Tillage, Green Manure And Residue Retention Improve Aggregate-Associated Phosphorus Fractions Under Rice-Wheat Cropping

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Abstract

The sustainability of rice-wheat system (RWS) in north-western India is threatened due to the deterioration of soil health and emergence of new challenges of climate change caused by low nutrient use efficiency and large scale burning of crop residues. Phosphorus and phosphatase activities in the soil aggregates affected by different residue management practices remain poorly understood. Thus, soil samples were obtained after a five year field experiment to identify the effect of tillage, green manure and residue management on aggregate-associated phosphorus fractions. In rice, the main plot treatments were combinations of wheat straw and *Sesbania* green manure (GM) management: (1) puddled transplanted rice (PTR) with no wheat straw (PTRW₀), (2) PTR with 25% wheat stubbles (12-15 cm long) retained (PTRW₂₅), (3) PTR without wheat straw and GM (PTRW₀+GM), and (4) PTR with wheat stubbles (25%) and GM (PTRW₂₅+GM). Three sub-plots treatments in the successive wheat crop were (1) conventional tillage with rice straw removed (CTW_{R0}), (2) zero tillage (ZT) with rice straw removed (ZTW_{R0}) and (3) ZT with 100% rice straw retained as surface mulch (ZTW_{R100}). Results of the present study revealed that all phosphorus fractions were significantly higher in PTRW₂₅+GM followed by ZTW_{R100} compared with PTRW₀/CTW_{R0} treatment within both macro- and micro-aggregates. The total phosphorus (P), available P, alkaline phosphatase and phytin-P were significantly higher under ZTW_{R100} than CTW_{R0}. Principal component analysis identified NaOH-P_o, NaHCO₃-P_i and HCl-P as the dominant and reliable indicators for evaluating P transformation within aggregates under conservation agriculture based practices.

Introduction

Soils play an essential part in maintaining agroecosystem productivity and understanding the impacts of management practices for agricultural sustainability (Kibblewhite et al., 2008; Lavelle et al., 2014). Tillage and residue management practices under intensive tillage and residue burning agricultural practices improved soil structure, associated protection of SOM and biological activities (Sharma et al., 2019; Saikia et al., 2019a, b), which eventually improves organic matter, soil aggregation, and nutrient cycling in agricultural systems (Lal 1993; Montgomery 2007; Barrios 2007). Phosphorus (P), being the second most imperative nutrient, less available to plants due to its adsorption and precipitation with iron, aluminum and calcium in soils, thereby resulting in the rapid formation of non-labile P forms (Priyadarshi et al., 2018; Ahmed et al., 2019). Soil P transformations vary depending upon the soil type and management practices (Sharma et al., 2014). Moreover, the continuous application of phosphate fertilizers has led to the serious environmental threats including acidification, hardening and P leaching from the soil (Rigo et al., 2019). The sustainability of conventional RWS based on intensive tillage is threatened by scarcity of water, energy and labour, higher production cost and environmental pollution due to burning of crop residues and deteriorating soil health (Montgomery 2007; Srinivasan et al., 2012; Chauhan et al., 2012) and emerging challenges associate with climate change (Jat et al., 2016; Grant and Flaten 2019). To address the aforementioned issues, conservation agriculture (CA)-based practices (minimum tillage, residue retention and crop diversification) are being developed and promoted for rice and wheat production (Gathala et al., 2013). The alternative systems of tillage, green manure (GM) and residue management practices under CA-based practices can potentially lead to significant changes in the availability of nutrients in RWS (Bera et al., 2017; Saikia et al., 2019a). The CA-based practices holds the potential to enhance P availability by altering the soil microbial diversity and enzyme activity, which in turn affects the availability of soil P (Wang et al., 2011; Bhan and Behera 2014; Bezerra et al., 2015). These practices can increase the soil organic matter (SOM), carbon (C) sequestration, soil aggregation (Sithole et al., 2019) and contribute to higher crop yields (Xu et al., 2019).

Soil aggregate size, distribution and stability performs a important role in enhancing the physico-chemical and biological processes in soil (Jiao et al., 2006), and also affects the P forms and availability (Castro-Filho et al., 2002). The organic phosphorus (P_o) is usually found in chemically or physically protected forms, which are mineralized slowly into available forms for plant uptake, mostly as a byproduct of SOM decomposition or through the action of specific enzymes. The constant loss of P reservoir in the soil owing to crop harvesting, runoff and leaching can also consume P_o and P_i forms rapidly, and thus resulting in the deficiency of P to plant. This P loss is directly associated with the stability of soil aggregates and nutrients distribution within aggregates (Liu et al., 2010). The P distribution among various fractions provides an indication of the potential stability of P in soil which may vary with different management practices. In addition, stable aggregates reduce soil erosion and degradation, surface runoff and crusting (Sithole et al., 2019). Additionally, these CA-based practices comprising ZT with crop residues

retention enhances soil aggregation, mean weight diameter of water-stable aggregates and also increases the resistance of aggregates to slaking (Sharma et al., 2019). We hypothesized that tillage, GM and residue management practices may lead to significant changes in P-fractions in soil aggregates. Furthermore, the focus was to elucidate the distribution of different fractions of P (P_i and P_o) in the aggregates and how these fractions affected the crop yield under CA-based RWS.

Materials And Methods

2.1 Site description

A field experiment (5-year) on irrigated RWS was initiated in 2011 with rice crop on a sandy loam soil classified as *Typic Ustochrept* (USDA classification) at the research farm of the Punjab Agricultural University, Ludhiana, Punjab (30°56'N, 75°52'E, 247m ASL) Punjab, India.

The electrical conductivity, pH (1:2 soil: water), oxidizable carbon (SOC) (Walkley & Black's, 1934), available-P (Olsen et al., 1954) and available-K (Jackson, 1967) content of 0–15 cm layer of soil was 0.34 dS m⁻¹, 7.81, 3.51 g kg⁻¹, 11.3 mg P kg⁻¹, 46.3 mg K kg⁻¹, respectively as explained in Saikia et al., (2019b). The region is characterized by a sub-tropical semi-arid type of climate with a hot summer (March-June), wet monsoon season (late June-mid September) and a very cold winter (October-February). There were four main plot treatment combinations of wheat straw and Sesbania green manure management in rice (PTR_{W0}, puddled transplanted rice with no wheat straw; PTR_{W25}, puddled transplanted rice with 25% anchored wheat stubbles retained; PTR_{W0} plus green manure, and PTR_{W25} plus green manure). The treatments in subplot consisted of three combinations of tillage and residue management in subsequent wheat (CTW_{R0}, conventional tilled wheat with rice residue removed; ZTW_{R0}, zero tilled wheat with rice residue removed and ZTW_{R100}, zero tilled wheat with 100% rice residue retained as mulch). Full details experimental information is provided in Saikia et al (2019a) and only details relevant to the present study are discussed here (Table 1).

Table 1
Description of treatments

Abbreviation	Treatment detail	Method of crop establishment
A. Rice (main plot treatments)		
PTR _{W0}	Conventional till puddled transplanted rice (PTR) with wheat straw removed (W ₀)	Residue of preceding wheat was removed. Pre- puddling tillage operations included two discings and two harrowings followed by plankings. Puddling (wet tillage) was done twice in 6–8 cm of standing water using a tractor-mounted puddler followed by planking. Rice seedlings were manually transplanted at 15 x 20 cm spacing
PTR _{W25}	PTR with anchored wheat straw (W ₂₅)	Anchored (10–12 cm high) wheat straw (25%) of preceding wheat was retained. All the tillage and rice crop establishment operations were same as in PTR _{W0}
PTR _{W0} +GM	PTR with green manure (GM)	Residue of preceding wheat was removed and zero till <i>Sesbania</i> green manure after wheat harvest. Green manure was chopped by two discings and then incorporated using two harrowings followed by planking. Puddling and rice establishment operations were same as in PTR _{W0}
PTR _{W25} +GM	PTR with anchored wheat straw + green manure	Anchored wheat residue of preceding wheat was retained and zero till <i>Sesbania</i> green manure was sown in standing stubbles. Green manure incorporation and puddling operations were same as in PTR _{W0} +GM. Rice seedlings were manually transplanted at 15 x 20 cm spacing
B. Wheat (sub-plot treatments)		
CTW _{R0}	Conventional till wheat (CTW) after removal of rice residue	All the residue of previous rice crop was removed. Tillage operations included two passes of harrows and two passes of tine plough followed by plankings. After pre-sowing irrigation, seed bed was prepared by two passes of tine plough followed by planking. Wheat was sown using seed cum fertilizer drill in rows 20 cm apart
ZTW _{R0}	Zero till wheat (ZTW) after removal of rice residue	Residue of previous rice crop was removed. Wheat was direct seeded in the no till plots in rows 20 cm apart using zero till seed cum fertilizer drill.
ZTW _{R100}	Zero till wheat with 100% rice residue as mulch	Residue of previous rice crop was retained. Wheat was direct seeded in rows 20 cm apart into rice residues using Turbo Happy Seeder (Sidhu et al. 2015).

2.2 Soil analysis

Undisturbed soil clods measuring about 50 cm in diameter from the soil layer (0–15 cm) were collected from each plot in duplicate after wheat harvest (after seven cycles of RWS) using hand shovels for analysis of aggregate size and different fractions of P. After shade drying, soil clods were left to fall from waist height on to a grassy surface to naturally break at of cleavage.

2.3 Soil physical characteristics

For aggregate analysis, the samples were passed through a 4.0 mm sieve. The aggregates retained over a 2.0 mm sieve were retained for aggregate size analysis. A nest of six sieves (2.0, 1.0, 0.50, 0.25, 0.11 and 0.053 mm) were used for wet sieving of aggregate (Yoder, 1936) and weighed each sieve after drying. The aggregate samples were collected from sieves 2 mm, 1–2 mm, below 0.25 mm for micro-aggregates and above 0.25 mm sieves for macro-aggregates and above using the sequential extraction procedure as given by Sui et al., (1999) was employed for P fractionation studies (Fig. 1). Total P in the samples was analyzed by the method given by Alexander and Robertson (1968). Available P was estimated using the methods described by Olsen et al., (1954) by using 0.5N NaHCO₃ (pH 8.5) as extracting agent. The intensity of blue color was directly proportional to the P content in soil was read on a colorimeter at a wavelength of 660 nm. The alkaline phosphatase (Alk-P EC 3.1.3.1) activity was assayed on the basis of p-nitrophenol (pNP) release after cleavage of enzyme-specific synthetic substrates (Tabatabai and Bremner 1969). This is based on the colorimetric estimation of the p-nitrophenol released when soil is incubated with buffered (pH 11)

sodium p-nitrophenyl phosphate solution. The phytin P was estimated by extraction of phytate with 15% $\text{CCl}_3\text{-COOH}$ (trichloroacetic acid) as described by Mega (1982).

2.4 Statistical analysis

The data were statistically analyzed using analysis of variance technique in split plot design using CPCS1, locally developed software (Cheema and Singh 1990). Mean separation for different treatments was performed using the Least Significant Difference (LSD) test. Differences in treatments on for dif $p < 0.05$ were considered statistically significant. The principal component analysis (PCA) method is statistical tool to avoid any biasness (Wold et al., 1987). The soil quality index (SQI) was calculated using integrated score and weight factor of each indicator using equation (Andrews et al., 2002)

$$\text{Soil quality index (SQI)} = \sum_{i=1}^n W_i \times S_i$$

Where, 'S' = indicator score and W = PCs weight factor

Results

3.1 Aggregate-associated inorganic and organic P fractions

The tillage, GM and residue management practices in the present study had posed significant effects on the P fractions across different sized aggregates (Fig. 2–3). In the micro-aggregates fraction (< 0.25 mm), the water soluble phosphorus (WS-P) in $\text{PTR}_{\text{W25}}+\text{GM}$ was significantly 29.2, 39.0, and 82.9% higher than $\text{PTR}_{\text{W0}}+\text{GM}$, PTR_{W25} and PTR_{W0} , respectively. Likewise, for other P fractions, $\text{PTR}_{\text{W25}}+\text{GM}$ recorded significantly higher $\text{NaHCO}_3\text{-P}_i$ than $\text{PTR}_{\text{W0}}+\text{GM}$, PTR_{W25} and PTR_{W0} by 8, 46, 52 for $\text{NaHCO}_3\text{-P}_i$; $\text{NaHCO}_3\text{-P}_o$ by 7.4, 27.5, 49.4% and NaOH-P_i by 22.5, 5.5, 22.5%, respectively. In contrast to the above fractions, the significantly highest levels of NaOH extractable P_o (13.6 mg kg^{-1}) were obtained in treatment $\text{PTR}_{\text{W0}}+\text{GM}$. Moreover, the HCl-P was the dominant P-fraction, followed by $\text{NaHCO}_3\text{-P}_i$. In contrast to other P-fractions, the maximum HCl-P in aggregate size < 0.25 mm ($p < 0.004$) and > 0.25 mm ($p < 0.03$) was recorded in treatment $\text{PTR}_{\text{W25}}+\text{GM}$ followed by $\text{PTR}_{\text{W0}}+\text{GM}$, respectively. Similar results were observed for the relative distribution of P under aggregate size > 0.25 , 1–2 and > 2 mm.

Among tillage and residue retention practices in wheat, ZTW_{R100} resulted in the significantly higher P concentration in all the inorganic and organic P-fractions (WS-P, $\text{NaHCO}_3\text{-P}_o$, $\text{NaHCO}_3\text{-P}_i$, NaOH-P_o , NaOH-P_i and HCl-P) across different aggregate size compared with ZTW_{R0} and CTW_{R0} (Fig. 2–3). The HCl-P was found to be dominant fractions which was increased significantly under ZTW_{R100} by 13.3 and 35.9%; 18.4 and 30.2%; 7.3 and 32.8% and 25.7 and 47.5% in < 0.25 mm, > 0.25 mm, 1–2 mm and > 2 mm size aggregates compared with ZTW_{R0} and CTW_{R0} , respectively. Hence, the comparison of various P fractions within different aggregate size classes revealed significantly higher concentration of P in $\text{PTR}_{\text{W25}}+\text{GM}$ and ZTW_{R100} .

3.2 Soil total, available and alkaline P

The distribution of P_i and P_o fractions within different aggregate classes showed maximum total P in the aggregate size 1–2 mm followed by > 2 mm (macro-aggregates) then > 0.25 mm and least in the < 0.25 mm (micro-aggregates) (Fig. 4). The average total P ranged from $84.8\text{--}135.0 \text{ mg kg}^{-1}$ with the highest observed in the treatment $\text{PTR}_{\text{W25}}+\text{GM}$ followed by $\text{PTR}_{\text{W0}}+\text{GM}$, PTR_{W25} and PTR_{W0} . Compared to the PTR_{W0} and PTR_{W25} treatments, the $\text{PTR}_{\text{W25}}+\text{GM}$ increased the soil total P by 59.2% and 27.7%, respectively, in the fraction 1–2 mm. Thus, the total P in aggregate fraction 1–2 mm accounted for the major P proportion (130 mg kg^{-1}), consistent with the overall distribution of aggregates under various treatments. Among the tillage and residue management practices in wheat, ZTW_{R100} accumulates the significantly higher total P over ZTW_{R0} and CTW_{R0} , in macro- as well as micro-aggregates. Here also, the aggregate size 1–2 mm possessed the maximum total P compared to other aggregate size particles.

The available-P was also highest in aggregate size, 1–2 mm followed by > 2 mm then > 0.25 mm while least was observed in < 0.25 mm (Fig. 5). The average available-P was recorded to be the significantly higher in $\text{PTR}_{\text{W25}}+\text{GM}$ by 12.2%, 18.0% and 20.4% compared with $\text{PTR}_{\text{W0}}+\text{GM}$, PTR_{W25} , and PTR_{W0} , respectively. Consistent with the results of total P, the ZTW_{R100} treatment also

exhibited significantly higher the available P by 32.5 and 13.3% in < 0.25 mm size, 7.4 and 10% in the > 0.25 mm size, by 18.7 and 13.1% in the 1–2 mm and by 15.3 and 5.8% in the > 2 mm over ZTW_{R0} and CTW_{R0}, respectively.

Among rice treatments, higher alkaline phosphatase activity and phytin-P content were observed in the treatment PTR_{W25}+GM which were 2.5 and 4.2% higher than PTR_{W0}+GM, 20.6 and 20.7% than PTR_{W25} and 54.1 and 22.6% than PTR_{W0}, respectively (Fig. 6–7). In both the aggregate fractions (< 0.25 mm and > 0.25 mm), significantly higher alkaline phosphatase activity ($p < 0.05$) and phytin-P ($p < 0.05$) content were recorded in treatment PTR_{W25}+GM. The macro-aggregate fraction contributed higher towards the enzyme activity and phytin-P content than in micro-aggregate. In wheat treatments, when 100% rice residue was incorporated along with GM in ZT wheat, the alkaline phosphatase activity and phytin-P content were highest irrespective of the type of fraction (Fig. 6). The average activity varied from 59.3 to 82.0 $\mu\text{g pNPg}^{-1}\text{h}^{-1}$ and 25.98 to 21.65 mg kg^{-1} in the ZTW_{R100}, ZTW_{R0} and CTW_{R0}, respectively. Thus, our results indicated that among the different sized fractions, 1–2 mm possessed maximum available P, total P and alkaline phosphatase activity and phytin-P content compared with other aggregate size particles.

3.3 Crop yield and nutrient uptake

Conservation agriculture based practices in rice significantly affected the grain yield (Figure or Table 2). The grain yield in PTR_{W25}+GM increased by 11%, 15% and 26% compared with PTR_{W0}+GM, PTR_{W25} and PTR_{W0}, respectively. Similarly, the tillage based crop establishment treatments in wheat significantly affected the grain yield, straw yield, grain and total P uptake (Table 3). The increase in grain yield under ZT along with residue retention was 19% and 9% higher than ZT and CT without residue, respectively. Like grain yield, rice residue management practices showed higher effect on grain yield attributes. The grains spike⁻¹ was significantly higher under ZTW_{R100} than that of ZTW_{R0}. Grain yields of wheat were significantly related to total P and NaOH-Po fraction ($r = 0.997^{**}$ and 0.988^{*} , respectively, $p < 0.05$) (Table 4). The available P and alkaline phosphatase activity also exhibited significant relationships with wheat grain ($r = 0.968^{**}$ and 0.949^{**} , respectively, $p < 0.05$).

Table 2
Yield and yield attributes of wheat in affected by treatments applied to rice and wheat

Treatment	Grain yield (t ha ⁻¹)	Straw yield	Harvest Index	1000 grain weight	Spike length (cm)	No of grains/ spike
A. Rice establishment methods						
PTR _{W0}	4.71b	6.69	0.412	31.2	12.7	64.7
PTR _{W25}	5.15b	6.8	0.429	31.1	12.4	67.8
PTR _{W0} +GM	5.36ab	6.92	0.435	31.2	12.6	68.4
PTR _{W25} +GM	5.96a	6.98	0.459	33.2	12.6	70.2
LSD (0.05)	0.8	NS	NS	NS	NS	NS
B. Wheat establishment methods						
CTW _{R0}	5.31ab	6.76b	0.44	32.6	12.6	68.9a
ZTW _{R0}	4.81b	6.71b	0.42	29.1	12.4	63.9b
ZTW _{R100}	5.77a	7.08a	0.45	33.8	12.7	70.5a
LSD (0.05)	0.54	0.22	NS	NS	NS	4.9
Interaction (A X B)	NS	NS	NS	NS	NS	NS
LSD- least significant difference; NS, non-significant.						

Table 3
Effect of tillage, green manure and residue management practices on phosphorus content and uptake in wheat
after five years of rice-wheat cropping system

Treatments	P in grain (%)	P in straw (%)	P uptake by grain (Kg ha ⁻¹)	P uptake by straw	Total P uptake	PHI
A. Rice establishment methods						
PTR _{W0}						
PTR _{W25}	0.31	0.027	15.7	1.86	17.5	0.89
PTR _{W0} +GM	0.3	0.033	16	2.28	18.3	0.97
PTR _{W25} +GM	0.28	0.034	16.7	2.39	19	0.87
LSD (0.05)	NS	NS	NS	NS	NS	NS
B. Wheat establishment methods						
CTW _{R0}	0.28	0.03	14.8ab	2.07	16.9b	0.87
ZTW _{R0}	0.29	0.029	13.8b	1.96	15.8b	0.87
ZTW _{R100}	0.3	0.035	17.7a	2.49	20.2a	0.87
LSD (0.05)	NS	NS	3.2	NS	3.1	NS
Interaction (AX B)	NS	NS	NS	NS	NS	NS
LSD- least significant difference; NS, non-significant.						

Table 4
Pearson's correlation coefficients (r) between phosphorus fractions, biological activity and crop yield

Variable	WS-P	NaHCO ₃ -Pi	NaHCO ₃ -Po	NaOH-Pi	NaOH-Po	HCl-P	TP	Av-P	Alk-p	Phy-P	Yield
WS-P	1										
NaHCO ₃ -Pi	0.992**	1									
NaHCO ₃ -Po	0.954**	0.967**	1								
NaOH-Pi	0.868*	0.833*	0.865*	1							
NaOH-Po	0.930**	0.921**	0.959**	0.942**	1						
HCl-P	0.761*	0.752	0.718	0.835*	0.718	1					
TP	0.975**	0.966**	0.972**	0.943**	0.984**	0.793*	1				
Av-P	0.935**	0.944**	0.964**	0.842*	0.970**	0.608	0.957**	1			
Alk-P	0.979**	0.985**	0.932**	0.786*	0.904**	0.668	0.940**	0.950**	1		
Phy-P	0.972**	0.965**	0.909**	0.878**	0.881**	0.865*	0.950**	0.864*	0.929**	1	
Yield	0.972**	0.962**	0.963**	0.934**	0.988**	0.765*	0.997**	0.968**	0.949**	0.937**	1

*,**Significant at 0.05 and 0.01 probability level, respectively.

WS-P- Water soluble phosphorus; NaHCO₃-P_i- Sodium bicarbonate inorganic phosphorus; NaHCO₃-P_o- Sodium bicarbonate organic phosphorus; NaOH-P_i – Sodium hydroxide inorganic phosphorus; NaOH-P_o– Sodium hydroxide organic phosphorus; HCl-P Hydrochloride phosphorusTP -Total Phosphorus; Av-P -Available phosphorus; Alk-P Alkaline phosphatase activity; Phy-P- Phytin-P

3.4 Principal component analysis

Principal component analysis was performed to extract most influential soil parameters from each PC on the basis of eigenvector weight value or loading factors (Table 5). Only the highly weighted variables were retained in the minimum data set (MDS). The PC1 and PC2 explained 88.0% variability in the data set, where PC1 explained 74.68 % and PC2 explains 13.32%. Hence, the bold-face values (NaOH-P_o and NaHCO₃-P_i for PC1, HCl-P for PC2) were considered to be highly weighted eigen vectors and were initially selected in the MDSThe amount of variability explained by PC1 was 74.7%, with eigenvalue of 7.47, which includes NaOH-P_o, with the highest positive factor loading value (0.95), and NaHCO₃-P_i (0.93) (Table 5). The component PC2 explained variance of about 13.3% and eigenvalue of 1.33 with the highest positive loading value for HCl-P with positive factor loading (0.78).Based on the percent variance to total variance, the weight of each PC ranged from 0.15 to 0.85.

Table 5
Loading values and percent contribution of assayed soil variables at surface soil layer on the axis identified by the principal component analysis

Soil variables	PC1		PC2	
	Loading value	Contribution of variables (%)	Loading value	Contribution of variables (%)
WS-P	0.864	9.99	0.425	13.6
NaHCO ₃ -P _i	0.934	11.7	-0.123	1.13
NaHCO ₃ -P _o	0.875	10.2	0.311	7.25
NaOH-P _i	0.911	11.1	-0.308	7.11
NaOH-P _o	0.950	12.1	-0.258	5.02
HCl-P	0.480	3.08	0.784	46.1
TP	0.794	8.44	0.192	2.75
Av-P	0.885	10.5	-0.417	13.0
Alk-P	0.922	11.4	-0.225	3.81
Phytin P	0.926	11.5	0.054	0.22
Eigenvalue		7.47		1.33
Variability (%)		74.7		13.3
Cumulative %		74.7		88.0
weight		0.85		0.15
WS-P- Water soluble phosphorus; NaHCO ₃ -P _i - Sodium bicarbonate inorganic phosphorus; NaHCO ₃ -P _o - Sodium bicarbonate organic phosphorus; NaOH-P _i – Sodium hydroxide inorganic phosphorus; NaOH-P _o – Sodium hydroxide organic phosphorus; HCl-P Hydrochloride phosphorus; TP- Total phosphorus; Av-P- Available phosphorus; Alk-P – Alkaline phosphatase				

Position of different variables and treatments in the orthogonal space were defined by the two PCs (Fig. 8). The first principal component clearly separated < 0.25 mm and > 0.25 mm size aggregates from 1–2 mm and > 2 mm size aggregates. It also clearly separated PTR_{W25}+GM and PTR_{W0}+GM from PTR_{W0} and PTR_{W25} treatment and ZTW_{R100} treatments from ZTW_{R0} and CTW_{R0} treatments in the factorial space. The variables (NaOH-P_o, NaHCO₃-P_i and HCl-P) are related to the large size aggregates (both 2 mm and > 2 mm). These variables are also found to be related to PTR_{W25}+GM, PTR_{W0}+GM and ZTW_{R100} treatments. The results displayed that the contribution of NaOH-P_o toward SQI was highest under PTR_{W25}+GM (0.643) followed by PTR_{W25} (0.508) in rice treatments and CTW_{R0} (0.584) followed by ZTW_{R100} (0.589) in wheat treatments (Fig. 9). For NaHCO₃-P_i the maximum contribution toward SQI was observed under PTR_{W25}+GM (0.710) followed by PTR_{W0} (0.659) in rice treatments and ZTW_{R100} (0.711), followed by CTW_{R0} (0.701) in wheat treatments. The HCl-P contributed maximum to SQI under PTR_{W25}+GM (0.137) in rice treatments and ZTW_{R100} (0.145) followed by CTW_{R0} (0.136) in wheat treatments. The relative order of contribution of the selected indicators to SQI was 37.2% for NaOH-P_o, 48.8% for NaHCO₃-P_i and, and 9.1% for HCl-P (Fig. 10). The radar plot represented the specific contribution of MDSs toward SQI. NaHCO₃-P_i had the highest MSDs (49.3–61.6), HCl-P (6.9–12.8–16.4) had the lowest, whilst NaOH-P_o (25.6–42.7) in-between for residue retention and green manure CA-based RWS (Fig. 11).

Discussion

4.1 Particle size phosphorus fractions in aggregates

Retention of crop residue promotes microbial activity which enhances the aggregates cohesion and hydrophobicity (Wallis and Horne 1992). Hangen et al., (2002) reported the destruction of soil macro-pores in conservation tillage and further reduction in the loss of dissolved P through leaching. In the present study, the comparison of P-fractions among different aggregate size indicated that PTR_{W25}+GM and ZTW_{R100} recorded the highest P-forms under CA-based RWS. Also, the application of green manure and crop residue management practices has resulted in enhanced P content predominantly in aggregate size 1–2 mm relative to other sized aggregates. This may be probably because smaller aggregates possess larger surface area, higher P sorption, and hence less P availability. Whereas, larger soil aggregates have less surface area, reduced P fixation and enhanced P availability (Mitran et al., 2018). As defined by Verma et al., (2005) and Chimdi et al., (2014), the water extractable and NaHCO₃-P (P_i and P_o) are considered as readily desorbable or labile phosphorus pools. This water soluble-P represent the readily available-P. The NaHCO₃-P_i is the most biologically available inorganic P fraction and NaHCO₃-P_o is considered as the easily mineralized P fractions in the form of phospholipids and nucleic acid (Harrison, 1987). In our study, NaOH-P (P_i and P_o) fractions were observed to be higher in treatment PTR_{W25}+GM and ZTW_{R100}. Therefore, rice residue management practices are anticipated to have a positive impact on increasing P availability which contributes towards increased crop yield (Sharma et al 2021). Moreover, the present results indicated the dominance of HCl-P in all the aggregate size classes which is consistent with the results of Castillo and Wright (2008) who also observed the highest percentage of total P (41%) in Ca-bound P fraction (HCl-P) for sugarcane. Our findings also corroborated with the previous results by Ranatunga et al., (2013), who observed that long-term poultry litter application in pasture soil recorded highest level of HCl-P in 1–2 mm macro-aggregate. The NaOH-P and HCl-P are sparingly labile-P and on long-term basis, these forms might play an essential role in the in plant nutrition. The RWS in the current study indicated the dominance of organic phosphorus fractions which may be due to the degradation of organic P and release of inorganic P for plants. The increase in P concentration under ZT is consistent with previous tillage studies by Essington and Howard (2000) who observed significantly higher organic P in ZT than CT. Our results also indicated that the wheat stubble and green manure in rice exhibited increased total and available P concentrations in the macro-aggregate fractions. This might be due to the long-term addition of crop residue to soil, which increased the soil total phosphorus and available phosphorus contents (Ahmed et al., 2019). The ZT and residue retention might have increased the labile P, P_o accumulation and its mineralization by phosphatases. A higher dissolved reactive P concentration in the leachate was reported by Gaynor and Findlay (1995) in ZT than CT. Previous studies have reported that ZT combined with straw retention, protects soil structure and aggregate-association is an effective measure to improved soil structure soil fertility to increased higher yields (Xu et al., 2019; Sharma et al 2019).

4.2 Soil alkaline phosphatase activity

The alterations in the soil biological dynamics could be easily revealed by the variations in enzyme activities (Dick and Kandeler 2005). The mineralization of P_o to available P_i is driven by phosphatases in the soil (Nannipieri et al., 2011). Phosphatase enzymes play key roles in the soil system as good indicator of soil fertility (Dick and Tabatai 1992; Dick et al., 2000). The long-term crop residue management practices caused significant increase in microbial population and microbial biomass C or N in the soil (Gianfreda et al., 2005; Wei et al., 2015), and thus providing energy and a favorable environment for the accumulation of soil enzymes (Jiao et al., 2011). Gupta and Germida (1988) observed that the macro-aggregates had higher phosphatase activity in crop residues retention and ZT than CT in their respective micro-aggregates, which corresponds with the present results. The higher aggregate associated inorganic P in our study may be due to higher microbial proliferation resulting from the retention of crop residues, addition of GM and ultimately enhancing P_o mineralization over time. Similar findings were also mentioned by Margenot et al., (2015), who determined increased alkaline phosphatase activity (41%) under RT than CT. The highest activities of most of the enzymes under rice residue management practices in wheat are in agreement with the earlier findings of Sharma et al., (2019). They observed that higher enzyme activities are associated with macro-aggregates than micro-aggregates due to improvement of organic carbon status of soils under rice residue retention in wheat. Higher phytin-P content in ZTW + R may be due to higher build up of organic matter (Saikia et al., 2019a; Yadav and Tarafdar 2004) that resulted in increased release of P from phytate present in the soil.

4.3 Yield and nutrient uptake

Significantly higher grain yield in treatments $PTR_{W0}+GM$ and $PTR_{W25}+GM$ could be attributed to the addition of green manure which helps to enhance the availability of nutrients. Furthermore, the GM addition provides other essential nutritive substrates along with favorable conditions required for plants growth during the period of grain filling (Diez et al., 2010). Similarly, higher wheat yield was recorded under ZT with residue retention compared with CT. This enhanced yield might be related with the improvement in soil physical properties and water retention especially under ZT with residue retention than CT for nutrient accessibility (Singh et al 2019). The present results were consistent with the findings of Zhang et al., (2013) who reported slight increase in the yields of rape and rice by the NT than CT across three years. Nandan et al., (2018) reported higher grain yield by the crop establishment practices based on ZT than CT in wheat and maize. The highest increase in productivity was recorded in maize (7–10%), followed by wheat (5–11%) and rice (3–8%) by retention of crop residues. The wheat grain yield was significantly higher by 7.3% and 17.5% in ZT with residue retention in comparison with CT and ZT with no residue, respectively. Also, the 11.5% higher productivity was recorded in puddled transplanted rice with wheat stubble with GM followed by ZT with residue retention compared with CT under RWS (Thind et al., 2019). Significant increase in yield and macro-nutrients uptake in wheat and rice by tillage and rice-straw management practices was also reported by Sharma et al., (2019).

4.4 Principal component analysis

The alterations in the soil properties were represented by the PCs with higher eigen values (Zhang et al., 2016; Biswas et al., 2017) and for the interpretation, only PCs with eigen values > 1 were retained (Ana et al., 2008). The data points for ZT are separated clearly from the data points for CT in the PCs defined factorial space (Fig. 8). The most influential variables for PC1 were $NaOH-P_o$, $NaHCO_3-P_i$ and $HCl-P$ for PC2 on the basis of eigen vector weight value (Table 4). Thus, these parameters can be considered as potential indicators of P transformation under tillage, GM and residue management practices in RWS. These transformations act as a base for the decomposition of plants, aggregation in soil, soil tilth and availability of nutrients (Smith et al., 1993). Among the PC1 indicators, $NaOH-P_o$ accumulates more in the form of very stable organic compounds in soil than $NaHCO_3-P_o$ such as inositol phosphates and their phytins (Cosgrove 1976; Condon and Goh 1990). In PC2, $NaHCO_3-P_i$ was found to have significant correlation because $NaHCO_3-P_i$ is the most biologically available inorganic P fraction and $NaHCO_3-P_o$ is considered as the easily mineralized P fractions in the form of phospholipids and nucleic acids (Harrison 1987). In PC3, $HCl-P$ was representative variable to benefit largely as Ca-P and residual-P as P in mineral matrices and very stable humic substances.

The data point pertaining to the above variables are closely positioned to sustainable management practices (i.e. $PTR_{W25}+GM$ and ZTW_{R100}). This might be due to the positive effect of legume crops grown in RWS has been reported to favor the net C build-up, associated aggregation and hydraulic properties (Masri and Ryan 2006). Bera et al., (2017) indicated a clear separation between ZT with crop residues and CT with no residue by PCA in wheat under RWS.

Conclusions

This study concludes that tillage intensity, residue retention and green manure significantly enhance P fractions within aggregates compared with conventional tillage practices. The crop residues addition along with zero tillage preferred the higher amount of $NaOH-P_o$, $NaHCO_3-P_i$ and $HCl-P$ fractions in micro-aggregates than macro-aggregates and may act as dominant fractions in soil ensuring the P availability under RWS in sandy loam soils. The information on P fractions among different aggregates would be beneficial in the modification of current input management practices aimed for higher availability of P to plants along with sustained crop productivity. Therefore, tillage, green manure and residue management should be recommended and popularized for the sustainability of RWS.

Declarations

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Ethical Approval

Not applicable.

Consent to Participate

Not applicable.

Consent to Publish

Not applicable.

Authors Contributions

Sandeep Sharma set and conducts the experiment, Sukhjinder Kaur analysis of the data and provides the material, Sandeep Sharma and OP Choudhary writes this manuscript.

Competing Interests

The authors declare that they have no competing interests.

Availability of data and materials

All data generated or analysed during this study are included in this published article.

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Figures

Figure 1

Sequential fractionation scheme for phosphorus

Figure 2

Effect of tillage, green manure and residue management practices on phosphorus fractions in micro-aggregate (<0.25 mm) and macro-aggregate (>0.25 mm) after five years of rice-wheat cropping system. Vertical bars are the standard errors of the mean ($p < 0.05$). First and second stacked bars indicate micro-aggregate and macro-aggregate, respectively. The values above the vertical bars represent least significant difference test

Figure 3

Effect of tillage, green manure and residue management practices on phosphorus fractions in micro-aggregate (1-2 mm) and macro-aggregate (>2 mm) after five years of rice-wheat cropping system. Vertical bars are the standard errors of the mean ($p < 0.05$). First and second stacked bars indicate 1-2 mm and >2 mm, respectively. The values above the vertical bars represent least significant difference test

Figure 4

Effect of tillage, green manure and residue management practices on total phosphorus within aggregates after five years of rice-wheat cropping system. Vertical bars are the standard errors of the mean ($p < 0.05$). The values above the vertical bars represent least significant difference test.

Figure 5

Effect of tillage, green manure and residue management practices on available phosphorus within aggregates after five years of rice-wheat cropping system. Vertical bars are the standard errors of the mean ($p < 0.05$). The values above the vertical bars represent least significant difference test.

Figure 6

Effect of tillage, green manure and residue management practices on alkaline phosphatase within aggregates after five years of rice-wheat cropping system. Vertical bars are the standard errors of the mean ($p < 0.05$). The values above the vertical bars represent least significant difference test.

Figure 7

Effect of tillage, green manure and residue management practices on phytin-P within aggregates after five years of rice-wheat cropping system. Vertical bars are the standard errors of the mean ($p < 0.05$). The values above the vertical bars represent least significant difference test.

Figure 8

PTRWS₀-puddled transplanted rice with no wheat straw, PTRWS₂₅-puddled transplanted rice with 25% anchored wheat straw retained, GM-Green manure, CT-R-conventional tillage wheat with rice straw removed, ZT-R-zero tillage wheat with rice straw removed, ZT+R-ZTW with 100% rice straw retained as surface mulch, WS-P Water soluble phosphorus, TP Total phosphorus, Av-P Available phosphorus, Alk-P Alkaline phosphatase

Figure 9

Average effect of rice and wheat treatments on soil quality index and the individual contribution of each of the key indicators. Note- PTRW₀-puddled transplanted rice with no wheat straw, PTRW₂₅-puddled transplanted rice with 25% anchored wheat straw

retained, GM-Green manure, CTWR0-conventional tillage wheat with rice straw removed, ZTWR0-zero tillage wheat with rice straw removed, ZTWR100-ZTW with 100% rice straw retained as surface mulch; Po- Organic phosphorus, Pi- inorganic phosphorus

NaOH-PO NaHCO3-Pi HCL-P

Figure 10

Overall contribution of the selected soil quality indicators to soil quality index

Figure 11

Contribution (%) of selected indicators to soil quality under rice and wheat treatments PTRWS0-puddled transplanted rice with no wheat straw, PTRW25-puddled transplanted rice with 25% anchored wheat straw retained, GM-Green manure, CTWR0-conventional tillage wheat with rice straw removed, ZTWR0-zero tillage wheat with rice straw removed, ZTWR100-ZTW with 100% rice straw retained as surface mulch; FC-Field capacity