	k_A is first-order rate coefficient
Second-order	$1/C_A = 1/C_{A0} + k_A t$	k_A is second-order rate coefficient
Power function	$\ln C_A = \ln k_A + b \ln t$	k_A is rate coefficient and b is empirical constant
Elovich	$C_A = (1/\beta) \ln(\alpha\beta) + (1/\beta) \ln t$	α is initial P release rate coefficient and β is release constant
Parabolic diffusion	$C_A = R t^{1/2} + C$	R is diffusion rate constant

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Table 3 Statistical criteria for judging the suitability of different kinetic models fitted to describe P release kinetics in different soils

Soil	Parabolic diffusion equation		Power function equation		Elovich equation	
	S.E. _M	R ²	S.E. _M	R ²	S.E. _M	R ²
Soil-1	0.076	0.78**	1.13	0.92**	1.13	0.97**
Soil-2	0.077	0.79**	1.25	0.90**	1.25	0.97**
Soil-3	0.091	0.85**	1.45	0.98**	1.45	0.99**
Soil-4	0.088	0.90**	1.61	0.99**	1.61	0.99**
Soil-5	0.112	0.96**	0.99	0.99**	0.99	0.98**
Soil-6	0.075	0.94**	1.31	0.99**	1.31	0.98**
Soil-7	0.060	0.92**	1.42	0.99**	1.42	0.98**
Soil-8	0.041	0.94**	1.23	0.99**	1.23	0.98**
Soil-9	0.064	0.96**	1.38	0.96**	1.38	0.97**
Soil-10	0.068	0.94**	1.55	0.99**	1.55	0.98**
Soil-11	0.077	0.95**	1.88	0.99**	1.88	0.98**
Soil-12	0.079	0.88**	1.92	0.97**	1.92	0.99**
Soil-13	0.069	0.95**	1.60	0.99**	1.60	0.99**
Soil-14	0.069	0.98**	1.39	0.99**	1.39	0.99**
Soil-15	0.070	0.91**	1.30	0.99**	1.30	0.99**
Soil-16	0.073	0.93**	1.78	0.99**	1.78	0.99**

[†]S.E._M=Standard error of mean, ^{*}R²=Coefficient of determination

*Relationship significant at $p<0.05$

**Relationship significant at $p<0.01$

Table 4 Phosphorus release constants of different kinetics models for four groups of soils varying in selected properties chemical properties

Soil	Elovich		Parabolic diffusion		Power function	
properties	α	β	R	C	k_A	b
	($\mu\text{g g}^{-1} \text{h}^{-1}$)	($\mu\text{g g}^{-1}$)	($\mu\text{g g}^{-1} \text{h}^{-1/2}$)	($\mu\text{g g}^{-1}$)	($\mu\text{g g}^{-1} \text{h}^{-1}$)	($\mu\text{g g}^{-1}$)
Soil-1	2.72	14.7	1.37	14.9	0.145	2.68
Soil-2	2.45	12.9	1.24	13.0	0.148	2.54
Soil-3	2.13	12.5	1.11	12.5	0.130	2.53
Soil-4	1.93	11.2	1.03	11.1	0.129	2.42
Average	2.31	12.8	1.19	12.9	0.138	2.54
Soil-5	1.68	5.5	0.93	5.3	0.191	1.75
Soil-6	2.22	12.9	1.22	12.6	0.127	2.57
Soil-7	2.42	19.0	1.31	18.7	0.101	2.95
Soil-8	2.10	25.7	1.15	25.4	0.069	3.25
Average	2.10	15.8	1.15	15.5	0.122	2.63
Soil-9	2.34	16.4	1.30	16.1	0.109	2.81
Soil-10	2.63	17.3	1.44	17.0	0.117	2.86
Soil-11	3.19	18.0	1.76	17.6	0.131	2.91
Soil-12	3.29	19.0	1.73	19.0	0.132	2.95
Average	2.86	17.7	1.56	17.4	0.122	2.88
Soil-13	2.37	15.2	1.30	15.0	0.119	2.73
Soil-14	2.72	17.6	1.49	17.3	0.118	2.88
Soil-15	3.04	18.6	1.63	18.4	0.125	2.93
Soil-16	2.22	14.2	1.20	14.0	0.119	2.66
Average	2.59	16.4	1.40	16.2	0.120	2.80

Table 5 Regression coefficients for modelled terms in a stepwise regression analysis relating P release constants to clay (%), soil organic carbon (%), available P (mg kg⁻¹) and calcium carbonate (%)

Equation	Dependent variable	Predictor (s) [#]	Constant	Clay	SOC	Available P	CaCO ₃	R ²
10	α	1,2,3	1.79	-0.03	2.58	0.01		0.55*
11		1,2,3,4	1.54	-0.25	2.91	0.01	-0.30	0.70**
12	β	1,2,3	3.94	-0.16	4.50	0.85		0.82**
13		1,2,3,4	2.01	-0.09	7.01	0.89	-2.29	0.90**
14	R	1,2,3	0.89	-0.02	1.34	0.01		0.58*
15		1,2,3,4	0.76	-0.01	1.52	0.01	-0.16	0.71**
16	c	1,2,3	4.09	-0.17	4.65	0.83		0.81**
17		1,2,3,4	2.15	-0.10	7.16	0.87	-2.29	0.89**
18	k _A	1,2,3	0.21	-0.00	0.06	-0.01		0.91**
19		1,2,3,4	0.21	-0.00	-0.06	-0.01	0.00	0.91**
20	b	1,2,3	1.71	0.00	0.36	0.06		0.76**
21		1,2,3,4	1.60	0.00	0.05	0.06	-0.14	0.81**

*Significance tested by *t*-test at *p*<0.05.
** Significance tested by *t*-test at *p*<0.01.
[#]1,2,3,4 represent clay, SOC, available P and CaCO₃
R²=Coefficient of determination

Table 6 Langmuir and Freundlich phosphorus sorption constants for different group of soils

Soil reference	Langmuir sorption constants						Freundlich sorption constants		
	R_1^2	R_2^2	A.M. ₁ [†]	A.M. ₂ [‡]	B.E. ₁ [▼]	B.E. ₂ [▲]	R^2	S.R. [▲]	S.E. [▼]
			($\mu\text{g P g}^{-1}$)		(ml P g^{-1})($\times 10^{-3}$)			($\mu\text{g g}^{-1}$)	(ml g^{-1})
Group-I									
Soil-1	0.82**	0.99**	58.8	200.0	46.2	8.0	0.99**	32.6	3.82
Soil-2	0.94**	0.99**	60.6	256.4	69.9	7.3	0.99**	34.6	5.15
Soil-3	0.95**	0.99**	62.5	270.3	124.0	10.4	0.99**	39.8	7.96
Soil-4	0.98**	0.99**	64.5	333.3	322.9	12.7	0.99**	72.8	14.69
Group-II									
Soil-5	0.97**	0.99**	77.5	333.3	238.9	18.4	0.98**	63.8	15.14
Soil-6	0.92**	0.99**	76.3	320.5	101.6	11.6	0.99**	38.7	8.63
Soil-7	0.89**	0.99**	74.6	299.4	59.0	7.8	0.99**	34.2	5.68
Soil-8	0.76**	0.99**	66.7	250.0	42.4	7.3	0.99**	30.5	3.95
Group-III									
Soil-9	0.41	0.99**	111.1	350.9	163.6	16.8	0.98**	33.4	8.95
Soil-10	0.96**	0.99**	100.0	335.6	57.1	9.8	0.99**	33.3	7.03
Soil-11	0.93**	0.99**	83.3	257.1	52.2	10.6	0.99**	32.6	5.62
Soil-12	0.76**	0.99**	71.4	243.3	40.7	7.0	0.99**	28.8	3.99
Group-IV									
Soil-13	0.94**	0.99**	58.8	266.7	132.8	13.0	0.99**	42.3	8.38
Soil-14	0.89**	0.99**	53.8	257.1	85.0	10.1	0.99**	39.6	6.18
Soil-15	0.89**	0.99**	50.5	250.0	75.0	9.0	0.99**	38.2	5.79
Soil-16	0.86**	0.99**	83.3	322.6	162.2	17.7	0.98**	54.5	12.79

[†]A.M.₁=Adsorption maxima for first sorbed layer, A.M.₂[‡]=Adsorption maxima for second sorbed layer,
[▼]B.E.₁=Bonding energy for first sorbed layer, [▲]B.E.₂=Bonding energy for second sorbed layer, [▲]S.R.=Rate of P
sorption, [▼]S.E.=Extent of P sorption

*Relationship significant at $p < 0.05$

**Relationship significant at $p < 0.01$

R^2 =Coefficient of determination

Table 7 Langmuir desorption constants for surface soil (0-15 cm) sample varying in physical and chemical properties

Soil reference	Langmuir desorption constants					
	R_1^2	R_2^2	$D.M._1^{\dagger}$ ($\mu\text{g P g}^{-1}$)	$D.M._2^{\ddagger}$	$Kd_1^{\vee}$ (ml P g^{-1})	$Kd_2^{\star}$
Group-I						
Soil-1	0.88**	0.99**	25.0	400.0	20.00	0.250
Soil-2	0.80**	0.98**	23.3	333.3	14.33	0.188
Soil-3	0.81**	0.99**	21.7	285.7	11.50	0.175
Soil-4	0.77**	0.97**	19.2	250.0	8.67	0.143
Group-II						
Soil-5	0.99**	0.96**	23.3	256.4	2.87	0.126
Soil-6	0.96**	0.98**	33.3	303.0	3.75	0.138
Soil-7	0.96**	0.99**	40.0	357.1	4.17	0.147
Soil-8	0.90**	0.99**	52.6	454.5	6.33	0.183
Group-III						
Soil-9	0.39	0.97**	19.6	238.1	2.32	0.117
Soil-10	0.85**	0.95**	22.2	277.8	3.21	0.138
Soil-11	0.73**	0.99**	30.3	312.5	4.07	0.160
Soil-12	0.94**	0.99**	43.5	400.0	4.60	0.208
Group-IV						
Soil-13	0.82**	0.99**	19.6	303.0	17.0	0.206
Soil-14	0.73**	0.99**	23.8	344.8	20.0	0.223
Soil-15	0.77**	0.99**	25.0	416.7	26.7	0.267
Soil-16	0.77**	0.99**	18.0	232.6	13.3	0.195

[†]D.M.₁=Desorption maxima for first sorbed layer, D.M.₂[‡]=Desorption maxima for second sorbed layer,
[✓]Kd₁=Constant related to P mobility for first sorbed layer, [★]Kd₂=Constant related to P mobility for second sorbed layer
*Relationship significant at $p<0.05$
**Relationship significant at $p<0.01$
 R^2 =Coefficient of determination

Table 8 Regression coefficients for modelled terms in a stepwise regression analysis relating P release constants to clay (%), soil organic carbon (%), available P (mg kg⁻¹) and calcium carbonate (%)

Equation	Dependent variable	Predictor (s) [#]	Constant	Clay	SOC	Available P	CaCO ₃	R ²
22	BE ₁	1,2,3,4	0.12	0.02	-0.30	-0.01	0.04	0.65*
23	SR	1,2,3,4	45.0	1.78	-28.9	-1.33	7.56	0.54*
24	SE	1,2,3,4	10.0	0.49	-11.5	-0.36	0.73	0.58*

*Significance tested by *t*-test at $p < 0.05$.

[#]1,2,3,4 represent clay, SOC, available P and CaCO₃

R²=Coefficient of determination

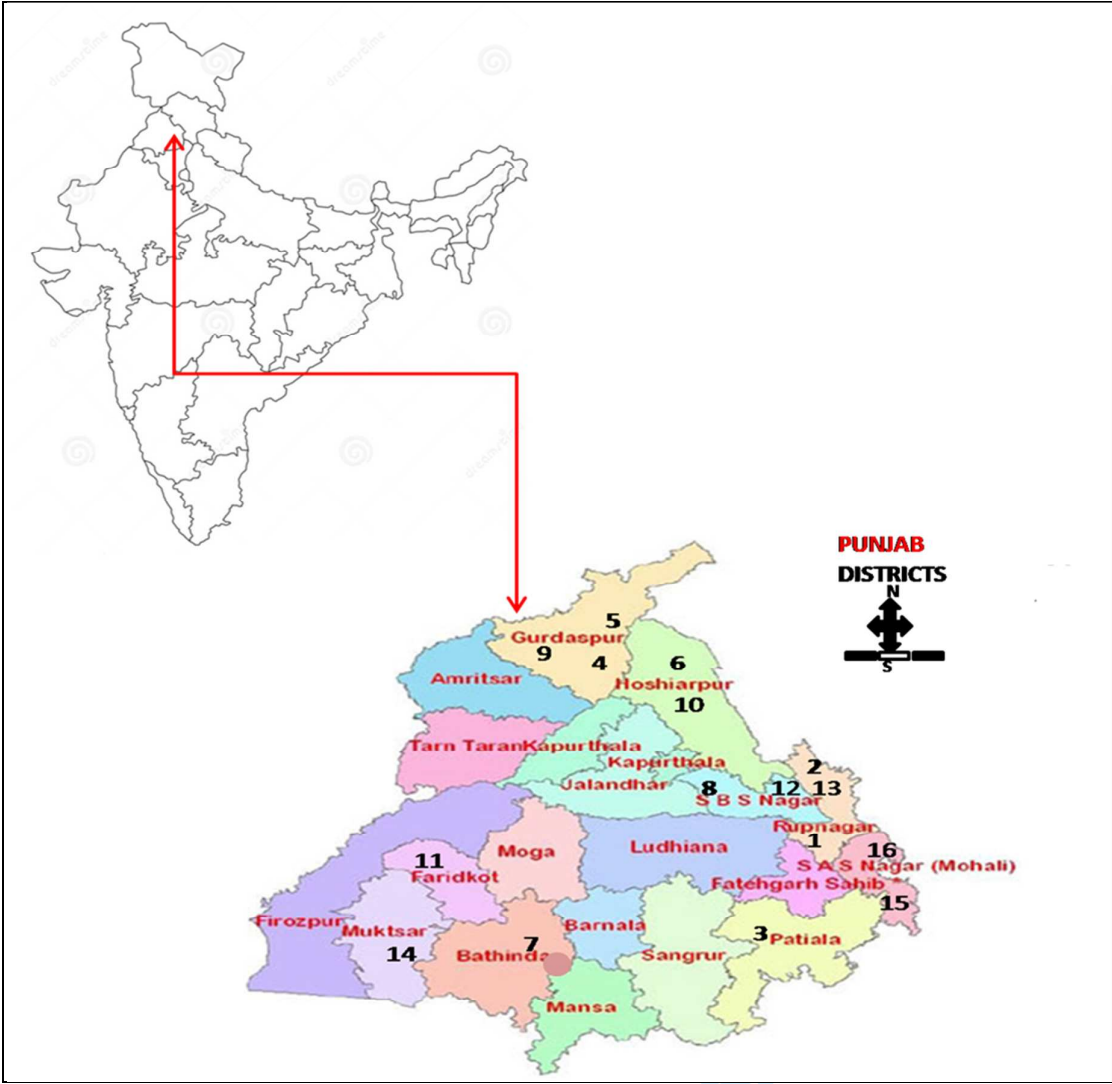


Figure 1. Location of soil sampling sites in north Indian state of Punjab

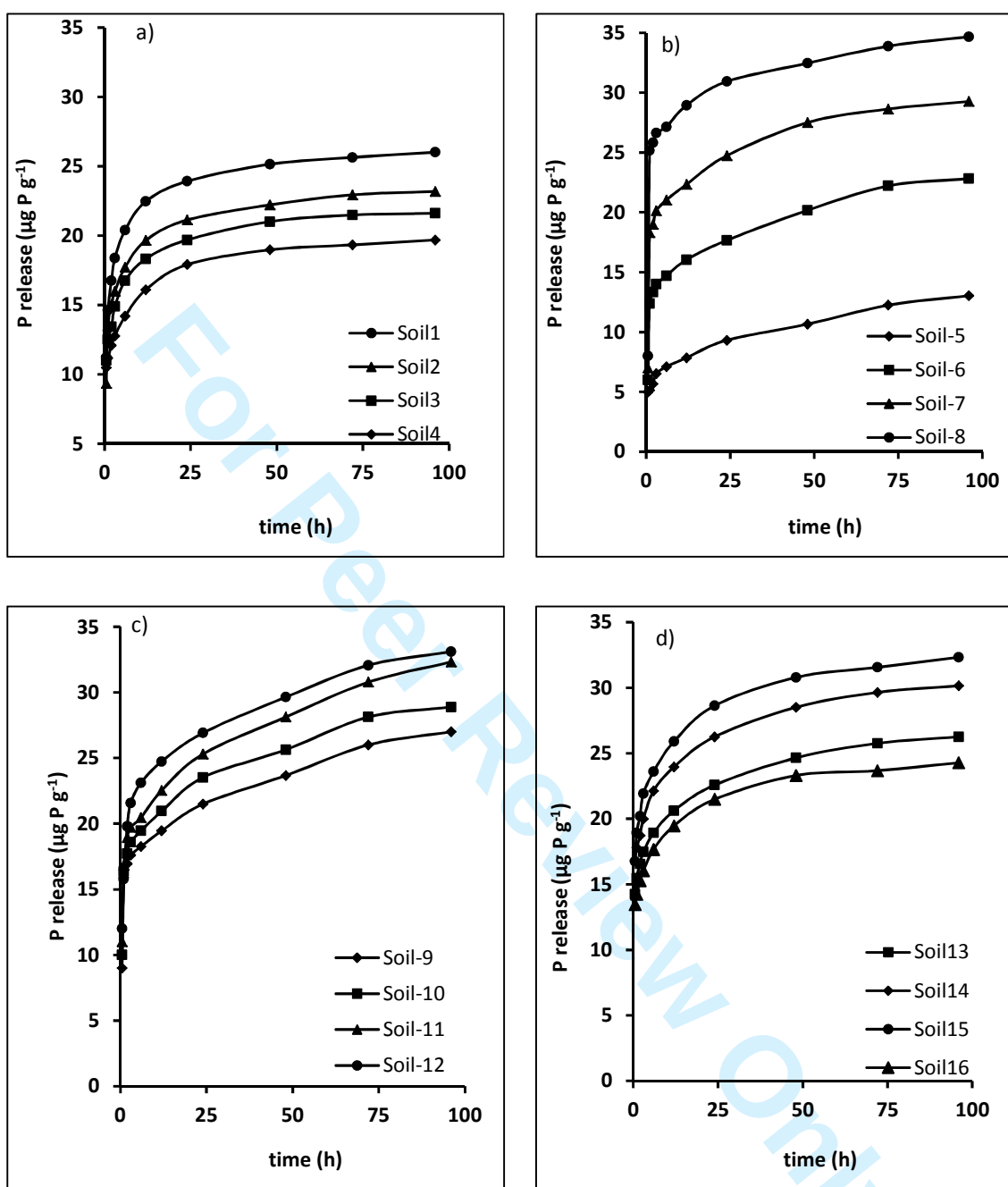


Figure 2. Relationship between amount of P released (C_A) and time in soils varying in a) clay content, b) available P concentration, c) organic C content, and d) CaCO_3 content

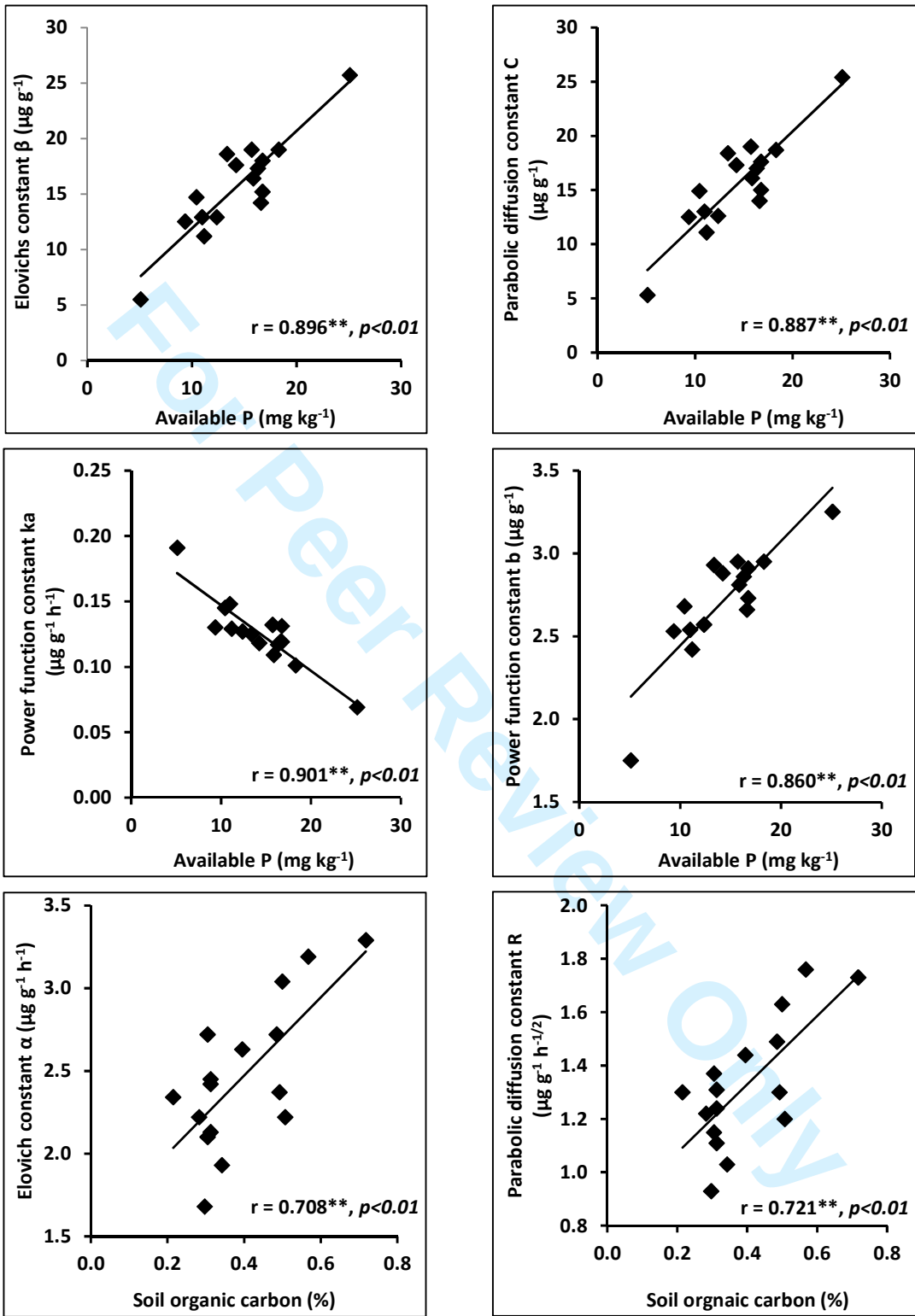


Figure 3. Relationship of phosphorus release coefficients with available P and soil organic carbon

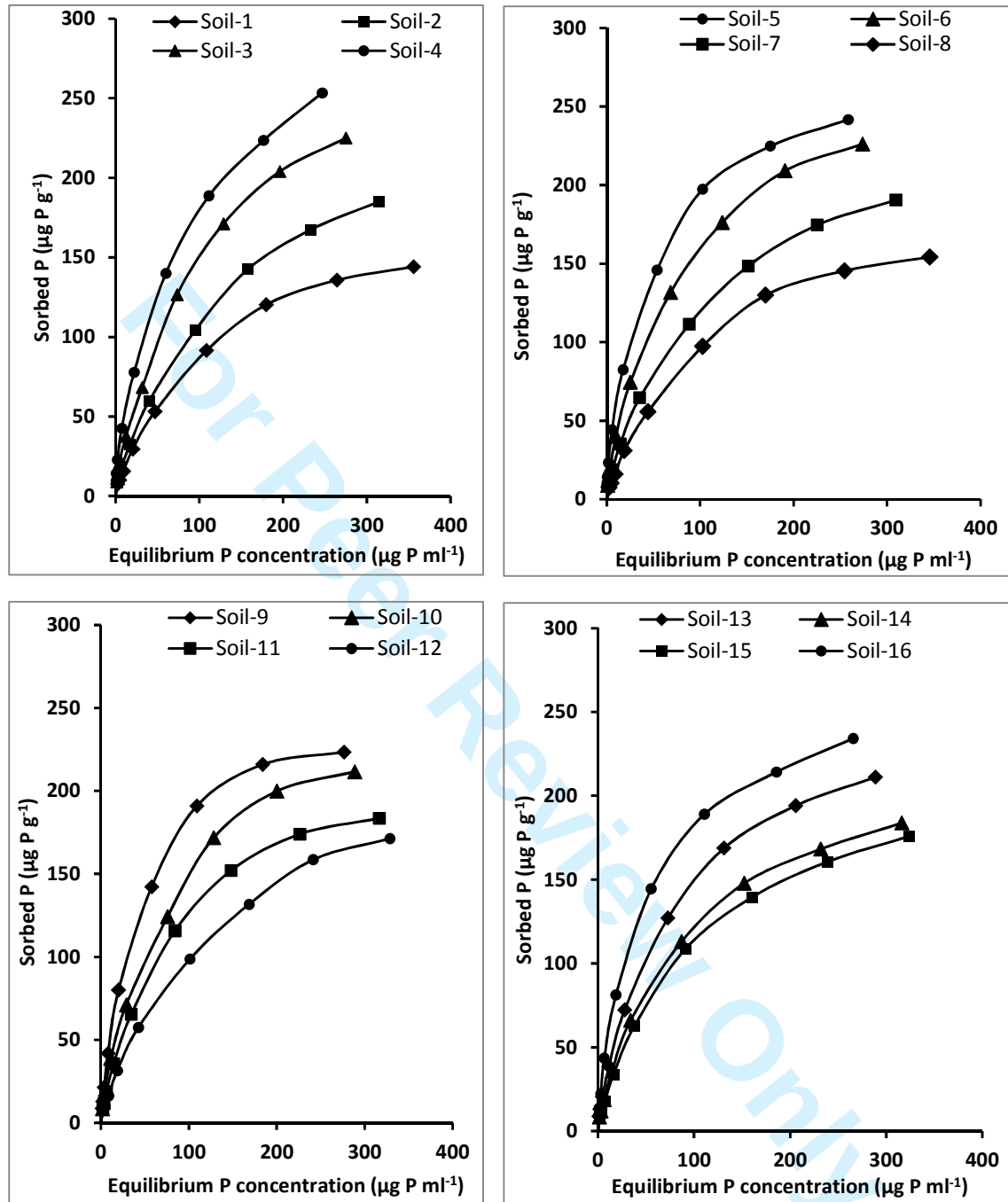


Figure 4. Effect of selected soil properties on P sorption behavior (Soils 1-4: variable soil clay content, Soil-5-8: variable available P concentration, Soils 9-12: variable soil organic carbon concentration, Soils 13-16: variable calcium carbonate content)



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Effect of Rates and Source of Phosphorus Application on Soil Properties under Rice-Wheat Cropping System

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ABSTRACT

Effect of two rates of phosphorus (P) application viz. 0 and 30 kg P₂O₅ ha⁻¹ to rice in rice-wheat sequence was studied on soil properties. Phosphorus was applied either through single super phosphate (SSP) or rock phosphate (RP) with and without farmyard manure (FYM). Compared to CK, greatest amount of available nutrients, total organic carbon (TOC) and labile C fractions were observed under farmyard manure and rock phosphate treated plots. Plots treated with FYM and fertilizer-P either alone or in combination significantly (p<0.05) increased TOC and WEOC in surface (0-7.5 cm) and subsurface (7.5-15 cm) soil. Beneficial effects of fertilizer-P application through RP were relatively less than SSP application. Rock phosphate with FYM treated plots showed greater increase in available nutrients and organic carbon, compared to SSP treated plots. Regardless of the treatment, effects of different treatments on soil properties was more in surface (0-7.5 cm) soil and decreased with depth. The KMnO₄-C was one of the largest pool of soil organic and constituted 13.8% of TOC. Carbon mineralization was higher at 35⁰C than at 25⁰C. Cumulative amount of CO₂-C evolved in soil followed the order FYM F₁P_{30RP} > F₁P₀ > F₀P_{30SSP} > F₀P_{30RP} > F₀P₀ > CK. Carbon management index (CMI) also improved considerably with FYM and fertilizer-P applications in soils, indicates the greater C stabilization in soil. Farmyard manure and RP applications improved soil properties to greater extent compared to their sole applications, indicating the need for combined use of FYM and RP in these alluvial soils.

Keywords: Rice-wheat, Rock phosphate, Farmyard manure, Available P, Organic carbon, Carbon mineralization

INTRODUCTION

Rice (*Oryza sativa*)-wheat (*Triticum aestivum*) is the dominant cropping system in the Indo-Gangetic Plains (IGP) of India. This is exhaustive cropping system leading to nutrients mining. Therefore, imbalanced nutrient management practices and, concomitant decrease in effort of adequate nutrients return to the soil is adversely affecting soil properties such available nutrients like N, P K and soil organic carbon and its labile pool (Benbi and Biswas 1997; Akande *et al.*, 2011; Benbi *et al.*, 2015a). Benbi and Biswas (1999) have reported that P availability in soils is directly related to amount of P added to soil of these semiarid and subtropical regions. Generally, inorganic fertilizers viz. urea, single super phosphate (SSP), diammonium phosphate (DAP), murate of chloride and muriate of potash (MOP) are applied to correct the nutrients deficiencies. But, sudden hike in price of chemical fertilizers is far beyond the reach of poor farmers. However, due to the lower solubility of rock phosphate (RP), its application needs longer time to be dissolve compared SSP in neutral to alkaline soils. Which necessitates the direct applications of the indigenous source such as farmyard manure along with fertilizer-P such as low grade rock phosphate, could be the possible alternate for soil fertility point of view (Akande *et al.*, 2011; Benbi *et al.*, 2015a; Deshpande *et al.*, 2015). Because huge amount CO₂ evolved during the process of decomposition of organic manures and resulted in the formation of weak organic acids such as carbonic acid, citric, oxalic, tartaric etc. which dissolved or solubilized RP and results in release of phosphate and calcium into the solution, thus increases the efficiency of RP (Biswas and Narayanasamy, 2006). Compared to organic amendments applications, regular cultivation with nil organics application tends to deplete 39-43 % of TOC in soil, while only chemical fertilizer applications are not significant factor affecting SOC sequestration (Ghosh *et al.*, 2012; Liang *et al.*, 2012). Farmyard manure in combination with NPK tends to significant increase in TOC than sole application of NPK (Kundu *et al.*, 2007). The conjoint application of NPK+FYM (at 10 Mg ha⁻¹ yr⁻¹) to a sandy loam soil under maize-wheat cropping system showed the significant increase in WEOC, compared with N, NP and NPK applied soils (Kaur *et al.*, 2008). Compost application either alone or in combination with N showed significant increase in WEOC and KMnO₄-oxidizable C, and CMI than the N applied soils under maize-wheat cropping system for 22 years (Lou *et al.*, 2011). In a 41 years study on a sandy clay loam soil under rice-rice cropping system, NPK+FYM application at 5.0 Mg ha⁻¹ yr⁻¹ significantly increased MBC, compared with control (Mohanty *et al.*, 2013). Application of NPK alone and NPK+FYM significantly increased MBC in soils under four experiments (23-26 years) on rice-wheat cropping at Ludhiana, Kanpur, Sabour and Kalyani (Nayak *et al.*, 2012). Significantly higher annual cumulative soil CO₂ fluxes in manure treated than CK have been reported by Zhang *et al.*, (2013). Labile organic carbon fractions are readily accessible sources to microorganisms, have direct impact on plant nutrient supply and respond to nutrient management practices. Ultimately, fertilizers (NPK) and manure applications had significant influence on nutrient availability viz. mineral N, available P, K, soil organic carbon and its labile

pools such as hot water soluble carbon, water extractable organic carbon, microbial biomass carbon and potassium permanganate oxidizable carbon in soils (Benbi and Biswas 1999; Nishanth and Biswas 2008; Benbi and Brar, 2009; Schulz *et al.*, 2011; Benbi *et al.*, 2015a; Benbi *et al.*, 2015b). But, the effect of FYM with or without low grade rock phosphate applications on properties of sandy loam soils under rice-wheat system has not been studied extensively. Therefore, considering all these aspects, the present study was planned to investigate i) the effect of rate and source of P application on soil nutrient availability, ii) the effect of rate and source of P application on soil organic carbon and its labile fractions, and C mineralization.

METHODS AND MATERIALS

Experimental site and soil characteristics

A field experiment was established during 2006 on rice (*Oryza sativa* L.)-wheat (*Triticum aestivum* L.) cropping systems at Research farm of Punjab Agricultural University (PAU), Ludhiana, India (Latitude: 30° 56'N, Longitude: 75° 52'E and mean sea level=247.5m). The study location is at the center of Punjab state which forms the north-western part of the country. The climate of the place is sub-tropical, semi-arid. During 1970-2005, the experimental area received ~750 mm rainfall annually, of which ~80% was received during the *kharif* season extending from 1 May to 31 October. (Kaur and Hundal, 2008). Important physical and chemical properties of the surface (0-15 cm) soils at the start of experiment are given below (Table I).

Field experiment

The six treatments in experiment of an rice-wheat system included i) application of nil and 30 kg P₂O₅ ha⁻¹ to rice through single super phosphate (SSP) and rock phosphate (RP) and ii) application of farmyard manure (FYM) at 10 Mg ha⁻¹ (dry weight basis) with or without fertilizer application to rice. Except in control plot wheat was fertilized with 60 kg P₂O₅ ha⁻¹ through SSP (Table II). Each treatment was replicated three times and arranged in a randomized complete block design (RBD) on a plot size of 3.0 m X 8.0 m (24 m²). Fertilizer N was applied through urea in three equal splits viz. at the time of puddling, 3 and 6 weeks after transplanting to rice. Whole of P as SSP or RP and K as potassium chloride was applied as a basal dose to rice and wheat, respectively. The field was submerged with maintaining 5-6 cm water head. After puddling, 30-35 d old rice seedlings were transplanted in rows 20 cm apart with plant-to-plant distance of 15 cm, ensuring 33 plants m⁻² area in second week of June. Rice crop was harvested manually in the fourth week of October each year. After rice, wheat crop was sown 100 kg ha⁻¹ in second week of November in rows 22.5 cm apart (*rabi* season). In wheat, half dose of fertilizer N was applied as urea at the time of sowing and remaining, one week after first irrigation. Wheat was irrigated with canal or ground water and an irrigation of about 7.5 cm was applied when required depending on the visual inspection of the field. Wheat crop was harvested manually in the third week of April each year.

Soil samples collection and analysis

Soil samples were collected from 0-7.5, 7.5-15, 15-30 and 30-60 cm soil depths, after wheat harvest in May 2013. The soil samples were collected from three sites within a plot and composited. Soil samples were collected with a metallic soil core sampler (inner diameter 7 cm and 7.5 cm length) from each depth. Soil bulk density (D_b) was determined by the core method using metallic cores (inner diameter=7 cm). Soil cores collected from each sampling site were oven dried at 105°C for 24 h, and dry soil weight was recorded (Blake and Hartge, 1986). The D_b (Mg m^{-3}) was calculated as:

$$D_b = \frac{Ws}{Vt}$$

Where, ' Ws ' is weight of soil (Mg) and ' Vt ' is the volume of soil sample (m^3)

Soil samples were air dried in shade, ground to pass through 2 mm sieve for analysis. Soil pH (1:2 soil to water ratio) and EC (1:2 soil : water suspension) were determined using a glass electrode and electrical conductivity meter, respectively. Mineral N (NO_3^- -N and NH_4^+ -N) was determined by extracting the soil samples with 2M KCl, followed by mineral N estimation by steam distillation of extract using MgO and Devarda's alloy (Mulvaney, 1996). Available P was determined using a soil to solution (0.5 M NaHCO_3 , pH 8.5) ratio 1:20 after 30 min of shaking (Olsen *et al.*, 1954). Phosphorus in the extract was determined colorimetrically by ascorbic acid method (Murphy and Riley, 1962) and colour intensity was measured at 760 nm wavelength. Available K was extracted by shaking 5 gram soil with 25 ml of 1 N ammonium acetate (pH 7.0) followed by flame photometric determination (Jackson, 1967). Total organic carbon was determined by using 1N potassium dichromate and concentrated H_2SO_4 , followed by heating at 150°C for 1 hour and titration with ammonium ferrous sulphate and diphenylamine indicator (Snyder and Trofymow, 1984). Soil organic carbon was determined using wet oxidation method (Walkley and Black, 1934). Water extractable organic C was determined by shaking 10 g soil with 20 ml deionized water for 1 h (McGill *et al.*, 1986). Hot water soluble C was determined by moderately boiling 20 g soil with 100 ml distilled water for 1 h under a reflux condenser. The amount of C in the extract was determined by chromo-sulfuric acid method (Schulz *et al.*, 2003). Potassium permanganate oxidizable C was determined by oxidation with 33 mmol l^{-1} (25 ml) KMnO_4 solution (Blair *et al.*, 1995). Non-labile C, was calculated as the difference between TOC and KMnO_4 -C. Microbial biomass carbon of soil was determined by chloroform fumigation extraction method (Vance *et al.*, 1987) using a recovery factor (KEC) of 0.41 (Voroney and Paul, 1984).

Carbon management index (CMI) was worked out for the soils (0-7.5 and 7.5-15 cm soil depth). The mean value of control soil samples was used as the reference in the experiment. Based on changes in soil TOC between the reference (control) and a treated sample, carbon management index (CMI) was calculated using a mathematical procedure of Blair *et al.*, (1995):

CMI=CPI X LI X 100

Where, CPI is the C pool index and LI is the lability index.

The CPI and the LI were calculated as:

CPI= $\frac{TOC_{treated} (g\ kg^{-1}\ soil)}{TOC_{control\ (reference)} (g\ kg^{-1}\ soil)}$

LI= $\frac{L_{treated}}{L_{control\ (reference)}}$

Where, *L* refers to the C lability, calculated as

L= $\frac{Content\ of\ labile\ C\ (KMnO_4-C)\ (g\ kg^{-1}\ soil)}{Content\ of\ non-labile\ C\ (g\ kg^{-1}\ soil)}$

Carbon mineralization was studied in the laboratory by conducting aerobic incubation under controlled conditions. Fifty grams of each air-dried surface soil (0-15 cm) was wetted to field capacity moisture and placed in a 500 ml conical flask along with vials containing 10 ml of 1 M l⁻¹ NaOH to trap CO₂ and water to maintain humidity. The soils were incubated for 36 d at 25 and 35°C in a BOD incubator. Alkali traps were replaced daily during the first week and every 2 or 3 d thereafter. Evolved CO₂ was determined by titrating alkali in the traps with 0.1 M l⁻¹ HCl. The cumulative amount of CO₂-C evolved in the 36 d incubation was referred to as C mineralization.

Statistical analysis

Statistical and correlation analysis were performed with SPSS for Windows 16.0 (SPSS Inc., Chicago, U.S.A.). Data were subjected to analysis of variance (ANOVA) in a completely randomized block design. Mean separation for different treatments was evaluated at 95% confidence interval using the Duncan’s multiple range test (DMRT).

RESULTS

Soil reaction and electrical conductivity (EC)

Soils under different treatment were near neutral to slightly alkaline in reaction (pH 6.90-7.47) and non-saline (EC 0.07-0.15 dS m⁻¹). Under all soil depth, application of P through single super phosphate or rock phosphate (RP) either alone or in combination with FYM did not influence soil pH and EC significantly. Irrespective of the treatment, soil pH increased and soil electrical conductivity (EC) decreased with depth (*Data has not given*).

Ammonical and nitrate-N distribution

Fertilizer-P and farmyard manure application either alone or in combination significantly ($p < 0.05$) increased NH_4^+ -N throughout soil profile compared with no P application (CK) (Fig. 1). Different rates and source of P application in rice led to significant increase in NO_3^- -N than CK. In surface (0-7.5 cm soil), application of P through SSP ($\text{F}_0\text{P}_{30\text{SSP}}$) to rice significantly increased the NH_4^+ -N and NO_3^- -N concentration in soil than the soils that received same amount of P through RP ($\text{F}_0\text{P}_{30\text{RP}}$). The NH_4^+ -N and NO_3^- -N concentration was significantly higher in FYM (F_1P_0) treated plots than fertilizer-P treated plots. However, effect was more pronounced in FYM and fertilizer-P ($\text{F}_1\text{P}_{30\text{RP}}$) treated plots. In 15-30 and 30-60 cm soil, concentration of NH_4^+ -N was higher FYM and fertilizer-P treated ($\text{F}_1\text{P}_{30\text{RP}}$) plots compared with plots treated with SSP ($\text{F}_0\text{P}_{30\text{SSP}}$). The profile distribution of NH_4^+ -N and NO_3^- -N concentration showed that concentration of NH_4^+ -N and NO_3^- -N was higher in the surface 0-7.5 cm soil, and it decreased with depth, under all the treatments (Fig. 1).

Available phosphorus and potassium

Compared to CK, available P was significantly higher in FYM or fertilizer treated plots in the surface (0-7.5 cm) soil (Table III). The FYM application significantly increased available P concentration by 16.9% compared to $\text{F}_0\text{P}_{30\text{RP}}$. The effect of FYM application in improving available P concentration was more pronounced in soils amended with both fertilizer-P and FYM in rice ($\text{F}_1\text{P}_{30\text{RP}}$) compared with FYM alone in rice (F_1P_0). In 0-7.5 and 7.5-15 cm soil depth, available K was significantly higher in plots treated with FYM either alone (F_1P_0) or in combination with fertilizer-P in rice ($\text{F}_1\text{P}_{30\text{RP}}$) compared to other treatments (Table III). The concentration of available K did not differ significantly among treatments involving FYM application. Application of P either through SSP or RP did not influence available K concentration significantly than control (CK) (Table III). Available P and K concentration was higher in surface soil (0-7.5 cm) and decreased with depth. The treatments did not differ significantly below 15 cm soil depth (*Data has not given*).

Soil carbon fractions

Plots treated with FYM and fertilizer-P either alone or in combination significantly increased TOC and WEOC in surface (0-7.5 cm) and subsurface (7.5-15 cm) soil (Fig. 2). Application of FYM and fertilizer-P ($\text{F}_1\text{P}_{30\text{RP}}$) showed greatest amount of TOC, WEOC, HWSC and MBC and the least under CK up to 15-30 cm soil depth. In surface (0-7.5 cm), fertilizer-P application to wheat at $60 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1}$ (F_0P_0) resulted in 14.3% increase in TOC concentration, compared to CK. Further, application of fertilizer-P to both the crops through SSP ($\text{F}_0\text{P}_{30\text{SSP}}$) significantly increased the TOC concentration than through RP ($\text{F}_0\text{P}_{30\text{RP}}$). Application of FYM in combination with P fertilizer ($\text{F}_1\text{P}_{30\text{RP}}$) to rice significantly increased TOC concentration by 24.6% over FYM application alone (F_1P_0). Beneficial effects of fertilizers and manure

application was similar in the sub-surface soil (7.5-15 cm) but the two treatments F_0P_{30SSP} and F_0P_{30RP} did not differ significantly. Higher TOC was recorded in surface (0-7.5 cm) soil which decreased with soil depth (Fig. 2). It is because of the fact that C input through all exogenous sources viz. root and leaf litter biomass as well as applied FYM is restricted to the soil plough depth (0-15 cm). Compared to FYM application (F_1P_0), FYM in combination with fertilizer-P (F_1P_{30RP}) application significantly increased WEOC by 23.3%. Plots treated with fertilizer-P during both the crops through SSP (F_0P_{30SSP}) showed 14.3% increase in WEOC than treated with RP (F_0P_{30RP}). On an average, WEOC comprised ~0.5% of TOC concentration in the soil. In 15-30 cm soil, Application of FYM either alone or in combination with fertilizer-P significantly increased the concentration of WEOC compared to absolute control. In 30-60 cm soil depth, all treatments exhibited similar WEOC concentration (Fig. 2). Fertilizer-P and FYM application either alone or in combination to both crop led to significant increase in HWSC compared to CK (Fig. 2). Hot water soluble C was significantly higher in the soils receiving FYM along with fertilizer-P (F_1P_{30RP}), compared to soils receiving FYM alone (F_1P_0). Application of P through SSP (F_0P_{30SSP}) significantly increased concentration of HWSC by 12.8% over F_0P_{30RP} treatment. On an average, HWSC comprised ~5.1% of TOC in soil and it was 10-times higher than the WEOC concentration (Fig. 3). In surface soil (0-7.5 cm), application of P through SSP significantly increased MBC by 19.2% over rock phosphate (RP) treated plots. Plots receiving FYM along with fertilizer-P (F_1P_{30RP}) showed 28.2% higher MBC than receiving only FYM (F_1P_0) (Fig. 2). In sub-surface soil (7.5-15 cm), highest concentration (151.2 mg kg^{-1}) of soil MBC was observed under FYM and RP treated plots and the lowest (75.2 mg kg^{-1}) in CK plots.

Beneficial effects of different treatments were higher on TOC and its fractions in surface (0-7.5 cm) soil and decreased with depth (Fig. 2). In 15-30 cm soil, compared to CK, FYM along with fertilizer-P (F_1P_{30RP}) application increased TOC, WEOC, HWSC and MBC significantly by 32.3, 23.0, 28.1 and 34.5 %, respectively. However, all the treatment exhibited similar WEOC, HWSC and MBC at 30-60 cm soil depth.

Soil bulk density

In surface soil (0-7.5 cm), the lowest D_b (1.42 Mg m^{-3}) was observed in plots receiving FYM in conjunction with P through rock phosphate (F_1P_{30RP}) and the highest (1.55 Mg m^{-3}) in unamended control (Fig. 3). The soil D_b followed the order $CK > F_0P_0 > F_0P_{30RP} > F_0P_{30SSP} > F_1P_0 > F_1P_{30RP}$ up to 15 cm soil depth and increased with depth.

Carbon mineralization

Carbon mineralization was higher at 35°C than at 25°C , but the magnitude varied with the field treatment. At the end of incubation, the cumulative amount of $\text{CO}_2\text{-C}$ evolved in different treatments ranged

between 158.2 and 528.0 mg C kg⁻¹ at 25°C, and between 259.1 and 828.5 mg C kg⁻¹ at 35°C (Table IV). Regardless of the temperatures, cumulative amount of CO₂-C evolved in soil followed the order FYM F₁P_{30RP} > F₁P₀ > F₀P_{30SSP} > F₀P_{30RP} > F₀P₀ > CK.

Potassium permanganate oxidizable carbon (KMnO₄-C)

In 0-7.5 cm and 7.5-15 cm soils, fertilizer P and FYM application either alone or in combination to rice increased KMnO₄-C by 64-152% than their no application (CK) (Table V). Potassium permanganate oxidizable carbon (KMnO₄-C) concentration increased by 17.5% in soils receiving fertilizer-P and FYM (F₁P_{30RP}) over plots receiving FYM alone (F₁P₀). In sub-surface soil (7.5-15 cm), effect of different treatment was similar that observed in 0-7.5 cm soil. However, KMnO₄-C concentration did not differ significantly between treatment F₀P_{30SSP}, F₁P₀ and F₁P_{30RP} (Table V). The effect of different treatment decreased with depth and all treatment did not differ significantly at 30-60 cm soil depth (*Data has not given*). In surface soil (0-7.5 cm), application of fertilizer P through single super phosphate (F₀P_{30SSP}) increased non-labile C by 13.6% over rock phosphate treated (F₀P_{30RP}) plots. Significantly higher (25.9%) non-labile C was observed in treatment F₁P_{30RP} over F₁P₀ treatment. In surface (0-7.5 cm) and sub-surface (7.5-15 cm) soil, application of fertilizer-P with FYM (F₁P_{30RP}) showed highest non-labile C and the lowest in CK. Higher concentration of non-labile C in the treatments involving FYM application shows the stabilization of organic C in the soil. This could be due to the application of already stabilized material in soil. The C lability, lability index (LI), C pool index (CPI) and C management index (CMI) also improved considerably with fertilizer-P application with FYM at both the soil depths (Table V). Therefore, it can be concluded that the application of fertilizer-P with FYM could be a C sustainable management option for crop production.

Correlation among soil phosphorus and carbon pools and soil properties

Soil C pools and available nutrients revealed highly significant positive correlation with different soil C pools for soil plough depth (0-15 cm) (Table VI). Highly significant positive correlation among TOC, KMnO₄-C, WEOC, HWSC and MBC revealed that there exists a dynamic relationship governing the existence of each-other. These C pools also showed highly significant linear positive correlation with available P, K and mineral-N in the soil plough depth.

DISCUSSION

Rate and source of P application did not influence soil pH and EC while value of these parameters changed with depth. Several studies (Bhat, 2013; and Yadav, 2014) have reported increase in soil pH and decrease in EC with depth. The increase in pH with depth may be attributed to i) leaching of bases from the surface to lower layers, ii) decrease in SOC concentration with depth (Singh *et al.*, 2008; Kumar and Singh,

2010) and iii) decrease in ammonium oxidation to nitrate (Schoenau, 2006). The decrease in EC with depth shows decrease in salt content of the soil. The results on pH and EC show that the experimental soil was free from acidity/alkalinity and salinity problems. Increase in the concentration of $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^-\text{-N}$ with FYM application was probably because of mineralization of organic N contained in manure commensurate with plant uptake. This could have also resulted in lower losses of N (Yadav *et al.*, 2000). These results are similar to those reported by Begum *et al.*, (2007), Beri *et al.*, (1989). Integrated nutrient management is reported to enhance the ammonification and nitrification process (Jagtap *et al.*, 2007) leading to greater $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^-\text{-N}$ in soil.

After 7 cycles of rice-wheat cropping, single super phosphate and RP showed similar available P, however SSP is more soluble than RP. Indicating that RP had enough time to dissolve in the soil considering the time interval, amount, and rainfall distribution pattern after the RP (Akanke *et al.*, 2011). Significant improvement in available P with FYM and RP application may be attributed to P supplementation through FYM and solubilization of mineral P and decreased rate of P sorption in the presence of FYM (Sarora and Vig, 1992; Sui and Thompson, 2000). Compared to di-ammonium phosphate (DAP), rock phosphate enriched with rice straw compost showed greater increase of available P after 45 d of incubation in a sandy loam soil. Therefore, indicating the beneficial role of rock phosphate in P in presence of organic manure (Biswas and Narayanasamy, 2006). At 7.5-15 cm soil depth, available P concentration did not differ significantly in treatments F_0P_0 and CK. However, other treatments significantly increased the concentration of available P in soils compared with CK. Plots amended with FYM in conjunction with rock phosphate ($\text{F}_1\text{P}_{30\text{RP}}$) showed significant increase in available P compared to alone fertilizer or FYM amended plots. Higher concentration of available P in the plough layer (0-15 cm) was due to the application of fertilizer-P in the seed zone, greater biomass addition in upper soil and formation of stable and meta-stable compounds of low P solubility in the soil (Toor and Bahl, 1997; Alleoni *et al.*, 2012), which do not allow movement of P to lower layers. Similar results were earlier reported by Galvani *et al.*, (2008) and Pizzeghello *et al.*, (2011). Significant increase in available K in FYM treated soils has also been reported by Naidu *et al.*, (2009); Prasad and Mathur (1997). Desai *et al.*, (2009) observed that application of crop residues and FYM improved available K in organic-treated soils compared with chemical fertilizers treated soils. Singh *et al.*, (2008) observed increase in available K in soils dressed with FYM, vermicompost, green manure and rice residue alone or in combination with bio-fertilizers. A significant change in available K content in plough layer (0-7.5 and 7.5-15 cm) for the treatments involving FYM application could be attributed to the supplementation of K through applied FYM and decrease in K fixation by soil clay.

Soil decreased with fertilizer-P and FYM application and increased with depth. Several researchers have reported decrease in soil D_b with NPK, FYM and NPK+FYM application (Bi *et al.*, 200; Nayak *et al.*, 2012). The application of organic matter besides leading to dilution because of low D_b of added organic

matter improves soil aggregation, resulting in decreased soil D_b (Halvorson *et al.*, 1999; Benbi and Senapati, 2010; Huang *et al.*, 2014). Soil D_b increased with depth though the effect of different treatments was non-significant below 15 cm soil depth (Fig. 3). This may be due to decrease in soil organic carbon with depth (Rasool *et al.*, 2008; Kukal *et al.*, 2009).

Application of fertilizer-P through SSP to both crop in a rice-wheat sequence increased TOC compared to RP application. It may be because of the higher availability of P to plant roots when P is applied through SSP than RP. Akande *et al.*, (2011) have reported the greater P availability in SSP treated soils compared to rock phosphate treated soil, because P from SSP is more readily due to higher solubility. Therefore, increased TOC with fertilizer-P application is due to the increased root growth and biomass, which adds organic matter to the soil. A greater proportion of root biomass is also restricted to the plough depth than the lower soil layers. Adoption of integrated nutrient management and FYM application tends to significant increase in SOC concentration in a soil plough layer under rice-wheat cropping system (Brar *et al.*, 2013). Bhattacharaya *et al.*, (2010) observed 47% higher SOC concentration in soil plough layer receiving NPK+FYM than alone NPK dressed soil. Fertilizer application stimulates crop biomass production and thus increases the amount of residue retained in the soil and therefore, enhances C accumulation in the soil (Schuman *et al.*, 2002). Under chick-wheat cropping system, Deshpande *et al.*, (2015) noticed 41-51% increase of organic carbon in soils under RP+fresh cow dung+phosphorus solubilising bacteria (PSB) treatment. A significant linear relationship between cumulative C input to the soil and amount of C sequestered in soils under rice-wheat cropping system (Srinavasarao *et al.*, 2012). Thus, an improvement in TOC concentration in a soil with FYM application might be due to additional input through manure (Moharana *et al.*, 2012). Ghosh *et al.*, (2012) reported 2.09-times higher crop C input to soil with the NPK+FYM application over the control treatment, after 25-years long-term experiment under rice-wheat cropping system. Similarly, Tong *et al.*, (2014) reported 6.1-times higher annual crop C input to soil with NPK + pig manure application compared to the control treatment in a 17 years long-term fertilizer experiment under maize-wheat cropping system.

Water extractable organic C, which represents an array of molecules in a soluble phase that remain in equilibrium with solid SOC, responded to rates and source of P application. A significant increase (~2.21-times) in WEOC in the soil plough layer (0-15 cm) as a result of 9-years of rice-wheat cropping with NPK+FYM application, over the CK treatment was reported by Brar *et al.*, (2013). A higher increase in WEOC in FYM dressed plots compared to NPK alone indicates that added organic manure contains much soluble organic matter (Chantigny *et al.*, 2002). Hot water soluble C constituted 5.01% of TOC which is relatively greater than WEOC (0.51% of TOC) and MBC (2.96% of TOC). Considerably higher amounts of C in the HWC was due to the fact that it would have extracted not only the microbial biomass-C but also

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root exudates, soluble carbohydrates and amino acids (Gregorich *et al.*, 2003), C bound to soil enzymes would also be extracted because most of the soil enzymes in these soils would be denatured at 80 °C, however in our study the boiling temperature was higher than 80°C. The application of inorganic fertilizers either alone or in combination leads to significant increase in HWSC due to increase in C input (Ma *et al.*, 2011). Several researchers have reported the increase in HWSC with FYM and fertilizer application compared to CK (Ghani *et al.*, 2003; Schulz *et al.*, 2011; Liang *et al.*, 2012; Benbi *et al.*, 2015b)

Microbial biomass C plays an important role in nutrient cycling and has been recognized as component of active soil organic matter that helps in maintaining function and sustainability of terrestrial ecosystems (He *et al.*, 2003). Soil MBC comprised 2.8% of TOC concentration in the plough layer. This concentration is in the range (1-5% of TOC) reported by Jenkinson and Ladd (1981). In a rice-wheat cropping system, significant increase in soil MBC with FYM application has also been reported earlier by Kaur *et al.*, (2008). After 16 years of rice based cropping system in semi-arid tropics, Banger *et al.*, (2009) also reported a significant improvement in MBC with FYM application in the plough layer. In four long-term field experiments under rice-wheat cropping system conducted in different agro-climatic conditions in India, an enhancement of 78.8 to 162.9% in soil MBC with fertilizer+FYM application has been reported (Nayak *et al.*, 2012).

Increase in C mineralization with different rate and source of P application may be due to the increase in organic carbon and its labile fractions in soils. Because fertilizer and manure application tends to increase the soil organic carbon which had a significant effect on CO₂ production due to increase in microbial activities (Dash *et al.*, 2014). Compared to fertilizers applications, farmyard manure and fertilizer applications tend to increase the C mineralization. Because their regular applications enhance WEOC which acts as an important source of energy for microbial growth compared to fertilizers alone application (Kaur *et al.*, 2008). Our results corroborate with the findings of Mohanty *et al.*, (2013), who observed higher CO₂ evolution rates for the soils receiving leaf-litter or NPK+FYM, compared to the CK soils. Marinari *et al.*, (2010) reported that cumulative CO₂ production was significantly higher in organically treated than chemically fertilized soils. Greater C mineralization at 35°C than at 35°C and 15°C temperature has been reported by Benbi *et al.*, (2014); Benbi and Khosa (2014).

The concentration of KMnO₄-C was higher in surface soil (0-7.5 cm) and decreased with depth. It may be due to decrease on organic carbon in soil. Moharana *et al.*, (2012) reported that FYM at 20 Mg ha⁻¹ yr⁻¹ application either alone or in conjunction with NPK significantly increased KMnO₄-C concentration over control. Blair *et al.*, (2006) have reported that in surface soil (0-10 cm), KMnO₄-C increased by 70% after 96 years of FYM application, compared to CK.

Compared to CK, fertilizer-P along with FYM applications increased TOC by 97%. In surface (0-7.5 cm) soil, WEOC, HWSC, MBC and KMnO₄-C comprised 0.51, 5.01, 2.96 and 13.6 % of TOC, respectively.

Similarly, Benbi *et al.*, (2015b) have also reported that WEOC, HWSC and $\text{KMnO}_4\text{-C}$ comprised 0.32-0.50%, 3-3.3% and 15-20% of TOC after 11 years of FYM and fertilizer applications under rice-wheat system in the same region.

Correlation matrix showed strong positive correlation among the soil properties, indicating the beneficial effects of fertilizers and FYM application on soil fertility. Several researchers have reported the positive and significant correlation among TOC, HWSC, MBC and WEOC (Ghani *et al.*, 2003; Benbi *et al.*, 2015b).

CONCLUSIONS

Fertilizer-P or farmyard manure applications showed positive influence on soil properties. Compared to CK, greatest amount of available nutrients, TOC and its labile fractions were observed under farmyard manure and rock phosphate treated plots. But trends were reversed for soil D_b . Beneficial effects of fertilizer-P application through RP was relatively less than SSP application. However, except soil D_b , RP with FYM treated plots showed greater increase in available nutrients and organic carbon, compared to SSP treated plots. Compared to CK, farmyard manure and RP applications increased TOC and available P by 97% and 72%, respectively, in surface (0-7.5) soil. Regardless of the treatment, effects of different treatments on soil properties was more in surface (0-7.5 cm) soil and decreased with depth. Below plough layer (0-15 cm) soils, treatments did not influence available P, available K and soil D_b . The $\text{KMnO}_4\text{-C}$ was one of the largest pool of soil organic and constituted 13.8% of TOC. Whereas, WEOC was smallest one and constituted only 0.51% of TOC. Carbon mineralization was higher at 35°C than at 25°C , but the magnitude varied with the field treatment. Regardless of the temperatures, cumulative amount of $\text{CO}_2\text{-C}$ evolved in soil followed the order $\text{F}_1\text{P}_{30\text{RP}} > \text{F}_1\text{P}_0 > \text{F}_0\text{P}_{30\text{SSP}} > \text{F}_0\text{P}_{30\text{RP}} > \text{F}_0\text{P}_0 > \text{CK}$. Carbon management index (CMI) also improved considerably with fertilizer-P and FYM applications in surface and subsurface soils, indicates the greater C stabilization in soil. Farmyard manure and RP applications improved soil properties to greater extent compared to their sole applications, indicating the need for combined use of FYM and RP in these alluvial soils.

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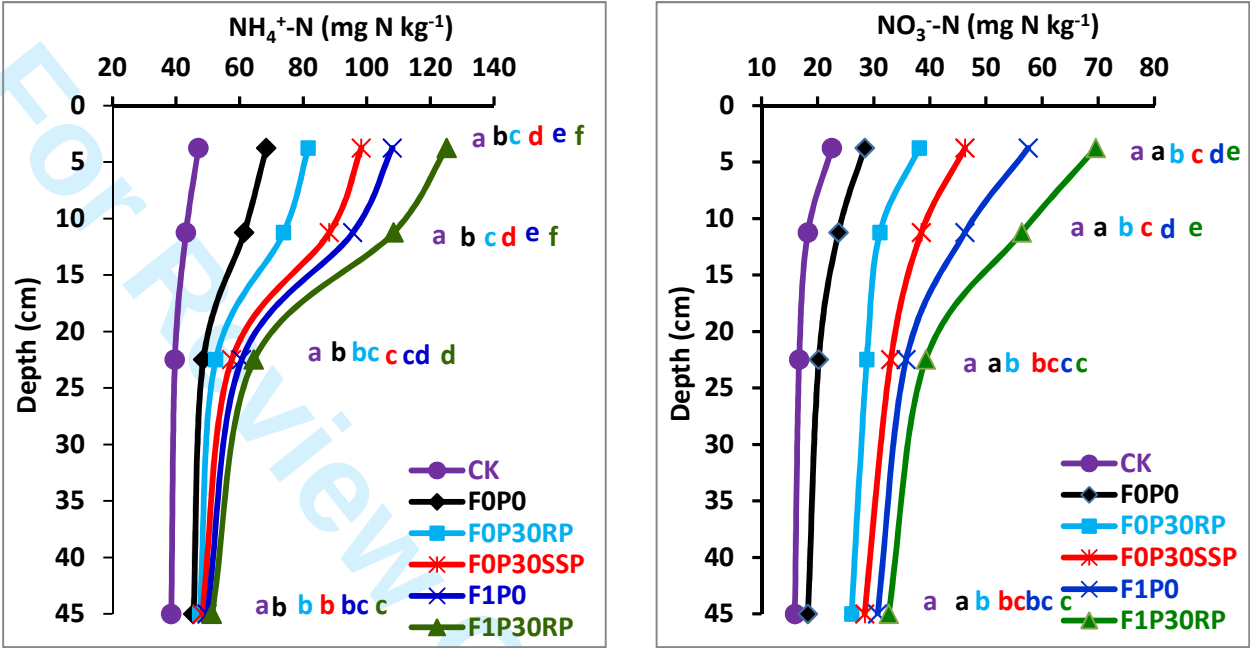


Fig. 1 Effect of amount and source of P application on profile distribution of $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^-\text{-N}$ in soils after 7 cycles of rice-wheat cropping. Mean values for a soil property at a given depth followed by different letters differ significantly ($p < 0.05$) by Duncan's multiple range test (DMRT).

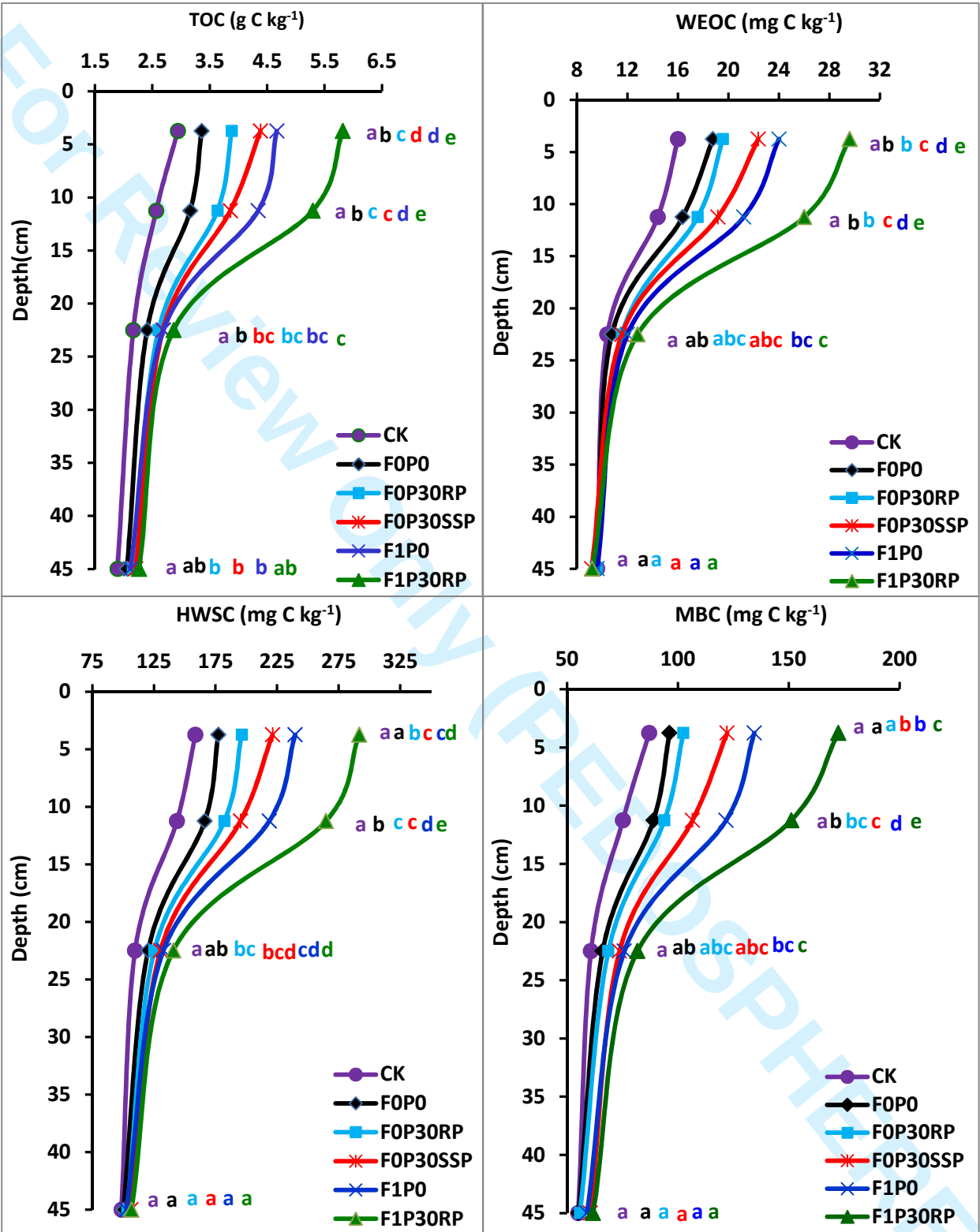


Fig. 2 Effect of amount and source of P application on profile distribution of total organic carbon (TOC), water extractable organic carbon (WEOC), hot water soluble carbon (HWSC) and microbial biomass carbon (MBC) in soil after 7 cycles of rice-wheat cropping. Mean values for a soil property at a given depth followed by different letters differ significantly ($p < 0.05$) by Duncan's multiple range test (DMRT).

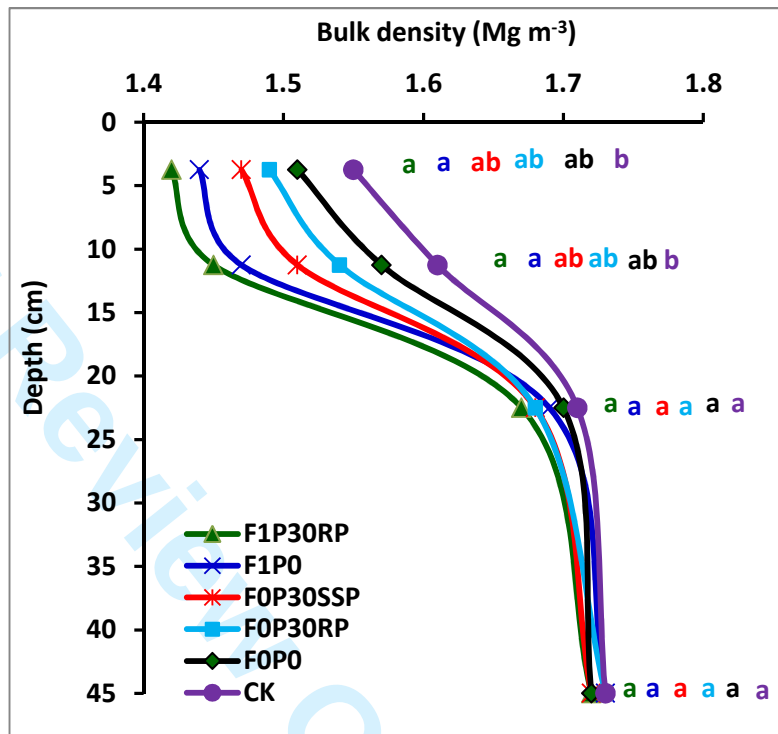


Fig. 3 Effect of amount and source of P application on soil bulk density (D_b) at different soil depths after 7 cycles of rice-wheat cropping. Mean values for a soil property at a given depth followed by different letters differ significantly ($p < 0.05$) by Duncan's multiple range test (DMRT).

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Table I Important physical and chemical properties of the surface (0-15 cm depth) soil at the start of the experiment in 2006

Soil property	Value
pH (1 :2 soil to water ratio)	7.22
EC (1 :2 soil :water suspension, dS m ⁻¹)	0.21
Soil organic carbon (g kg ⁻¹)	5.72
Available N (kg N ha ⁻¹)	141.0
Available P (kg P ha ⁻¹)	21.8
Available K (kg K ha ⁻¹)	89.6
Sand (%)	62.2
Silt (%)	15.5
Clay (%)	22.29
Soil texture	Sandy loam

Table II Treatment details applied to rice and wheat crops

Treatment reference	Treatment acronym		Nutrient applied ($\text{kg ha}^{-1} \text{yr}^{-1}$) to	
	Rice	Wheat	Rice	Wheat
CK	P ₀	P ₀	120 N + 30 K ₂ O	120N + 30 K ₂ O
F ₀ P ₀	P ₀	P ₆₀ SSP	120 N + 30 K ₂ O	120N + 60 P ₂ O ₅ + 30 K ₂ O
F ₀ P _{30RP}	P ₃₀ RP	P ₆₀ SSP	120 N + 30 P ₂ O _{5(RP)} + 30 K ₂ O	120N + 60 P ₂ O ₅ + 30 K ₂ O
F ₀ P _{30SSP}	P ₃₀ SSP	P ₆₀ SSP	120 N + 30 P ₂ O _{5(SSP)} + 30 K ₂ O	120N + 60 P ₂ O ₅ + 30 K ₂ O
F ₁ P ₀	FYM	P ₆₀ SSP	120 N + 30 K ₂ O + 10 t FYM	120N + 60 P ₂ O ₅ + 30 K ₂ O
F ₁ P _{30RP}	FYM+P _{30RP}	P ₆₀ SSP	120 N + 30 P ₂ O _{5(RP)} + 30 K ₂ O + 10 t FYM	120 N + 60 P ₂ O ₅ + 30 K ₂ O

CK=Control, RP=Rock phosphate, SSP=Single super phosphate, FYM=Farmyard manure

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Table III Effect of amount and source of P application on available P and available K concentration in the surface (0-7.5 cm) and sub-surface (7.5-15 cm) soil after 7 cycles of rice-wheat cropping

Treatment	Available P (mg kg ⁻¹)		Available K (mg kg ⁻¹)	
	0-7.5 cm	7.5-15 cm	0-7.5 cm	7.5-15 cm
CK	11.2a [†]	10.5a	91a	85a
F ₀ P ₀	13.5b	12.1ab	93a	86a
F ₀ P _{30RP}	14.2b	13.1bc	95a	88a
F ₀ P _{30SSP}	14.8bc	13.5bc	97a	90a
F ₁ P ₀	16.6c	14.8cd	114b	103b
F ₁ P _{30RP}	19.3d	17.8d	119b	108b

[†]Mean values within a column followed by different letters differ significantly ($p<0.05$) by Duncan's multiple range test (DMRT)

Table IV Effect of rate and source of P application on cumulative $\text{CO}_2\text{-C}$ evolved (mg kg^{-1}) of surface soil (0-15 cm) at 36 d of incubation.

Treatment	Cumulative $\text{CO}_2\text{-C}$ evolved (mg kg^{-1})	
	Temperature ($^{\circ}\text{C}$)	
	25 $^{\circ}\text{C}$	35 $^{\circ}\text{C}$
CK	158.2	259.1
F_0P_0	241.6	375.8
$\text{F}_0\text{P}_{30\text{RP}}$	301.1	452.7
$\text{F}_0\text{P}_{30\text{SSP}}$	357.3	550.9
F_1P_0	400.4	649.6
$\text{F}_1\text{P}_{30\text{RP}}$	528.0	828.5

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Table V Effect of amount and source of P application on $\text{KMnO}_4\text{-C}$ (g kg^{-1}), non-labile C (g kg^{-1}), lability index (LI), soil carbon pool index (CPI) and carbon management index (CMI) in the surface (0-7.5 cm) and sub-surface (7.5-15 cm) soil after 7 cycles of rice-wheat cropping

Treatment	KMnO ₄ -C		Non labile-C		Lability		LI		CPI		CMI	
	Depth (cm)											
	0-7.5	7.5-15	0-7.5	7.5-15	0-7.5	7.5-15	0-7.5	7.5-15	0-7.5	7.5-15	0-7.5	7.5-15
CK	0.319a [†]	0.305a	2.62a	2.26a	0.122	0.135	--	--	--	--	--	--
F ₀ P ₀	0.388a	0.356a	2.97a	2.80a	0.131	0.127	1.07	0.94	1.14	1.23	122.4	116.1
F ₀ P _{30RP}	0.524b	0.472b	3.36b	3.16b	0.156	0.149	1.28	1.11	1.32	1.41	169.1	156.9
F ₀ P _{30SSP}	0.568b	0.512b	3.82c	3.35b	0.149	0.153	1.22	1.14	1.49	1.50	182.3	171.0
F ₁ P ₀	0.685c	0.582bc	3.98c	3.76bc	0.172	0.155	1.41	1.15	1.59	1.69	224.3	194.5
F ₁ P _{30RP}	0.805d	0.682c	5.01d	4.61c	0.161	0.148	1.32	1.10	1.98	2.06	260.9	226.5

[†]Mean values within a column followed by different letters differ significantly ($p<0.05$) by Duncan's multiple range test (DMRT)

Table VI Correlation matrix depicting relationship among different soil carbon pools and soil properties

	KMnO ₄ -C	WEOC	HWSC	TOC	Av. P	Av. K	MBC	NH ₄ ⁺ -N
WEOC	0.97**							
HWSC	0.98**	0.99**						
TOC	0.98**	0.99**	0.99**					
Av. P	0.98**	0.99**	0.99**	0.99**				
Av. K	0.92*	0.93**	0.94**	0.92**	0.93**			
MBC	0.95**	0.99**	0.99**	0.99**	0.98**	0.95**		
NH ₄ ⁺ -N	0.98**	0.96**	0.97**	0.97**	0.97**	0.88*	0.95**	
NO ₃ ⁻ -N	0.98**	0.98**	0.99**	0.99**	0.98**	0.95**	0.98**	0.98**

*Correlation is significant at $p < 0.05$ level (2-tailed)**Correlation is significant at $p < 0.01$ level (2-tailed)

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