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Research article

Double zero-tilled bed-planting and optimized P-fertilization in maize-wheat rotation: An empirical investigation on root architecture, carbon-phosphorus dynamics, and soil carbon pools

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ABSTRACT

Degradation of natural resources impairs environmental quality and sustainability of agricultural production systems. Conservation agriculture (CA) is a promising approach to ensure food security and agricultural sustainability. Likewise, plant nutrition especially phosphorus (P) optimization is highly essential for improved root architecture, cost-effectiveness and eco-friendliness under CA-management. Hence, current study assessed the influence of double zero-tilled bed-planting and optimized P-fertilization strategy on root architecture, carbon-phosphorus dynamics, and carbon management index in maize-wheat rotation (MWR) in south-Asian semi-arid agro-ecology. Results explained that CA based double zero-tilled permanent bed-planting (PRBZT) system harnessed higher root attributes over conventionally-tilled flat bed-planting (FBCT) system in MWR. Macro-aggregates, total water-stable aggregates, mean weight diameter and soil organic carbon under PRBZT system were 48.6, 11.5, 25 and 11.6 % higher over FBCT, respectively. PRBZT had ~13.2–15.6 % enhanced soil phosphorus solubilizing bacteria, dehydrogenase enzyme activity, alkaline phosphatase activity, acid phosphatase activity and soil microbial biomass carbon over FBCT. In contrast, lability of soil organic carbon, pH, soil bulk density and micro-aggregates were found higher under FBCT. PRBZT plots had significantly higher soil carbon pools, carbon pool index, carbon management index, water-use efficiency over FBCT, partially addressing *SDG-6* with *enhanced water-use efficiency*. The P-fertilization with P_{50}+PSB + AMF+2FSP had 12.3, 57.2, 4.3 and 70.2 % higher available-NPK and phosphorus solubilizing bacteria over P_0, respectively. The actual positive P-budgeting was revealed under CA, hence, addressing *SDG-12*. This study highlights that crop residue-retention @ 6 t ha^{-1}year^{-1} under double zero-tilled permanent bed-planting (PRBZT) system combined with optimized phosphate fertilizer management is an effective agro-technology with fertilizer-P savings of ~34.7 % and a

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positive phosphorus budget in MWR. This may ensure optimal nutrient P-availability, minimal P-loss, and stabilized soil P-fractions vis-à-vis significant positive influence on soil carbon fractions and carbon management index in MWR in resource-constrained semi-arid south-Asia. Overall, PRBZT system combined with optimized phosphate fertilizer management may be recommended for enhancing productivity, root architecture, resource-use efficiency, and soil carbon pools in south-Asian Indo-Gangetic Plain Region, which directly support several SDGs; *SDG-2* (Zero-hunger), *SDG-13* (Climate action) and *SDG-15* (Life on land) thereby advancing ecosystem-resilience and productivity in the ensuing South-Asian climate crisis.

List of acronyms

Abbreviations	Full form
ACP	Active carbon pool
AMF	Arbuscular mycorrhizal fungi
CA	Conservation agriculture
CMI	Carbon management index
CPI	Carbon pool index
CT	Conventional tillage
FBCT	Flat bed conventional tillage
FBZT	Flat bed zero tillage
LC	Labile carbon
LLC	Less labile carbon
MWR	Maize–wheat rotation
NLC	Non labile carbon
PCP	Passive carbon pool
PFP_P	Partial factor productivity of applied phosphorus
PSB	Phosphorus solubilizing bacteria
PRBZT	Permanent raised bed zero tillage
RBCT	Raised bed conventional tillage
SBD	Soil Bulk Density
SEWP	System economic water productivity
SIWP	System irrigation water productivity
SOC	Soil organic carbon
SOM	Soil organic matter
SWUE	System water-use-efficiency
VLC	Very labile carbon

1. Introduction

In recent years, the intensified drive to boost food production has led to various challenges, notably the reduction of organic matter in soil, which compromises soil health, decreases resource efficiency, accelerates nutrient depletion, as well as degrades natural resource base (Singh et al., 2011; Choudhary et al., 2018; Varatharajan et al., 2019a) particularly in areas where tillage practices are coupled with crop residue burning (Jayaraman et al., 2021) leading to environmental concerns lining with SDG 13 (Climate Action) and SDG 15 (Life on Land). Intensive tillage drastically alters the natural soil structure, breaks down soil aggregates, paces SOC loss and blends crop residues with soil, leaves the surface bare and highly vulnerable to erosion (Maity et al., 2021). This leads to steady decline in yields of crop and soil productivity, negatively affecting soil health and the economic viability of agricultural systems, posing obstacles to SDG 2 which focuses on sustainable food production systems.

As a result, a viable substitute for maintaining the agricultural production system and soil health is conservation agriculture [CA] (Jayaraman et al., 2021). Conservation tillage, a core practice of CA, is increasingly seen as a sustainable alternative to conventional tillage due to its ability to reduce soil erosion and nutrient loss, improve soil carbon balance, and boost crop productivity at lower production costs (Margenot et al., 2017). By promoting these practices, CA aligns with **SDG 12 and SDG 15**.

Under CA, the optimum use of inorganic fertilizers shows a great promise for maintaining long-term crop production, preserving soil health, and improving farm profitability (Bana et al., 2022; Ankit et al., 2022) addressing both **SDG 1** and **SDG 8** through increased profitability and improved livelihoods. Instead of relying on traditional methods, CA has proven to be an effective approach for achieving long-term output gains in many cropping systems (Rajanna et al., 2023). This approach is also highly effective in safeguarding natural resources including energy, water, soil, and overall quality of the environment (Jat et al., 2018; Biswakarma et al., 2023), advancing progress toward **SDG 6** and **SDG 7 by** integrating CA into agricultural systems, toward more sustainable and resilient food systems that support both human and planetary health.

The predominant cropping system in South Asia's Indo-Gangetic Plain Region is the Rice-Wheat Cropping System, which spans 13.5 million hectares and feeds about 20 % of the population of world (Ladha et al., 2015). Yet, challenges like burning of residues in the field, particularly rice residue, contribute to emission of greenhouse gases thereby reduces carbon sequestration in this region (Singh et al., 2020a). These issues directly affect **SDG 13 and SDG 15** by exacerbating climate change.

So, diversifying rice cultivation during the *kharif* season with alternative crop like maize offers a promising strategy to address declining farm productivity and profitability (Layek et al., 2018). Maize crop holds a significant importance due to its diverse applications, providing essential resources for food, fodder, animal feed, and as an input material for a variety of products. Hence maize-wheat cropping system (MWRMWR) stands out as a promising option meant for crop diversification, offering lower water requirements, increased wheat productivity through timely planting, and better soil health compared to the Rice-Wheat Cropping System (Dhanda et al., 2022). This shift aligns with **SDG 2** by improving food security, **SDG 6** through reduced water use, and **SDG 12** by promoting sustainable agricultural practices. By adopting MWRMWR, farmers can contribute to a more sustainable and productive agricultural system that addresses environmental challenges while ensuring economic viability. This crop diversification strategy fosters resilience in the face of climate change, enhances soil quality, and supports long-term agricultural sustainability, towards more resilient food system by directly contributing to multiple SDGs.

Phosphorus (P) is an indispensable macronutrient, next to nitrogen, and has a crucial function in many plant functions, together with gene transfer, photosynthesis, respiration, reproduction, root development, flowering, formation of seed, and yield (Pattanayak et al., 2009). P frequently acts as a growth-limiting factor for plants because of its poor solubility and reactivity in soil (Aulakh et al., 2007). Additionally, the elevated cost of P fertilizers poses a significant barrier for resource-limited farmers in applying the recommended P doses (Choudhary et al., 2008) thereby affecting **SDG 1** and **2** by limiting crop yields and food security. As a result, there is a demand for new efficient P management practices to enhance P-use efficiency in high-demand cropping systems such as the MWR, which requires greater P inputs. Improving P management not only ensures better crop growth and yield but also contributes to SDG 12. Enhanced P-use efficiency can reduce the reliance on expensive inputs, improving farm profitability and aligning with SDG 8 and SDG 15.

Research has shown that foliar application of P as a KH_2PO_4 solution in wheat can lead to superior plant height, P uptake, and biomass as compared to sole application to soil, demonstrating the effectiveness of foliar P absorption (Rafiullah et al., 2018). Implementing foliar P fertilization within MWR could be a novel approach for ensuring sustainable food and nutritional security under current socio-economic conditions, particularly within the framework of CA. Furthermore, the integration of beneficial microbes is a growing area of research, aiming to develop microbe-based solutions that positively impact crops, soil health, and the broader ecosystem (Gupta et al., 2020). Crop residues placed over soil boost soil health by raising the amount of organic carbon in the soil, which can increase the soil's capacity to absorb P (Corbeels et al., 2020).

As noted by Kumawat et al. (2018), using phosphate solubilizing bacteria (PSB) and arbuscular mycorrhizal fungi (AMF) in combination with crop-residue retention can lessen the need of P fertilizer while simultaneously boosting crop yields, improving soil P bioavailability, and enhancing P-use efficiency (PUE). These inoculations are essential for preserving soil fertility, supporting the health of soil microbes, and boosting crop output.

Given this background, a trial was carried out to test the hypothesis that CA based tillage practices combined with optimized phosphate fertiliser management could lead to higher sustainable crop productivity, improved resource-use efficiency, and changes in the carbon pool and soil P fractions in the Indo-Gangetic Plain Region of India. The study intended to (i) evaluate and quantify the effects of tillage and P fertilization on productivity, nutrient acquisition, PUE, and P fractions in soil, and (ii) assess the status of SOC, its various fractions, indices, as well as P budgeting in MWR on semi-arid IGP region.

2. Methodology

2.1. Experimental Details and weather conditions

A field study was conducted at the ICAR–IARI farm in New Delhi over two consecutive years, 2018–19 and 2019–20, in MWR. The research plot be situated in the semi-arid subtropical climatic condition [Altitude 228.6 m; Latitude 28°63′N and Longitude 77°15′E] (Supplementary Fig. 1), defined by cold winters and hot, dry summer. Throughout the study period, key meteorological data were recorded monthly, as shown in Supplementary Fig. 2. The mean annual rainfall in the experimental area was ~650 mm, with about 80 % taking place in the 'South-West Monsoon' and the remaining 20 % during 'Western Disturbances' from December to February. The highest average temperatures, ranging between 40 and 46 °C, were observed in May and June, whereas the chilling months were December and January, with mean lowest temperatures between 2 and 6.2 °C. The usual annual evaporation was recorded at around 850 mm. To assess initial properties of the soil (Supplementary Table 1), randomly samples of soil were taken at a depth of 0–15 cm. The top soil was identified as sandy-loam textured alluvium-derived Typic Ustocrept with a neutral to slightly alkaline pH.

2.2. Experimental information

Twenty distinct treatment combinations were used in the trial involving four different crop establishment and tillage management techniques under main-plot. The crop establishment and tillage management practices are: M1- Conventional Tillage under Flat Bed (FBCT), Raised Bed CT for maize and ZT for wheat (RB-CT/ZT), Zero Tillage under Flat Bed (FBZT), and Zero Tillage under Permanent Raised Bed (PRBZT) (Fig. 1). Combined with five distinct phosphorus fertilization techniques under sub-plots: P_{100} (100 % recommended P), P_{50}+2FSP (50 % phosphorus applied as basal plus two sprays of P as 2 % di-ammonium phosphate at knee-high stage, also at pre-tasseling stage for maize, and at tillering stage, also at pre-flowering stage for wheat), P_{50}+PSB + AMF, P_{50}+PSB + AMF+2FSP, and P_0 (no phosphorus) [Supplementary Table 2]. The recommended nitrogen and potassium was applied in all the treatments. The experimentation was replicated thrice in a split plot design with each gross plot was 5.0 × 4.2 m. Crop residues amounting to 3 t ha^{-1}, were retained in all zero-tillage plots, after sowing. This practice helped in conserving soil moisture and suppressing weed growth.

2.3. Crop management

The hybrid maize 'PMH-1′ and variety 'HD-2967′ of wheat were cultivated in the *monsoon* and *winter* seasons of 2018-19 and 2019-20, respectively. Potassium was applied at the recommended rates, and phosphorus was applied according to the specific treatment during sowing. Nitrogen was administered equally in splits of three for maize: at sowing, at knee-high stage, and at pre-tasseling stage. For wheat, half the nitrogen was provided at sowing, remaining nitrogen was given in equal parts at maximum tillering stage and pre-flowering stage. A solution containing 2 % di-ammonium phosphate was used for foliar P fertilization, sprayed at a rate of 750 L water per ha. In zero-tillage plots,

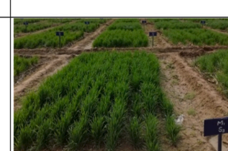
Crop establishment and tillage management practices	Maize (July-November)		Wheat (November-April)	
FBCT		(Flat bed–conventional tillage and no residue)		(Flat bed–conventional tillage and no residue)
RBCT/ZT		(Raised bed–conventional tillage and no residue)		(Raised bed–zero tillage and residue 3 t ha^{-1})
FBZT		(Flat bed–zero tillage and residue @ 3 t ha^{-1})		(Flat bed–zero tillage and residue @ 3 t ha^{-1})
PRBZT		(Permanent raised bed–zero tillage and residue @ 3 t ha^{-1})		(Permanent raised bed–zero tillage and residue @ 3 t ha^{-1})

Fig. 1. Spatial configuration of Crop establishment and tillage management practices under MWCS.

glyphosate (41 % SL) at 1.0 kg active ingredient per hectare was sprayed using 750 L water per hectare immediately after harvesting the preceding crop and one week before sowing. Both maize and wheat were cultivated following standard agronomic practices, except where specific treatments required adjustments.

2.4. Root studies

The root architecture was analyzed by scanning the root samples under RHIZO instrument (Win-RHIZO, Regent Instruments Inc.) for image analysis. Diverse root parameters, including average root diameter, surface area of root, root length density, volume of root, root length, root: shoot ratio, root dry weight, root contribution in total plant dry weight and specific root length were obtained using the RHIZO device. The samples of root were taken from both crops at the flowering stage. A soil volume of 30 cm^3 was excavated with plant as center, and the roots were extracted following the standard procedure. Roots were washed in still water having sodium hexametaphosphate to take away adhered soil, as described by Aggarwal and Sharma (2002); Rana et al. (2014). After washing, the roots were separated followed by air-drying before measurements were taken. Sun-dried roots were oven dried for 48 h at 60–65 °C, furthermore the dry weight were determined using an electronic digital scale.

2.5. Phosphorus-use efficiency

2.5.1. Partial factor productivity

For estimation of partial factor productivity of applied-P (PFPp), the yield (grain) from various treatments was divided by total P applied through various means, using following equation (1) (Rana et al., 2014):

$$PFP_p\ (\text{kg ha}^{-1}) = \frac{\text{Grain yield}\ (\text{kg ha}^{-1})}{\text{Total applied} - \text{P}\ (\text{kg ha}^{-1})} \tag{1}$$

2.5.2. P induced nitrogen recovery efficiency the phosphorus induced nitrogen recovery efficiency (PiNRE) was computed (Prasad and Shivay, 2015) according to equation (2)

$$\text{PiNRE} = \frac{\text{Uptake of N}\ (\text{kg ha}^{-1})\ \text{in P treatment} - \text{Uptake of N}\ (\text{kg ha}^{-1})\ \text{in conrol}}{\text{N applied N}\ (\text{kg ha}^{-1})} \tag{2}$$

2.5.3. P induced potassium recovery efficiency

The phosphorus induced potassium recovery efficiency (PiKRE) was computed (Prasad and Shivay, 2015) by using equation (3):

$$\text{PiKRE} = \frac{\text{Uptake of K}\ (\text{kg ha}^{-1})\ \text{in P treatment} - \text{Uptake of K}\ (\text{kg ha}^{-1})\ \text{in conrol}}{\text{K applied}\ (\text{kg ha}^{-1})} \tag{3}$$

2.6. Water-use and its efficiency

2.6.1. Total water-use efficiency

In maize and wheat, the total water-use efficiency was calculated by means of following equation (4) (Rana et al., 2014):

$$\text{TWUE}\ (\text{kg ha}^{-1}\ \text{mm}^{-1}) = \frac{\text{Y}}{\text{TWU}} \tag{4}$$

Where, Y - Grain yield (kg ha^{-1}), and TWU - total amount of seasonal water used in ha–mm.

2.6.2. Irrigation water productivity

In maize and wheat, the irrigation water productivity was calculated by means of following equation (5) (Rana et al., 2014):

$$\text{Irrigation water productivity}\ (\text{kg m}^3) = \frac{\text{Grain yield}\ (\text{kg ha}^{-1})}{\text{Irrigation water applied}\ (\text{m}^3)} \tag{5}$$

2.6.3. Economic water productivity

The economic water productivity in maize and wheat was computed as given in equation (6) (Igbadun et al., 2006):

$$\text{WP}_\text{E}\ (\text{INR ha}^{-1}\ \text{mm}^{-1}) = \frac{P \times \text{Y}}{\text{TWU*}} \tag{6}$$

Where,

WP_E - economic water productivity (INR ha^{-1} mm^{-1}); P - market price of grains (INR q^{-1}), and Y - grain yield (kg ha^{-1}).

2.7. Soil sampling and analysis

Soil samples were taken from the plough layer (0–15 cm) of each plot by means of a screw auger after the experiment concluded. A composite soil sample was created by combining three samples that were obtained from various locations within each plot. The soil samples were air-dried at room temperature and passed through a 2-mm sieve after removing visible roots and crop residues. The collected samples were analyzed for physico-chemical and biological properties; including SOC pools, as well as soil available N, P and K. The P concentration in soil was analyzed using the phosphorus fractionation method initially developed by Chang and Jackson (1957) and soon after refined by Kuo (1996). The P-fractions in the soil were assessed using the extract as shown in Supplementary Fig. 3.

2.8. Carbon fractions

To determine the various fractions of SOC, a modified method of Walkley and Black (1934) as adapted by Chan et al. (2001) was utilized. This method involves subjecting the soil sample to progressively stronger oxidizing situation using H_2SO_4 concentrations of 12 N, 18 N, and 24 N with three different ratios of H_2SO_4 to aqueous solution i.e., 0.5:1, 1:1, and 2:1, equivalent to H_2SO_4, respectively. The oxidizing power of each H_2SO_4 solution was varied by adjusting the amount of H_2SO_4 used i.e, 5 ml, 10 ml, and 20 ml for the respective ratios. The carbon oxidized by 24 N H_2SO_4 solutions is corresponding to the oxidizable carbon determined by the regular Walkley and Black (1934) means. Based on the quantity of carbon oxidized under these varying conditions, the total SOC can be separated into four distinct organic carbon pools:

Very Labile (VL): SOC oxidizable under 12 N H_2SO_4.

Labile (L): Calculated as the variation in SOC oxidizable by 18 N and 12 N H_2SO_4.

Less Labile (LL): The variation in SOC oxidizable by 24 N and 18 N H_2SO_4.

Non-Labile (NL): The remaining SOC after oxidation with 24 N H_2SO_4, representing the non-labile fraction compared to total organic carbon.

Active and Passive Carbon Pool is calculated using the following equations (7) and (8):

$$\text{Active Carbon Pool} = \text{VL SOC} + \text{L SOC} \tag{7}$$

$$\text{Passive Carbon Pool} = \text{LL SOC} + \text{NL SOC} \tag{8}$$

2.9. Carbon indices

In this experiment, the Carbon Pool Management Index (CPMI) was utilized to review and track variations in soil carbon dynamics across different treatments. The lability of SOC of a given soil is calculated from the carbon fractions. The SOC's lability index (LI) was found from the ration of lability of SOC of treatment soil to lability of SOC of soil before the start of experiment (Blair et al., 1995) according to equations 9 and 10.

$$\text{Lability of SOC} = \frac{(\text{SOC}_{\text{VLC}} + \text{SOC}_{\text{LC}} + \text{SOC}_{\text{LL}})}{\text{SOC}_{\text{NL}}} \tag{9}$$

$$\text{LI} = \frac{\text{Lability of SOC in Sample SOC}}{\text{Lability of SOC in Reference SOC}} \tag{10}$$

Carbon Pool Index (CPI): Determined by means of equation (11) (Blair et al., 1995).

$$\text{CPI} = \frac{\text{Sample SOC}}{\text{Reference SOC}} \tag{11}$$

Carbon Management Index (CMI): Determined by the method described by Blair et al. (1995), using the unamended soil (control) as the reference sample. Computed from the equation

$$\text{CMI} = \text{CPI} \times \text{LI} \times 100 \tag{12}$$

2.10. Phosphorus budgeting

P budgeting for soil was determined by subtracting P outputs from P inputs. The rate as well as P content of the applied fertilizer was used to compute the P inputs. The P outputs were computed using yield along with grain/straw P concentrations, which were ascertained chemically (on a composite basis) for each growing season.

2.11. Statistical analysis

SPSS software (Version 22.0) was used for carrying out statistical analysis. The data underwent analysis of variance to find out statistical significance. To compare the treatment mean differences amongst crop establishment and tillage management and P-fertilization practices, the Least Significant Difference (LSD) was calculated at a 5 % probability level using the specified formula.

$$\text{LSD} = S.Ed. \times t \textit{ value at error degree of freedom}$$

Multivariate analysis was performed to have a deeper comprehension of the connection between various root parameters and grain-P uptake by using JMP® software from SAS. There were significant correlations ($p < 0.05$ and $p < 0.01$) found using the Pearson's correlation matrix between P fractions of soil.

The ard-algorithmic cluster analysis approach was used to create a heatmap, and squared Euclidean distance was used to differentiate between dissimilar clusters. This approach was used to cluster, related crop establishment and tillage management and P managed plots, as well as P fractions of the soil. In a two-dimensional heatmap, cells within a data matrix are represented by colored frames, with their color reflecting their position on a scale. The color intensity corresponds to the cell's location within the matrix. Analysis of hierarchical clusters for both columns and rows was performed to examine their organization. The dendrogram, as part of the heatmap, illustrates the results of Ward's clustering hierarchy [Strauss and Maltitz, 2017; Gupta et al., 2022].

A biplot is a statistical tool used to visually represent multivariate datasets, allowing for the identification of relationships within the variable's variance-covariance structure. It helps in interpreting the Euclidean distance among observations in a space with multiple dimensions and the annotation values across variables [Alkan et al., 2015].

In Matlab R2019b v 9.7 (MathWorks Inc., USA), the biplot method was utilized to perform Principal Component Analysis (PCA) to explore the effects of crop establishment and tillage management and P fertilization practices on soil parameters in the MWR. A multivariate analysis tool called principle component analysis examines data using a group of related, quantifiable dependent variables in order to extract significant data, represent it as a new set of multivariate variables called principal components (PCs), and show the correlations between variables and observations (Singh et al., 2023). The variables with substantial factor loadings and principal components that had substantial eigen values were thought to be the most indicative of the features of the system. Thus, only PCs with eigen values ≥ 1 (Kaiser, 1960) were considered. PCA results were interpreted using loadings and component scores, also referred to as factor scores (Wold et al., 1987).

3. Results

3.1. Root studies at flowering stage

Under CA-based MWR, both crop establishment and tillage management and P-management practices has considerably ($p < 0.05$) influenced both maize and wheat root architecture at peak blossoming stage (Table 1 & Supplementary Table 3). All root indicators were appreciably influenced by crop establishment and tillage management for maize and wheat, but had no notable outcome on root length density and specific root length in maize and wheat. Parameter labeled, root length exhibited significant effect in maize but not in wheat. Treatment named PRBZT exhibited superior root surface area (1151.1; 261.6 cm^2), average root diameter (0.96; 0.45 mm), root volume (24.61; 12.01 cm^3), root length (4753.6; 1269 cm), root length density (158.45; 42.30 cm cm^{-3}) and root dry weight (25.63; 5.08 g) in maize as well as wheat, correspondingly. Treatments namely RBCT/ZT and PRBZT had highest specific root length in maize as well as wheat, in that order. By and large, the root architectural parameters across both years followed the trend of PRBZT > RBCT/ZT ≥ FBZT > FBCT, correspondingly.

Amongst P management techniques, P_{50}+PSB + AMF+2FSP had differed significantly with higher root surface area (1213.3; 265.26 cm^2), average root diameter (1.00; 0.462 mm), root volume (27.69; 13.11 cm^3), root length (4904.3; 1317.7 cm), root length density (163.48; 43.92 cm cm^{-3}), root dry weight (26.26; 5.44 g), shoot dry weight (82.63; 34.01 g), in line the substitute treatment P_{50}+PSB + AMF

Table 1
Influence of crop establishment methods and P-fertilization practices on root parameters of maize and wheat at flowering stage under MWR (2 years pooled data).

Treatments	Maize					Wheat				
	Root surface area (cm^2)	Average root diameter (mm)	Root volume (cm^3)	Root length (cm)	Root dry weight (g)	Root surface area (cm^2)	Average root diameter (mm)	Root volume (cm^3)	Root length (cm)	Root dry weight (g)
Crop establishment methods										
FBCT	925.7^{b}	0.86^{a}	18.58^{c}	4074.0^{b}	22.41^{d}	233.6^{b}	0.403^{d}	8.37^{c}	978.1^{a}	4.42^{d}
RBCT/ZT	1090.1^{a}	0.94^{a}	24.42^{a}	4679.7^{ab}	23.95^{bc}	246.2^{ab}	0.413^{c}	10.09^{b}	1178.8^{a}	5.00^{c}
FBZT	1080.3^{a}	0.88^{a}	19.85^{b}	4349.8^{ab}	23.74^{c}	253.4^{a}	0.446^{b}	11.57^{ab}	1163.4^{a}	5.03^{bc}
PRBZT	**1151.1^{a}**	**0.96^{a}**	**24.61^{a}**	**4753.6^{a}**	**25.63^{a}**	**261.6^{a}**	**0.451^{a}**	**12.01^{a}**	**1269.0^{a}**	**5.08^{a}**
Phosphorus fertilization practices										
P_{100}	1096.9^{b}	0.96^{a}	23.17^{c}	4548.3^{bc}	24.68^{c}	255.3^{bc}	0.431^{c}	10.59^{c}	1162.4^{abc}	4.80^{bc}
P_{50}+2FSP	1004.1^{c}	0.87^{bc}	18.85^{d}	4437.9^{c}	23.33^{d}	244.0^{c}	0.418^{d}	9.40^{d}	1071.0^{bc}	4.73^{c}
P_{50}+PSB + AMF	1189.5^{a}	0.99^{a}	25.46^{b}	4747.2^{ab}	24.70^{bc}	259.7^{abc}	0.438^{b}	11.54^{b}	1194.6^{ab}	5.24^{ab}
P_{50}+PSB + AMF+2FSP	**1213.3^{a}**	**1.00^{a}**	**27.69^{a}**	**4904.3^{a}**	**26.26^{a}**	**265.3^{a}**	**0.462^{a}**	**13.11^{a}**	**1317.7^{a}**	**5.44^{a}**
P_0	805.3^{d}	0.73^{c}	14.16^{e}	3683.7^{d}	20.70^{e}	219.1^{d}	0.393^{e}	7.91^{e}	990.9^{c}	4.20^{d}
Interaction	NS	S	S	NS	NS	NS	S	NS	NS	NS

[**Note:** FBCT: Flat bed–conventional tillage (FBCT) both in maize & wheat; RBCT/ZT: Raised bed–CT (RBCT) in maize & RB–zero tillage (RBZT) in wheat; FBZT: FBZT both in maize & wheat; PRBZT: Permanent raised bed–ZT (PRBZT) both in maize & wheat. P_{100}: 100 % P as basal; P_{50} + 2FSP: 50 % P as basal (P_{50}) + 2 foliar sprays of phosphorus (2FSP) as DAP (2 %) at knee-high stage (KHS) and pre-tasseling stage (PTS); P_{50} + PSB + AMF: P_{50} + PSB + AM-fungi (AMF); P_{50} + PSB + AMF + 2 FSP: P_{50} + PSB + AMF + 2FSP at KHS & PTS; P_0: 100 % N & K with no P (P_0) as control].

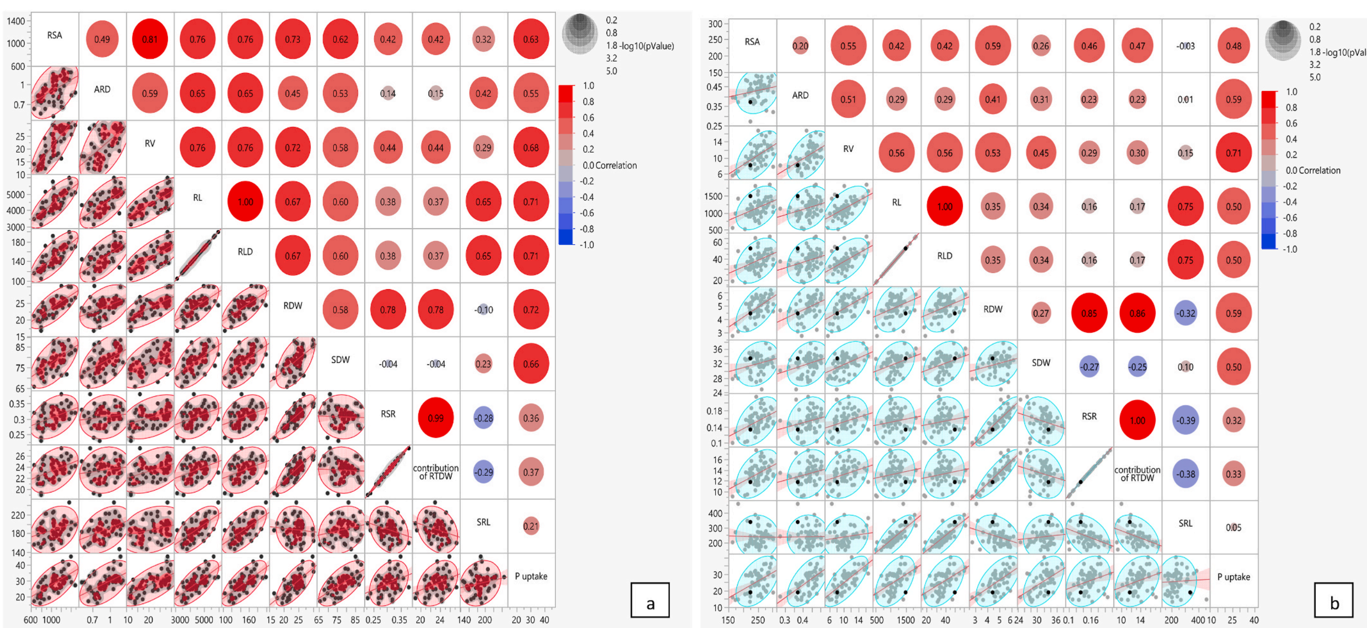


Fig. 2. Multivariate analysis showing correlation between root parameters under different crop establishment methods and phosphorus fertilization practices in maize (a) and in wheat (b) at flowering stage under MWCS (2 years pooled data). The upper triangle with circle displays the heat maps having significant correlation coefficient (p = 0.05), while lower triangle displays the scatter plot matrix with line fit.

exhibited higher root: shoot ratio (0.32; 0.164) and root contribution in total plant dry weight (24.07; 14.03 %) in maize and wheat, accordingly. The P fertilization techniques notably affected all the root parameters except for root: shoot ratio in wheat. In the present study, P_{50}+PSB + AMF+2FSP > P_{50}+PSB + AMF > P_{100}>P_{50}+2FSP > P_0 trend was observed for root architectural parameters under P management practices.

Interaction outcome between crop establishment and tillage management and P management techniques was found to have a substantial effect for average root diameter and shoot dry weight throughout the experimentation.

To obtain a comprehensive understanding of the relationship between root characteristics and grain-P absorption of CA-based MWR, multivariate analysis was performed (Fig. 2). It was noted that, all the root parameters showed affirmative association with grain-P uptake for maize as well as wheat crop. Barring root: shoot ratio, root contribution in total plant dry weight and specific root length, all seven metrics exhibited highly positive connection with grain-P uptake. Furthermore, grain-P uptake showed strong positive correlation with root surface area (r = 0.63; 0.48), average root diameter (r = 0.55; 0.59), root volume (r = 0.68; 0.71), root length (r = 0.71; 0.50), root length density (r = 0.71; 0.50), root dry weight (r = 0.72; 0.59), and shoot dry weight (r = 0.66; 0.50) for maize and wheat, respectively. A negative correlation was observed for specific root length with root dry weight (r = −0.10; −0.32), root: shoot ratio (r = −0.28; −0.39) and root contribution in total plant dry weight (r = −0.29; −0.39) and between shoot dry weight and root contribution in total plant dry weight (r = −0.04; −0.25) for maize and wheat, respectively (Fig. 2).

Table 2
Influence of Crop establishment methods and P-fertilization practices on partial factor productivity of applied phosphorus, P induced nitrogen recovery efficiency and P induced potassium recovery efficiency, system water-use-efficiency, system economic water productivity and system irrigation water productivity under MWR (2 years pooled data).

Treatments	PFP_P (kg ha^{-1} kg^{-1} of applied P)	PiNRE (%)	PiKRE (%)	SWUE (kg ha^{-1} mm^{-1})	SEWP (INR ha^{-1} mm^{-1})	SIWP (kg m^{-3})
Crop establishment methods						
FBCT	105.38^{d}	64.44^{d}	21.30^{d}	9.76^{d}	134.69^{c}	2.86^{d}
RBCT/ZT	113.90^{c}	72.67^{c}	24.11^{c}	10.47^{c}	146.64^{ab}	3.06^{c}
FBZT	116.10^{bc}	74.75^{b}	24.89^{bc}	10.57^{bc}	140.24^{bc}	3.09^{bc}
PRBZT	**119.75^{a}**	**78.57^{a}**	**26.36^{a}**	**11.15^{a}**	**151.33^{a}**	**3.26^{a}**
Phosphorus fertilization practices						
P_{100}	88.85^{d}	84.02^{d}	27.49^{d}	10.20^{d}	134.78^{d}	2.98^{d}
P_{50}+2FSP	140.52^{c}	89.49^{c}	28.47^{c}	10.60^{c}	147.18^{c}	3.10^{c}
P_{50}+PSB + AMF	188.76^{a}	90.86^{b}	29.50^{b}	10.89^{b}	149.12^{b}	3.19^{b}
P_{50}+PSB + AMF+2FSP	150.78^{b}	**98.67^{a}**	**35.35^{a}**	**11.38^{a}**	**160.74^{a}**	**3.33^{a}**
P_0	–	–	–	9.37^{e}	124.29^{e}	2.74^{e}
Interaction	S	S	S	S	S	S

[**Note:** FBCT: Flat bed–conventional tillage (FBCT) both in maize & wheat; RBCT/ZT: Raised bed–CT (RBCT) in maize & RB–zero tillage (RBZT) in wheat; FBZT: FBZT both in maize & wheat; PRBZT: Permanent raised bed–ZT (PRBZT) both in maize & wheat. P_{100}: 100 % P as basal; P_{50} + 2FSP: 50 % P as basal (P_{50}) + 2 foliar sprays of phosphorus (2FSP) as DAP (2 %) at knee-high stage (KHS) and pre-tasseling stage (PTS); P_{50} + PSB + AMF: P_{50} + PSB + AM-fungi (AMF); P_{50} + PSB + AMF + 2 FSP: P_{50} + PSB + AMF + 2FSP at KHS & PTS; P_0: 100 % N & K with no P (P_0) as control]. PFP_P: Partial factor productivity of applied phosphorus, PiNRE: P induced nitrogen recovery efficiency and PiKRE: P induced potassium recovery efficiency, SWUE: system water-use-efficiency, SEWP: system economic water productivity and SIWP: system irrigation water productivity.

3.2. Phosphorus-use efficiency

3.2.1. partial factor productivity

A critical assessment of the data embodied in Table 2, found that the crop establishment and tillage management practices had significant influence on PFP_P in MWR. Amongst various crop establishment and tillage management practices, maximum PFP_P was observed under PRBZT–PRBZT (119.75 kg ha^{-1} kg^{-1} of applied-P) and lowest under FBCT–FBCT (105.38 kg ha^{-1} kg^{-1} of P). The PFP_P ranged between 105.4 and 119.8 kg $ha^{-1}kg^{-1}$ of applied-P following the order of PRBZT > FBZT > RB-CT/ZT > FBCT. Amongst P management practices, P_{50}+PSB + AMF showed significantly highest PFP_P (188.76 kg $ha^{-1}kg^{-1}$ of applied-P) subsequently to P_{50}+PSB + AMF+2FSP with lowest magnitude under P_{100} (88.85 kg $ha^{-1}kg^{-1}$ of applied-P). During the experimentation, it was shown that the interaction among crop establishment and tillage management and P fertilization methods for PFP_P be establish noteworthy.

3.2.2. P-induced nitrogen recovery efficiency and P-induced potassium recovery efficiency

The P-induced nitrogen and potassium recovery efficiencies for different crop establishment and tillage management and P-fertilization techniques differed appreciably ($p < 0.05$) under MWR as specified in Table 2. The P-induced nitrogen and potassium recovery efficiency ranged between 64.44-78.57 and 21.30–26.36 %, respectively under the MWR. In total as a whole, the pattern of PRBZT > FBZT ≥ RBCT/ZT > FBCT was observed for both P-induced nitrogen and potassium recovery efficiency during the current study.

Correspondingly the P-fertilization techniques had notably affected the P-induced nitrogen and potassium recovery efficiencies during the experimentation. The P-induced nitrogen and potassium recovery efficiency ranged between 84.02 and 98.67, and 27.49 and 35.35 %, respectively under P-fertilization techniques based MWR. With significantly highest P-induced nitrogen and potassium recovery efficiency (98.67, 35.35 %) under P_{50}+PSB + AMF+2FSP, respectively and considerably lowest under control treatement. The considerable interaction effect among crop establishment and tillage management and P-fertilization practices for P-induced nitrogen and potassium recovery efficiency was noted for both years in the present study.

3.2.3. System water-use efficiency and system water productivity

The use efficiency of water, and economic and irrigation water productivities of different crop establishment and tillage managements and P-fertilization practices differed significantly ($p < 0.05$) under MWR (Table 2). It is apparent from the data that, system water-use efficiency, economic and irrigation water productivities ranged from (9.76–11.15 kg ha^{-1} mm^{-1}; 134.69–151.33 INR ha^{-1} mm^{-1} and 2.86–3.26 kg m^{-3}), accordingly under various crop establishment and tillage management methods. Significantly higher values (11.15 kg ha^{-1} mm^{-1}, 151.33 INR ha^{-1} mm^{-1} and 3.26 kg m^{-3}) were recorded under PRBZT practice and lowest values (9.76 kg ha^{-1} mm^{-1}, 134.69 INR ha^{-1} mm^{-1} and 2.86 kg m^{-3}) under FBCT–FBCT practice, respectively throughout the experimentation.

The P management practices, the P_{50}+PSB + AMF+2FSP had significantly maximum use efficiency of water, and economic and irrigation water productivities (11.38 kg ha^{-1} mm^{-1}; 160.74 INR ha^{-1} mm^{-1} and3.33 kg m^{-3}) which was statistically on par with P_{50}+PSB + AMF treatment under MWR during both the years. However, the ZT-plots registered considerably ($p < 0.05$) superior water-use efficiency and productivities of water than that for CT-plots. The above indices followed the sequence of P_{50}+PSB + AMF+2FSP > P_{50}+PSB + AMF > P_{50}+2FSP > P_{100}>P_0 (Table 2). During the experimentation, it was shown that the interaction among crop establishment and tillage management and P-fertilization techniques for above indices were noteworthy.

3.3. Soil physical properties

Assessment of the data revealed that crop establishment and tillage management had a substantial influence ($p < 0.05$) on bulk density, aggregates distribution and its stability; whereas no significant effect was found for percentage of micro-aggregates at the end of two years' cropping phase (Table 3). Across crop establishment and tillage management methods soil bulk density, percentage of macro aggregates, water stable aggregates and mean weight diameter ranged between (1.50–1.58 g m^{-3}), (22.02–32.73 %), (70.02–78.05 %) and (0.68–0.85 mm), respectively with highest and lowest values observed in PRBZT and FBCT, accordingly except for SBD; while FBZT and RB-CT/ZT incurred intermediate physical properties of soil. The double-ZT PRBZT system accounted for ~5.1 % lesser SBD, ~48.6, 11.5 and 0.25 % higher percentage of macro aggregates, water stable aggregates and mean weight diameter as to CT based FBCT. In contrast, the highest percentage of micro aggregates (48.01 %) was obtained under FBCT–FBCT plots. In general, soil physical properties followed the order of PRBZT > FBZT ≥ RBCT > FBCT under crop establishment and tillage managements in the current study.

Table 3
Physico-chemical properties of soil influenced by Crop establishment methods and P-fertilization practices in CA based MWR (after 2 years).

Treatments	BD (g cm^{-3})	Mac Ag % (>0.25 mm)	Mic Ag % (<0.25 mm)	TWA (%)	MWD (mm)	pH	SOC (%)	Available NPK (kg ha^{-1}) N	P	K	PSB (× 10^4 cfu g^{-1})	DHA (μg TPF g soil^{-1}day^{-1})	ALP (μg PNP g soil^{-1} hr^{-1})	Acid-P (μg PNP g soil^{-1} hr^{-1})	SMBC (mg kg^{-1})
Crop establishment methods															
FBCT	1.58^a	22.0^c	48.0^a	70.0^c	0.68^c	8.07^a	0.43^c	138.7^a	15.7^c	306.5^a	17.6^c	36.7^c	225.2^c	32.2^a	207.4^c
RBCT/ZT	1.56^{ab}	24.4^{bc}	46.8^a	71.2^{bc}	0.71^{bc}	7.95^a	0.44^{bc}	141.5^a	17.2^{bc}	314.4^a	18.4^{bc}	41.8^a	232.4^{bc}	36.4^a	221.1^{bc}
FBZT	1.52^{bc}	31.2^a	45.0^a	76.2^a	0.82^a	7.81^a	0.47^{ab}	145.1^a	19.4^a	321.2^a	21.0^a	38.5^{bc}	253.9^a	35.6^a	228.3^{ab}
PRBZT	**1.50^c**	**32.7^a**	45.3^a	**78.1^a**	**0.85^a**	7.73^a	**0.48^a**	147.9^a	**19.8^a**	324.2^a	**21.5^a**	**42.4^a**	255.1^a	37.1^a	239.8^a
Phosphorus fertilization practices															
P_{100}	1.54^a	27.3^{bc}	46.6^a	73.9^{ab}	0.76^b	8.07^a	0.45^a	144.7^a	16.7^{bc}	313.9^a	21.0^b	40.5^{ab}	244.0^{bc}	35.6^{bc}	233.2^a
P_{50}+2FSP	1.55^a	26.7^c	46.7^a	73.4^{bc}	0.75^c	8.01^a	0.44^{ab}	145.7^a	16.1^c	308.8^a	18.7^c	38.2^{bc}	238.4^{cd}	34.2^c	218.4^{bc}
P_{50}+PSB + AMF	1.53^a	29.5^a	45.1^a	74.6^{ab}	0.83^a	7.96^a	0.45^a	145.5^a	20.6^a	320.7^a	23.9^{ab}	42.5^a	258.1^a	38.2^a	239.1^a
P_{50}+PSB + AMF+2FSP	**1.53^a**	**31.7^a**	44.7^a	**76.4^a**	**0.84^a**	7.97^a	**0.46^a**	148.5^a	**21.0^a**	319.0^a	**24.0^a**	**43.1^a**	255.3^{ab}	37.9^a	236.5^a
P_0	1.58^a	23.2^d	47.7^a	71.0^c	0.71^d	8.08^a	0.42^b	132.2^a	13.4^d	305.9^a	14.1^d	35.7^c	229.7^d	32.3^d	206.6^c
Interaction	NS	NS	NS	NS	NS	NS	NS	NS	S	NS	NS	NS	NS	NS	NS

[**Note:** FBCT: Flat bed–conventional tillage (FBCT) both in maize & wheat; RBCT/ZT: Raised bed–CT (RBCT) in maize & RB–zero tillage (RBZT) in wheat; FBZT: FBZT both in maize & wheat; PRBZT: Permanent raised bed–ZT (PRBZT) both in maize & wheat. P_{100}: 100 % P as basal; P_{50} + 2FSP: 50 % P as basal (P_{50}) + 2 foliar sprays of phosphorus (2FSP) as DAP (2 %) at knee-high stage (KHS) and pre-tasseling stage (PTS); P_{50} + PSB + AMF: P_{50} + PSB + AM-fungi (AMF); P_{50} + PSB + AMF + 2 FSP: P_{50} + PSB + AMF + 2FSP at KHS & PTS; P_0: 100 % N & K with no P (P_0) as control]. BD: Bulk density, Mac Ag %: Macro aggregates % (>0.25 mm), Mic Ag %: Micro aggregates % (<0.25 mm), TWA: Total water aggregates, MWD: Mean weight diameter, SOC: Soil organic carbon, Available NPK (kg ha^{-1}), PSB: Phosphorus solubilizing bacteria (× 104 cfu g^{-1}), DHA: Dehydrogenase activity (μg TPF g soil^{-1} day^{-1}), ALP: Alkaline phosphatase activity (μg PNP g soil^{-1} hr^{-1}), Acid-P: Acid phosphatase (μg PNP g soil^{-1} hr^{-1}), SMBC: Soil microbial biomass carbon (mg kg^{-1}soil hr^{-1}).

It is apparent that P management practices appreciably ($p < 0.05$) influenced percentage of macro aggregates (31.65 %), water stable aggregates (76.36 %) and mean weight diameter (0.84 mm) with highest values under P_{50}+PSB + AMF+2FSP which remained at par with P_{50}+PSB + AMF at the end of two years' cropping phase. SBD and percentage of micro aggregates were found to be higher under control practice (1.58 g m^{-3} and 47.71 %) with lowest values under P_{50}+PSB + AMF+2FSP (1.53 g m^{-3} and 44.71 %), accordingly. Interaction outcome between crop establishment and tillage management and P fertilization practices was non-substantial for physical properties by the conclusion of two years' of cropping cycle.

3.4. Soil chemical properties

The chemical properties of soil (0–15 cm) under various crop establishment and tillage management and P-fertilization practices differed accountably for soil organic carbon and available P under MWR in the current study, whereas cautious testing of soil exposed that properties viz., soil pH, available N and K remained uninfluenced at the conclusion of two years' cropping cycle (Table 3). Avail-P ranged between 15.67-19.82 and 13.38–21.03 kg ha^{-1} for crop establishment and tillage management and P-fertilization practices, respectively. However, the ZT-plots registered significantly ($p < 0.05$) higher values for chemical properties of soil than that for CT-plots. Under FBCT practice, soil pH showed higher values (8.07) towards slight alkalinity where no residue was retained as compared to ZT-plots which are near neutral. However, Highest SOC (0.48 %), avail-N (147.86 kg ha^{-1}), avail-P (19.82 kg ha^{-1}) and avail-K (324.2 kg ha^{-1}) were found for PRBZT–PRTZT plots where crop residues was retained at the end of experimentation. Amongst P management practices, P_{50}+PSB + AMF+2FSP had the highest SOC (0.46 %), avail-N (148.47 kg ha^{-1}), avail-P (21.03 kg ha^{-1}) and avail-K (319.0 kg ha^{-1}). The sequence of P_{50}+PSB + AMF+2FSP > P_{50}+PSB + AMF > P_{100}>P_{50}+2FSP > P_0 was observed for soil chemical properties under P-fertilization practices in the current study, except soil pH. A significant interaction outcome was found for avail-P between crop establishment and tillage management, and P management practices from the experimentation.

3.5. Soil biological properties

Assessment of soil biological properties computed for CA-based MWR under various crop establishment and tillage management and P-fertilization treatments determined for furrow-slice at the end of cropping cycle were found significant (Table 3). The crop establishment and tillage management had a considerable effect except for acid phosphatase enzyme. The PSB count ranged between 17.57-21.54 × 10^4 cfu g^{-1} soil following the order of FBCT > RB-CT/ZT > FBZT > PRBZT. In comparison to FBZT, RB-CT/ZT, and FBCT, the PRBZT showed ~22.6, 17.0, and 2.8 % higher PSB count. The PRBZT system had considerable difference ($p < 0.05$) with higher values of soil microbial biomass carbon, dehydrogenase and alkaline phosphatase activity amounting to 239.8 mg kg^{-1}, 42.36 μg TPF g soil^{-1}24 hr^{-1} and 255.05 μg PNP g soil^{-1} hr^{-1}, in that order. The lowest values for biological properties were obtained under FBCT plots where no crop residues were retained under CT plots. In general, crop establishment and tillage management practices followed the order of CA based systems > CT based systems for soil biological parameters in the current study.

The P management techniques significantly influenced the soil biological properties at the end of experimentation. Amongst P management practices, P_{50}+PSB + AMF+2FSP resulted in considerably ($p < 0.05$) maximum PSB population (23.97 × 10^4 cfu g^{-1}) and dehydrogenase enzyme activity (43.13 μg TPF g soil^{-1}24 hr^{-1}); whereas highest acid phosphatase enzyme activity (38.17 μg PNP g soil^{-1} hr^{-1}), alkaline phosphatase enzyme activity (258.07 μg PNP g soil^{-1} hr^{-1}) and soil microbial biomass carbon (239.1 mg kg^{-1} soil) were observed under P_{50}+PSB + AMF treatment at the end of 2-years cropping cycle. Soil

Table 4
Influence of crop establishment methods and phosphorus fertilization practices on P fractions at 0–15 cm depth of soil under MWR (after 2 years).

Treatments	Soluble P (mg/kg)	Al-bound P (mg/kg)	Fe-bound P (mg/kg)	Ca-bound P (mg/kg)	Reductant soluble P (mg/kg)	Total inorganic P (mg/kg)	Organic P (mg/kg)	Total P (mg/kg)
Crop establishment methods								
FBCT	7.00^{c}	29.67^{a}	42.68^{a}	282.5^{a}	111.4^{a}	473.3^{a}	231.8^{d}	705.1^{c}
RBCT/ZT	7.69^{bc}	27.98^{ab}	39.41^{a}	262.9^{ab}	107.6^{ab}	445.6^{a}	264.1^{c}	709.7^{bc}
FBZT	8.65^{a}	27.01^{ab}	35.29^{bc}	233.3^{bc}	102.3^{bc}	406.6^{bc}	313.5^{b}	720.1^{ab}
PRBZT	$\mathbf{8.85^{a}}$	26.51^{b}	32.32^{c}	224.8^{c}	101.6^{c}	394.1^{c}	$\mathbf{335.1^{a}}$	729.2^{a}
Phosphorus fertilization practices								
P_{100}	7.46^{bc}	31.56^{a}	41.46^{a}	291.5^{a}	116.7^{a}	488.7^{a}	293.9^{b}	782.6^{a}
P_{50}+2FSP	7.17^{c}	29.45^{abc}	38.94^{abc}	259.2^{bcd}	111.3^{b}	446.1^{bc}	267.4^{c}	713.5^{d}
P_{50}+PSB + AMF	9.19^{a}	28.39^{c}	37.71^{bc}	246.3^{cd}	98.9^{e}	420.5^{cd}	328.9^{a}	749.4^{c}
P_{50}+PSB + AMF+2FSP	$\mathbf{9.39^{a}}$	28.44^{bc}	37.62^{c}	242.5^{d}	99.5^{de}	417.5^{d}	$\mathbf{333.8^{a}}$	751.3^{bc}
P_0	5.97^{d}	23.18^{d}	33.92^{d}	202.1^{e}	101.4^{cde}	366.6^{e}	228.9^{d}	595.5^{e}
Interaction	NS	NS	NS	NS	NS	NS	NS	NS

[**Note:** FBCT: Flat bed–conventional tillage (FBCT) both in maize & wheat; RBCT/ZT: Raised bed–CT (RBCT) in maize & RB–zero tillage (RBZT) in wheat; FBZT: FBZT both in maize & wheat; PRBZT: Permanent raised bed–ZT (PRBZT) both in maize & wheat. P_{100}: 100 % P as basal; P_{50} + 2FSP: 50 % P as basal (P_{50}) + 2 foliar sprays of phosphorus (2FSP) as DAP (2 %) at knee-high stage (KHS) and pre-tasseling stage (PTS); P_{50} + PSB + AMF: P_{50} + PSB + AM-fungi (AMF); P_{50} + PSB + AMF + 2 FSP: P_{50} + PSB + AMF + 2FSP at KHS & PTS; P_0: 100 % N & K with no P (P_0) as control].

biological properties followed the trend of P_{50}+PSB + AMF+2FSP > P_{50}+PSB + AMF > P_{100}>P_{50}+2FSP > P_0, respectively. No significant interaction effect was found among crop establishment and tillage management and P-fertilization treatments.

There were two primary PCs, the loading plots PC1 and PC2 of soil physico-chemical and biological properties and PCA biplots showed the scores of the study locations (Supplementary Fig. 4). The findings of PCA on soil properties had two main outputs, with eigen values > 1 (Kaiser, 1960), which showed ~ 92.1 % of the variability in total with 84.8 and 7.32 % for PC1 and PC2, respectively. However, as seen in PCA biplot; PC1 had considerable affirmative loadings on PSB, soil microbial biomass carbon, dehydrogenase activity, mean weight diameter, available N and P, and total water stable aggregates, and they were strongly associated with each other, respectively (Kohler and Luniak, 2005). Similarly, pH, BD and micro aggregates all exhibited a well-built loading on PC2 as well as be significantly connected with one another.

3.6. Phosphorus fractions

The soil P-dynamics of CA-based MWR was analyzed for furrow-slice layer under crop establishment and tillage management and P-fertilization practices and found to have a substantial ($p < 0.05$) influence on P dynamics (Table 4; Supplementary Table 4; Supplementary Fig. 5). It is apparent from the data that, soluble and loosely-bound P, aluminiumbound-P, ironbound-P, calcium bound-P, reductant soluble-P, organic-P and total inorganic-P ranged from 7.0 to 8.85; 26.51–29.67; 32.32–42.68; 224.8–282.5; 101.6–111.4; 231.8–335.1; 394.1–473.3 mg kg^{-1}, accordingly under various crop establishment and tillage management practices. Significantly elevated soluble-P, organic-P and total-P (8.85, 335.1, 729.2 mg kg^{-1}) were recorded for PRBZT practice subsequently by FBZT, RBCT/ZT with significantly least values (7.0, 231.8, 705.1 mg kg^{-1}) under FBCT–FBCT practice, accordingly. Under CA based MWR, total inorganic-P and organic-P contributed ~44.05 and 45.95 % to total P, respectively. FBCT had significantly higher iron, aluminium, calcium-bound P, reductant soluble-P, along with total inorganic-P (42.68, 29.67, 282.5, 111.4, 473.3 mg kg^{-1}), respectively over other crop establishment and tillage managements.

Amongst the P management practices, the P_{50}+PSB + AMF+2FSP had considerably highest soluble and loosely-bound P (9.39 mg kg^{-1}), which were at par with P_{50}+PSB + AMF (9.19 mg kg^{-1}) and significantly higher over P_{100}>P_{50}+2FSP > P_0 (5.97 mg kg^{-1}). Higher organic-P (333.8 mg kg^{-1}) was recorded in P_{50}+PSB + AMF+2FSP treatment. When P_{50}+PSB + AMF+2FSP was applied to the soil, there was a 57.3 and 45.8 % increase in soluble-P and organic-P over control, respectively (Table 4). Total-P followed the sequence of P_{100}>P_{50}+PSB + AMF+2FSP > P_{50}+PSB + AMF > P_{50}+2FSP > P_0. During the experimentation, it was shown that the interaction effect for various P fractions between establishment menthods and P fertilization was found non-significant.

The cluster heatmap in respect of P-fractions in soil showcased the formation of several clusters amongst themselves. The vertical row dendrogram in heatmap illustrates the clustering of P-fractions of soil, while dendrogram shows horizontal row clustering of crop establishment and tillage management and P management practices. The heatmap generated in respect of P-fractions (vertical dendrograms) and its treatments (Horizontal dendrogram) depicted that the total-P, organic and loosely-bound P (Outlier) were clustered together in one group by virtue of being available to plant and their direct correlation and contribution to crop yield. On the other hand, iron bound-P, reductant soluble-P, total inorganic-P, aluminium bound-P, calcium bound-P were seen to form a group of clusters as these P-fractions are similar in aspects of their non-contribution to the crop yield as documented in correlation (Supplementary Fig. 5) and less available as plant nutrition. Regarding crop establishment and tillage management and P-fertilization practices, Cluster (M3, M4) with (P3, P4) showed consistent advantages in system productivity compared to other practices.

To determine the link between various P fractions in crop establishment and tillage management and P management techniques, correlation coefficient by Pearson was used (Supplementary Table 4). Results exposed a considerably affirmative correlation ($p < 0.01$) among soluble-P with organic-P ($r = 0.94$). However, aluminium, iron, calcium-bound P, and reductant-P showed considerable affirmative association with inorganic-P (r = 0.932; 0.927; 0.998; 0.847), respectively. While total-P showed significant correlation with aluminium bound-P, calcium bound-P, reductant soluble-P, total inorganic-P and organic-P at 1 % level of probability. However, organic-P showed no considerable association with iron, aluminium, calcium bound-P, reductant-P and inorganic-P.

3.7. Carbon-pools and carbon management index

Soil carbon-fractions, lability of SOC, lability index, carbon pool and carbon management index were greatly influenced by crop establishment and tillage management and P-fertilization practices by the end of experimentation (Fig. 3). Among crop establishment and tillage management practices, PRBZT system had higher value of very labile (1.22 g kg^{-1}), labile (0.55 g kg^{-1}), less labile (0.92 g kg^{-1}), non-labile carbon (2.13 g kg^{-1}), carbon pool index (1.15) and carbon management index (108.36) over other crop establishment and tillage management

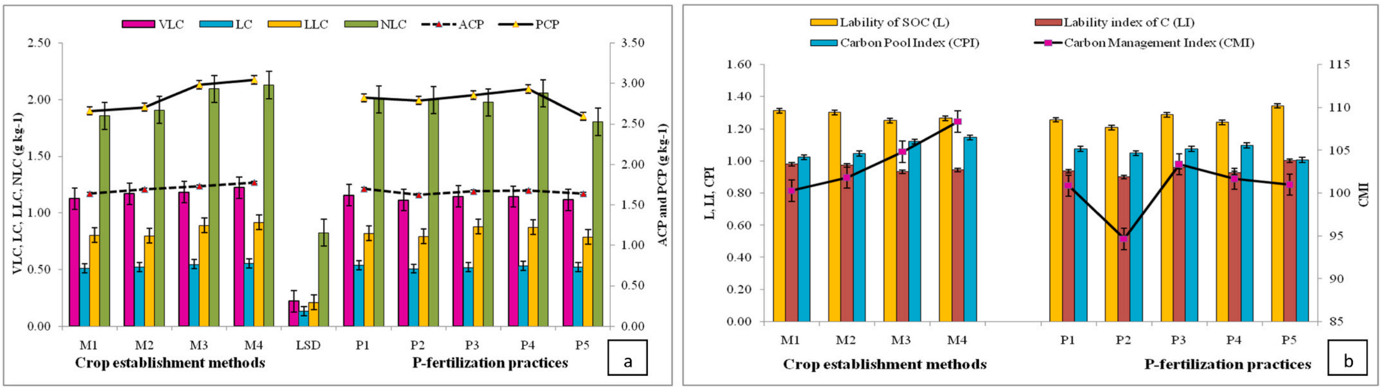


Fig. 3. Effect of crop establishment methods and P-fertilization practices on different carbon fractions (a) and carbon indices (b) of soil under MWCS. [**Note:** M1: Flat bed–conventional tillage (FBCT) both in maize & wheat; M2: Raised bed–CT (RBCT) in maize & RB–zero tillage (RBZT) in wheat; M3: FBZT both in maize & wheat; M4: Permanent raised bed–ZT (PRBZT) both in maize & wheat. P1: 100 % P as basal; P2: 50 % P as basal (P_{50}) + 2 foliar sprays of phosphorus (2FSP) as DAP (2 %) at knee-high stage (KHS) and pre-tasseling stage (PTS); P3: P_{50} + PSB + AM-fungi (AMF); P4: P_{50} + PSB + AMF + 2FSP at KHS & PTS; P5: 100 % N & K with no P (P_0) as control; VLC: Very labile carbon; LC: Labile carbon; LLC: Less labile carbon; NLC: Non labile carbon; ACP: Active carbon pool; PCP: Passive carbon pool].

Table 5
Influence of crop establishment methods and phosphorus fertilization practices on phosphorus nutrient budgeting under MWR (2 years pooled data).

Treatments	Initial available phosphorus (kg/ha)		Phosphorus added (kg/ha)		Phosphorus removed (kg/ha)		Available phosphorus after harvest (kg/ha)		Expected addition/ deletion (kg/ha)		Actual addition/ deletion (kg/ha)	
	2018–19	2019–20	2018–19	2019–20	2018–19	2019–20	2018–19	2019–20	2018–19	2019–20	2018–19	2019–20
Crop establishment and tillage management practices												
FBCT	12.92	14.33	28.96	28.96	46.62	47.17	14.33	15.67	−4.74	−5.29	1.41	1.34
RBCT/ZT	12.92	15.37	34.96	34.96	53.36	54.90	15.37	17.23	−5.48	−7.02	2.45	1.86
FBZT	12.92	16.21	40.96	40.96	51.95	56.96	16.21	19.38	−1.93	−3.08	3.29	3.17
PRBZT	12.92	16.35	40.96	40.96	58.07	61.69	**16.35**	**19.82**	−4.19	−7.81	**3.43**	**3.47**
Phosphorus fertilization practices												
P_{100}	12.92	14.60	51.60	51.60	49.84	52.63	14.60	16.71	+14.68	+11.89	1.68	2.11
P_{50}+2FSP	12.92	14.21	33.71	33.71	55.11	58.30	14.21	16.05	−8.48	−11.67	1.29	1.84
P_{50}+PSB + AMF	12.92	16.42	25.80	25.80	55.55	58.06	16.42	20.59	−16.83	−19.34	3.50	4.17
P_{50}+PSB + AMF+2FSP	12.92	17.09	33.71	33.71	64.17	69.44	**17.09**	**21.03**	−17.54	−22.81	**4.17**	**3.94**
P_0	12.92	13.07	0	0	37.84	37.47	13.07	13.38	−24.92	−24.55	0.15	0.31

[**Note:** FBCT: Flat bed–conventional tillage (FBCT) both in maize & wheat; RBCT/ZT: Raised bed–CT (RBCT) in maize & RB–zero tillage (RBZT) in wheat; FBZT: FBZT both in maize & wheat; PRBZT: Permanent raised bed–ZT (PRBZT) both in maize & wheat. P_{100}: 100 % P as basal; P_{50} + 2FSP: 50 % P as basal (P_{50}) + 2 foliar sprays of phosphorus (2FSP) as DAP (2 %) at knee-high stage (KHS) and pre-tasseling stage (PTS); P_{50} + PSB + AMF: P_{50} + PSB + AM-fungi (AMF); P_{50} + PSB + AMF + 2 FSP: P_{50} + PSB + AMF + 2FSP at KHS & PTS; P_0: 100 % N & K with no P (P_0) as control].

methods. Comparatively 7.96, 7.84, 15, 14.52, 12.75 and 8.05 % higher VLC, LC, LLC, NLC, CPI and CMI, respectively were obtained under PRBZT as to FBCT practice. However, Lability of SOC and lability index was found to be superior under conventional FBCT system. The active and passive carbon pool followed the sequence of CA based PRBZT > FBZT followed by CT based RBCT/ZT > FBCT for carbon fractions in the current trial. PRBZT resulted in 8.4 % improvement in active carbon and 14.29 % passive carbon pool, respectively over FBZT system.

The P–fertilization methods, was unsuccessful to exert any noteworthy changes on carbon fractions and carbon indices for the duration of the present study. However the highest Lability of SOC and lability index was found under P_0 treatment at the end of two-years of experimentation. However, relatively higher values of very labile carbon (1.16 g kg^{-1}), labile carbon (0.54 g kg^{-1}) and higher active carbon pool (1.70 g kg^{-1}) were noticed under P_{100} and higher less labile carbon (0.88 g kg^{-1}), non-labile carbon (2.06 g kg^{-1}) and passive carbon pool (2.93 g kg^{-1}) were observed under P_{50}+PSB + AMF+2FSP treatment, respectively. Remarkably, significant rise in carbon management index by 8.96 % was observed in P_{50}+PSB + AMF+2FSP followed by P_{50}+PSB + AMF > P_{100}> P_{50}+2FSP > P_0 treatment by the end of two years of experimentation.

3.8. Phosphorus nutrient budgeting under MWR

Phosphorus budgeting balance sheet under CA based MWR is depicted in Table 5. Amongst crop establishment and tillage management methods, the maximum quantity of nutrient-P added (40.96; 40.96 kg ha^{-1}) and P removed (58.07; 61.69 kg ha^{-1}) under PRBZT system, while least values for the same were for FBCT plots. The CA based systems (PRBZT and FBZT) had higher P addition (~41.4 %) and removal (~30.58 %) rates as to CT based plots (RBCT/ZT and FBCT). Available-P after harvest of the crops and actual addition of P to the cropping system was also found to be higher under PRBZT plots and least under FBCT plots throughout the experimentation. However, expected deletion was found to be higher (−5.48 kg ha^{-1}) under RBCT/ZT during first year and under PRBZT (−7.81 kg ha^{-1}) for second year of experimentation in our study. Amongst P management practices, maximum P was applied under P_{100} (51.6; 51.6 kg ha^{-1}) while no P was applied under P_0 treatment. The P removed was highest under P_{50}+PSB + AMF+2FSP treatment (64.17; 69.44 kg ha^{-1}). Likewise avail-P after crop (17.09; 21.03 kg ha^{-1}) and actual addition of P to system (4.17; 3.94 kg ha^{-1}) was also obtained to be high under P_{50}+PSB + AMF+2FSP treatment while lowest values were noticed under P_0 treatment throughout the experimentation. The actual addition of P to the system had the trend of P_{50}+PSB + AMF+2FSP > P_{50}+PSB + AMF > P_{100}>P_{50}+2FSP > P_0 under MWR in the current study.

4. Discussion

4.1. Effect of weather conditions

New Delhi, India, experiences a subtropical climate with hot, dry summers in addition to harsh, cold winters. A notable variation in weather parameters was observed during the cropping season (Supplementary Fig. 1). During the growing season of maize (July to October), the weekly mean temperature varied from 11.1 °C to 36.2 °C in 2018 and 15.2 °C–38.2 °C in 2019, accompanied by precipitation levels of 832 and 569.3 mm, respectively. For the wheat growing period (November to April), the weekly mean temperature ranged from 2.0 °C to 37.4 °C in 2018-19 and from 3.3 °C to 36.5 °C in 2019–20, accompanied by precipitation amounts of 144.1 and 312.3 mm, respectively. Weather significantly influence on need for water and fertilizer, pest and disease incidence, the effectiveness of cultural practices, nutrient mobilization, and the yield of crops (Behera et al., 2007). In maize, rainfall during peak growing period determines the output. Despite receiving more precipitation in 2018 than in 2019, the crop performed better in 2019, in terms of growth, root attributesand yield as adequate moisture was provided through irrigation during non-rainy phases. While there was an uneven distribution of the rainfall in wheat. The decrease in yield was observed in 2018–19 may have resulted from high temperature during terminal growth phase of wheat crop. The ideal temperature range for grain filling and anthesis is between 22 °C and 12 °C. Grain yield is significantly reduced by deviations from this range (Tewolde et al., 2006). According to Wardlaw and Wrigley (1994), heat stress during the anthesis stage can cause floral abortion. Furthermore, the rise in optimal temperature shortens the time taken to fill grains, which eventually results in a decreased yield because of a decrease in kernel weight (Kharub and Chander, 2010). During the two cropping years, there was no variation in other weather factors such as relative humidity, sunlight hours, and wind speed and had no discernible impact on crop growth and production.

4.2. Root architecture

In comparison to other crop establishment and tillage management methods, crop-residue retention under PRBZT produced noticeable impact on root architecture (Table 1 & Supplementary Table 3) because of better microclimate under residue-retained ZT plots, which had better soil moisture during periods of moisture stress and lower soil temperature during dry spells. Root development was greater in CA raised beds, as they offered lower mechanical resistance compared to CT flat-bed system (Ram et al., 2010, 2013). As stated to Gangaiah et al. (2012), retaining crop residues improved the soil's physical, chemical and biological properties favorable for root growth in the PRBZT system.The decomposition of crop residue under ZT plots enhanced the nutrient supply, leading to improved shoot and root development, which subsequently influenced growth and yield (Ram et al., 2006; Das et al., 2013). Improved root growth in wheat under PRBZT system can likely be attributed to enhanced nutrient bio-availability, reduced evaporation losses besides better soil moisture retention due to residue cover, and higher SOM content as to conventional tillage (Meena, 2010; Choudhary et al., 2018, 2020; Singh et al., 2007; Kihara et al., 2012).

Among P-fertilization techniques, P_{50}+PSB + AMF+2FSP practice differ noticeably ($p < 0.05$) to alternative P-fertilization techniques, as it had better root architecture in terms of root surface area, average diameter, root volume, root length, root length density, root dry weight, shoot dry weight, and root: shoot ratio (Table 1 & Supplementary Table 3). The conjunctive supply of P nutrition (P_{50}+PSB + AMF+2FSP) was found to have enhanced P-bioavailability (Suri et al., 2011). Better root development and growth may be primarily due to the availability and uptake of primary nutrients (N, P, K) in balanced form under integrated P fertilization practice, i.e. P_{50}+PSB + AMF+2FSP (Singh et al., 2011; Kumar et al., 2015, 2016). The increased availability of nutrients and enhanced metabolic processes that occur in P-applied plots, together with the fact that they are subject to a range of genetic and environmental factors, may be accountable for the positive effects of P-fertilization on plant development as compared to no P plots (Kumar et al., 2014). Pervasive rhizosphere under P-fertilized plots that efficiently utilise the nutrients supplied, thereby enhancing the growth of crop under MWR (Masood et al., 2011). Hence, enhanced nutrient-use efficiency under P_{50}+PSB + AMF+2FSP demonstrated its effectiveness by responsible consumption. Therefore, it was demonstrated that the combination supply of P_{50}+PSB + AMF+2FSP was superior to the solitary application of soil-applied P_{100} in maize in terms of exhibiting improved growth and development of roots.

4.3. Phosphorus-use efficiency

P-use efficiencies were considerably affected by crop establishment and tillage managements, with PRBZT showing higher use efficiency as to other establishment methods (Table 2). This may be due to enhanced root growth leading to enhanced nutrient uptake, resulting in higher phosphorus recovery efficiency and leading to increased grain yield in PRBZT practice (Gultekin et al., 2011; Varatharajan et al., 2019b). P fetilization techniques significantly influenced PFP_P, phosphorus induced nitrogen and potassium recovery efficiency, owing to differential uptake of P and yield across both experimental years (Kumar et al., 2015; Bai et al., 2017). The combination of P_{50}+PSB + AMF+2FSP yielded the highest PFP_P, PiNRE, and PiKRE, attributed to the capacity of PSB and AMF to conserve ~50 % of P fertilizer while enhancing root growth resulting in grain production. The enhanced use efficiency of P under P_{50}+PSB + AMF+2FSP treatment was mainly due to phosphate solubilizing bacteria in the rhizospheric involved in solubilizing insoluble bound-P from the soil by releasing organic acids and make it readily available for crop uptake (Nacoon et al., 2021). The AMF which is an endophytic fungi which readily interact with rhizospheric bacteria creating affirmative microbial community in the rhizosphere (Wahid et al., 2016). Thereby the AMF tends to form hyphal network thereby expanding the rhizospheric zone and supplies the solubilized readily available P from unreachable areas, than to maize and wheat supplied alone with P (Yufan Lu et al., 2023b). Since maize and wheat are amongst cereals with higher P demand, the conjunctive use of PSB and AMF tend to supply the P for root uptake throughout the crop growth period, inturn enhancing the productivity of both maize and wheat. The foliar sprays of P through di-ammonium phosphate during the critical stages of crop growth inturn helped in direct intake of supplied P through stomata (Rafiullah et al., 2018) causing no dearth of P nutrient and compensate the root uptake of P during critical stages of crop growth. Thereby it evident that, conjunctive application of P through soil, foliar and microbial means led to higher P efficiency by saving ~34.7 percent of P, inturn leading to better root growth and higher productivity of maize and wheat as compared to P_{50}+PSB + AMF and P_{50}+ 2FSP, which received either microbial or foliar means alone. Conversely, the lowest PFP_P, PiNRE, and PiKRE were observed with 100 % P application, likely due to limited root growth and also due to P fixation in the soil (Kumar et al., 2015, 2016). These findings align with those of Abid et al. (2016), which also highlight that P fixation led to minimal gains in root growth and grain yield under the P_{100} treatment despite equivalent P fertilizer input compared to P_{50}+PSB + AMF+2FSP (Kumar et al., 2016). Dwivedi et al. (2011) similarly reported that low P-utilization efficiency reduced agronomic and recovery efficiency, as grain yield failed to increase proportionally with fertilizer application rates due to the law of diminishing returns. Consequently, poor PUE, compounded by diminishing returns, resulted in lower root growth and recovery efficiency (Bashir et al., 2014). Enhanced P-use efficiency under CA systems partially contributes to achieving SDG-7 (Supplementary Fig. 6).

4.4. Water productivity

Crop establishment and tillage management methods significantly enhanced the irrigation and economic water productivity, and water-use efficiency of MWR compared to conventional methods, with the PRBZT practice achieving the highest values. This improvement is attributed to better moisture conservation, higher water holding capacity, reduced evaporation losses, higher water uptake and increased grain production (Sutaliya and Singh, 2005; Varatharajan et al., 2019a, 2019b). CA-based systems outperformed CT systems, owing to a more balanced nutrient supply and favorable physical, chemical, and microbiological soil characteristics (Choudhary et al., 2020; Singh et al., 2020a, 2020b). Crop-residue retention under CA functions as soil cover, enhancing soil infiltration rates and water holding capacity (Paul et al., 2014). In addition, residue retention in no-till plots moderates mean weekly temperatures by 0–1.5 °C, compared to tilled plots (Shen et al., 2018), and increases the mean aggregate diameter of soil particles. Consequently, soils managed with CA-based crop establishment and tillage management methods showed improved water storage capacity, better moisture retention and root attributes under ZT, and reduced evaporation losses. These factors likely contributed to enhanced soil water storage and lower evaporation in this study, leading to higher water-use efficiency. Furthermore, increased yields were achieved with reduced irrigation, contributing to water savings (Choudhary et al., 2018, 2020) and supporting **SDG 6** by promoting efficient water use in agriculture (Supplementary Fig. 6). Indoshi et al. (2025) also reported similar findings with the retention of crop residues under ridge and furrow system in maize in semi arid East-African Plateau has shown enhanced water-use efficiency and contributing to higher maize productivity. The results show the suitability of crop residue retention in other regions with semi-arid climatic condition.

P management practices had notable effect on irrigation water productivity and economic water productivity, and water-use efficiency, with the P_{50}+PSB + AMF+2FSP combination producing considerably superior results than remaining techniques. AM-fungi, in particular, showed considerable potential for solubilizing and mobilizing diffusion-limited nutrients and also in expanding fungal hyphal network with plant roots to meet plant nutritional needs (Harrier and Watson, 2003; Bai et al., 2016, 2017). As noted by Suri et al. (2012), AM-fungi facilitate nutrient access from deeper soil layers through an extensive hyphal network in association with plant roots, which also improves water relations. According to Auge (2006), mycorrhizal hyphae can penetrate soil pores that are inaccessible to plant roots. By extending the root system's reach by 10 to 1000 times through a network of hyphae, AM-fungi enhance nutrient and water uptake, increasing water productivity and nutrient use efficiency (Marschner and Dell, 1994; Harrier and Watson, 2003; Kumar et al., 2016). This approach aligns with SDG **2** by optimizing nutrient use for higher crop yields (Supplementary Fig. 6).

4.5. Soil physico-chemical and microbiological properties

4.5.1. Soil physical properties

At the end of cropping period, the percentage of micro aggregates was not significantly affected by various crop establishment and tillage management methods. However, percentage of macro aggregates (>0.25 mm), mean weight diameter, and total water stable aggregates were significantly influenced (Table 3). The PRBZT plots had the highest percentage of macro aggregates, total water stable aggregates, and mean weight diameter owing to retaining agricultural residues leading to better carbon indices (Ram et al., 2006, 2013). Consequently, PRBZT exhibited the lowest soil bulk density, while CT-based crop establishment and tillage management without crop-residue retention showed higher soil bulk density, due to no addition of organic matter to soil, and involved more mechanical soil disturbance during tillage (Boguzas et al., 2010). A lower soil bulk density helps retain soil moisture and nutrients, enhancing crop water and fertilizer utilization efficiency. The reduced soil bulk density not only affected by type of residue but also influenced by carbon sequestration associated with the amount of retention and thereby influencing porosity of the soil. The results were lining with the findings of Lu et al. (2024). Verhulst et al. (2011) observed that SOC additions improve soil biological activity under ZT plots with residue retention, resulting in lower soil bulk density. Similarly, Meena et al. (2015) found that soil bulk density generally decreases with residue accumulation. In CT systems, frequent tillage disrupts root growth due to sub-surface hard pan and also disrupts carbon sequestration and aggregate formation, resulting in fewer aggregates (Saad, 2014). Crop-residue retention enhances SOC content, which increases mean weight diameter and supports aggregate formation (Abail et al., 2013). Therefore, in this study, ZT combined with crop-residue retention and minimal soil disturbance under CA-based crop establishment and tillage management methods increased SOC content and water-stable aggregates (Boguzas et al., 2010).These findings align with SDG 15 (Supplementary Fig. 6).

The P_{50}+PSB + AMF+2FSP produced notably larger percentage of macro aggregates, total water stable aggregates and mean weight diameter among P-fertilization techniques; in contrast, the highest soil bulk density was seen under control treatment. The best soil physical characteristics were identified in the fertilized plot; this could be because of improved root development and proliferation, which raised the SOC content and produced lower soil bulk density, greater mean weight diameter, and higher total water stable aggregates (Khan et al., 2013). The AMF is essential for glomalin formation and soil aggregation, its administration in the aforesaid treatment also results in reduced soil bulk density, better mean weight diameter, and water-stable aggregates due to expanding fungal hyphal network with plant roots (Harrier and Watson, 2003; Kumar et al., 2016).

4.5.2. Soil chemical properties

Soil SOC and available P showed significant increase, with PRBZT plots having the highest SOC and available NPK levels, and FBCT plots with highest soil pH, particularly where no residues were retained. However, crop establishment and tillage management methods did not have a substantial impact on soil pH, available N, or available K (Table 3). The breakdown of agricultural residues by bacteria can release certain organic acids, slightly reducing soil alkalinity. Crop-residue retention in ZT plots generally boosts soil SOC due to higher soil organic matter content (Sharma et al., 2014). The retention of crop residues has shown enhanced SOC content leading to higher maize productivity (Indoshi et al., 2025). Variations in SOC concentrations across ZT plots may be due to differences in decomposition rates related to seasonal soil moisture (Karunakaran and Behera, 2016). By the end of the cropping phase, ZT plots with residue retention showed higher available NPK content than CT plots. Retaining crop residues in ZT systems supplements essential nutrients to the soil, mainly SOC and avail-N, thereby enhancing its natural fertility (Rohullah, 2016; Lu et al., 2024). In CA practices, residues decomposing on the soil surface retain NPK, whereas in CT systems, rapid aerobic decomposition often causes nutrient loss through leaching, reducing their availability for crop uptake due to restricted root growth (Ashish, 2015). Additionally, crop residue maintenance produces humic acids during decomposition, fostering microbial activity and raising SOC content in no tilled plots as to CT plots (Bajpai et al., 2006; Singh et al., 2020a, 2020b).

Additional analysis of the data shows that P-fertilization methods had no significant influence on soil pH, available-N, or K, but they did have an impact on SOC and available-P (Table 3). The application of P_{50}+PSB + AMF+2FSP produced the highest SOC; available-NPK may have been caused by the conjuctive application of P (P_{50}+PSB + AMF+2FSP), where PSB + AMF and foliar-P application enhanced P-solublization, mobilisation and absorption (Suri et al., 2011; Kumar et al., 2015, 2016). The SOC content was further improved by the higher root biomass produced under the P_{50}+PSB + AMF+2FSP treatment (Pooniya et al., 2015). In cropping systems, P application to every crop causes P accumulation because of low P usage efficiency and conversion to aluminium bound-P and iron bound-P, which can later be reversed as labile forms (soil solution P) by long-term P fertiliser management techniques (Balemi and Negisho, 2012). Therefore, in this situation, using P_{50}+PSB + AMF+2FSP as the basis for the cropping system may prove to be an efficient P management technique**.**

4.5.3. Soil biological properties

In the current investigation, the biological parameters of soil were significantly influenced by the crop establishment and tillage management procedures, with the exception of acid Phosphatase (Table 3). In the PRBZT plots where residues were preserved, higher phosphorus solubilizing bacteria population, dehydrogenase enzyme activity, acid and alkaline Phosphatase enzyme activity, and soil microbial biomass carbon were found; in the FBCT plots where no residues were retained, these values were lowest. Therefore, keeping residues on the soil surface may have improved the nutrient availability and raised the SOC content because the residues broke down has improved the bustle of the microorganisms and, ultimately, increased the phosphorus solubilizing bacteria and soil microbial biomass carbon as well as the enzymatic activities under ZT plots as opposed to tilled plots (Balato et al., 2003; Singh et al., 2020a, 2020b). Improved microbial-mediated enzymatic activity in the soil rhizosphere and higher root biomass were the outcomes of optimal and balanced nutrient supply under CA-based crop establishment and tillage management methods (Varatharajan et al., 2019b, 2019c). In contrast to CT without residues, Dong et al. (2009) discovered that soil microbial biomass carbon was highest under ZT with residue retention. Higher dehydrogenase and soil microbial biomass carbon activity under no-till crop-residue retention was similarly found by Kuotsu et al. (2014). The addition of NPK fertiliser was also related with an increase in soil microbial biomass carbon, alkaline phosphatase enzyme activity, and dehydrogenase enzyme activity. These enzymes are critical for maintaining soil fertility and health (Oberson et al., 2005). Improved soil microbial biomass carbon and enzymatic activities in the soil are a result of higher SOC content under high P fertilized plots, according to studies by Wang et al. (2008) and Turner and Wright (2014). Because of this, P management techniques had significant influence on biological qualities of soil in current experiment. P_{50}+PSB + AMF+2FSP led to a significantly higher PSB population with enhanced dehydrogenase enzyme activity (Tejada et al., 2008; Hai-Ming et al., 2014), while P_{50}+PSB + AMF treatment produced the highest levels of soil microbial biomass carbon and acid and alkaline Phosphatase enzyme activity leading to improved root growth and system productivity. These outcomes align with **SDG 15**.

4.6. Phosphorus dynamics

P is essential for many biological functions, such as the expression of genes, cell division, photosynthesis, energy production, breakdown of sugars, in addition to plant-to-plant transfer of nutrients (Wright, 2009). Despite being one of the rarest, most elusive, and immobile nutrients, its absence substantially restricts crop productivity. Even while most soils have significant total P reserves, P deficit is exacerbated by these reserves' low solubility. Conjunctive use of Phosphatic fertiliser is essential to solve this and maintain enough available P in the soil solution, which maximises crop output (Sharma et al., 2011; Harish et al., 2022b). Water-soluble P-containing fertilizers react swiftly with different soil constituents, fixing and holding P to form less soluble inorganic P-fractions (Suri et al., 2011). This procedure reduces PUE and has considerable financial losses. The low PUE of applied-P (~15–20 %) is a key barrier to sustainable agriculture; however there are several ways to improve PUE (Dwivedi et al., 2017; Kumar et al., 2017). Current analysis showed a notable maximal improvement of ~26.4 % for soluble P in PRBZT system as compared to CT based system (FBCT). The percentage of soluble and loosely-bound P in total P increased when retention of crop residues was done. In addition to biologically driven P release, decreased P-adsorption to mineral surfaces can improve soil P status and increase P-availability (Nanthakumar et al., 2014). The Al-bound P had a declining trend in the residue retained plot, which may be related to the relocation of native-P over time, which chelates inorganic-P through the build-up of soil organic matter (Singh and Reddy, 2012). Retention of residues increases soil microbial activity (Singh et al., 2020a,b), which helps to solubilise aluminium-bound P (Zhang et al., 2009). CT based system produced considerably ($p < 0.05$) more iron bound-P, aluminium bound-P, Calcium bound-P, and total inorganic P as compared to ZT based system. Additionally, compared to PRBZT, the FBCT practice generated a substantially ($p < 0.05$) larger (9.6 %) amount of Reductant soluble-P (111.4 mg kg^{-1}). At soil depth of 0–15 cm, iron bound-P was more common than aluminium bound-P; however, since crop residues remained on the soil surface, the iron bound-P fraction was also reduced. This P-fraction represents iron phosphate or is more tightly bound to iron oxides minerals, which are less available to plants (Pattanayak et al., 2009). According to Yi and Liang (2013), the addition of crop residues might lead to increased microbial action, which can contribute to the reduction or chelation of iron, thus available for crop uptake. The dissolution of phosphorus or iron phosphate associated with iron oxide minerals could be facilitated by this technique. Its composition is significantly impacted by phosphate fertiliser, which leads to an increase in iron phosphate content. Since the H_2SO_4 soluble P fraction primarily consists of stable and less plant available calcium phosphates. Yet, P-fertilization had a major influence on the proportion of Calcium bound-P, which makes up a sizable portion of P. Regardless of the type of fertilizer applied or the makeup of the calcium system, calcareous soils usually contain a sizable amount of calcium bound-P because it is stable at high pH levels (Yang et al., 2013). In the present investigation, the P-fraction was considerably reduced by treatments involving the crop residue retention. The solubilisation impact of agricultural residues on this occluded P-form may be the cause of this decline.

Crops grown under residue retained plots have a detrimental impact on other bound P groups, such as aluminium, iron, soluble reducing agents, and calcium binding groups, although soluble and loosely-bound P is increased by the same. Overall inorganic P decreased with crop residue retention. The application of SOM is known to have a considerable influence on the inorganic form of P in soil (Kumar et al., 2016). Crop residue retention increased soil microbial activity; hence, during the near the beginning stages of crop residue breakdown, a considerable amount of inorganic P may have converted to organic molecules. As a result, various P-bound pools become soluble, weakly bound, and organically bound P-pools are eventually formed (Yousefi et al., 2011). The percentage of soluble and loosely-bound P increased, likely as a result of using PSB, which could lower the dosage of P fertilizer and save cost (Suri and Choudhary, 2012). Additionally, PSB helps to solubilise insoluble P and improves plant uptake of it (Harish et al., 2022a, 2022b).

As predicted, the percentage of organically bound P increased when crop residues were retained. Because they contribute to this phenomenon through the enzymatic breakdown of organic components containing P, microbes and plants are associated with this activity (Singh et al., 2020a,b). The amount of soil organic matter and the organic-P sources' contribution to soil fertility are clearly correlated (Kumar et al., 2018). Due to their sluggish release, organically bound P stores are insufficient to supply all crop P needs, according to Kumawat et al. (2018). The crop residue provides carbon for the microbial population, which serves as an energy source and typically boosts their activity, facilitating the dissolution of bound P-pools. Consequently, P becomes immobilized in microbial biomass and other organic molecules, which makes it available for plant uptake when needed. Similar results were found for total-P as organic-P. Furthermore, P fertilizer improves both organic and inorganic P-fractions, which ultimately helps to rise the P content of the soil (Kumawat et al., 2016). The overall total P content rises when both the total inorganic and organic P content increases (Haokip et al., 2020). The study with high soil pH values are probably what caused the majority of P to stabilize as calcium phosphate, contributing to the observed patterns in soil P-distribution (Saha et al., 2014; Haokip et al., 2019).

The cluster heatmap in the current study showed that the total-P, Organic, and Loosely bound-P (Outlier) were all grouped together in one group due to their direct link with root growth and crop yield, availability for planting, and other factors. However, it can be observed that reductant soluble-P, iron bound-P, total inorganic-P, aluminium bound-P, and calcium bound-P form a cluster due to their similarity in not contributing to crop yield as shown by correlation and being less available for plant nutrition. The similar results were conferred by Singh et al. (2023).

4.7. Carbon fractions and carbon indices

SOC sequestration is a constructive tactic to combat global warming. SOC is the primary element of the farmland soil carbon pool, playing a crucial role in regulating soil quality and function, while also having a direct impact on climate change (Lu et al., 2023). Carbon fractions assist in offsetting greenhouse gas emissions from the environment, mostly CO_2, by storing carbon in the soil (Biswakarma et al., 2021; Choudhary et al., 2021). Agro-forestry, organic farming, conservation agriculture, and crop diversification are a few such farming methods that may improve carbon fraction and aid in the sequestration of carbon and the mitigation of climate change (Kumar et al., 2022; Harish et al., 2022b). Enhancing soil carbon sequestration can be achieved through different human driven carbon inputs, such as the retention of straw (Lu et al., 2024). Worldwide adoption of CA methods has demonstrated a positive influence on SOC, carbon fractions, and carbon pools (Rajanna et al., 2023). The essential element of soil fertility in addition to structure is SOC, that promotes microbial activity, root growth and improves nutrient availability, and helps maintain moisture (Babu et al., 2020; Singh et al., 2020a,b). The total quantity of carbon that is residing in the soil at a given point in time is referred to as the carbon-pool. By storing carbon dioxide from the atmosphere, expanding the carbon pool reduces greenhouse gas emissions while simultaneously enhancing soil fertility and structure, leading to better root growth and crop productivity. Higher porosity achieved due to retention of crop residues, enhances the oxygen availability in the soil and therby reduces NO_2 emission (Lu et al., 2024). According to Rajanna et al. (2023), a high carbon management index denotes sustainable soil management techniques that support carbon sequestration and general soil health. These carbon sequestering practices partially address SDG-13 (Supplementary Fig. 6).

Following the conclusion of two-year cropping cycles, various crop establishment and tillage management and P-fertilization techniques significantly affected soil carbon fractions and carbon management index in the present study. In comparison to FBCT system, the PRBZT system significantly improved very labile carbon by ~7.96 % among crop establishment techniques. Also numerous investigators have observed that soils with ZT systems had higher increased very labile carbon concentrations than soils with CT systems (Kaberi and Rajkhowa, 2023). It could be because, in contrast to conventional tillage, ZT systems usually require less soil disturbance. Soil structure and organic carbon content are preserved through reduced tillage and reduced foot movement. In open fields, soil disturbance can hasten the decomposition of soil organic matter and augment loss of carbon by oxidation or erosion (Yadav et al., 2021; Harish et al., 2022a, 2022b). The physico-chemical and biological properties of the soil and the residue availability influence the microbial activity of ZT plots and inturn influence the mineralization of the carbon into different forms (Lu et al., 2024). Retention of crop residue promotes carbon and nutrient cycling by aiding raise the labile pool of organic carbon ((Singh et al., 2020a,b, 2023)). The fundamental mechanism for SOC-sequestration in CA systems is this procedure (Kumar et al., 2022). Higher labile, less labile, and non-labile carbon were obtained with the PRBZT system as opposed to the CT-based FBCT method. Crop residues, which offer a steady supply of organic matter that decomposes quickly, could be the cause (Kumar et al., 2022; Gupta et al., 2022). Lower disturbance of the soil under ZT contributes to the protection of these carbon pools against loss and decomposition, which ultimately raises active and passive carbon pools (Kumar et al., 2021). This implies that tillage methods have a considerable influence on the distribution and state of soil carbon. At the end of two-year cropping cycle, the PRBZT led to favorable changes in soil very labile labile, less labile, labile carbon, active and passive carbon pools. It created a microclimate that is warmer and more stable, promoting a rise in plant biomass production and soil organic matter formation, which raises soil carbon fractions (Shrivas et al., 2023). Due to their dynamic character, the trends displayed here suggest that SOC sequestration might ends up in active as well as passive C-pools in varying amounts (Gupta et al., 2022). Additionally, after tillage methods, a sizable amount of SOC gains or losses are attributed to active C-pools (Sharma et al., 2021).

In P-fertilization practices, significantly higher very labile carbon was recorded under P_{100}, which is explained by P involvement in encouraging strong plant growth. More biomass is produced by healthy plants, including residues and roots, which breakdown into highly labile carbon components. The levels of very labile carbon go up as a result of increase in organic inputs. On the other side, passive carbon pool was considerably higher by 13.1 % in the P_{50}+PSB + AMF+2FSP over P_0 practice. According to Verma et al. (2024), the enhancement of passive carbon pools indicates improved soil organic matter stabilisation with phosphorus application. Because phosphorus promotes plant development, it increases root biomass and residue return to the soil, which helps stabilize passive carbon pools (Kumar et al., 2022). Better long-term stabilisation of very stable carbon fractions is shown by the small increase in non-labile carbon. According to Bhattacharyya et al. (2015), phosphorus promotes strong plant growth, which increases root biomass and soil organic matter that can be preserved in soil aggregates and lowers decomposition rates. Increased P-level application in the soil promotes microbial decomposition and nitrogen cycling, among other biological activities leading to better nutrient uptake and enhanced yields (Singh et al., 2020a,b). A larger carbon pool and greater carbon fractions result from faster organic matter degradation caused by increased microbial activity (Kumar et al., 2018, 2022). The ZT provides protection from extreme weather conditions including intense rain, drought, or strong winds in contrast to CT. According to Babu et al. (2020), these safeguards change SOC lability and lability-based indicators like lability index, carbon pool index, and carbon management index in addition to reducing soil erosion.

In the current experiment, at soil depths of 0–15 cm, increased carbon pool index and carbon management index were seen under the PRBZT plots as opposed to CT-based FBCT plots. The carbon pool index represents the amount of carbon that has accumulated relative to the reference carbon. According to Parihar et al. (2017), a larger carbon pool index value reflects greater SOC buildup in the soil. According to research on active and passive carbon pools, growing crops continuously under CA has a significantly greater influence on SOC content. This emphasizes the significance of integrating carbon by crop residues to improve soil carbon pools, which finally results in enhanced crop productivity(Babu et al., 2020; Kumar et al., 2022).

Increased carbon fractions in the CA environment were directly connected with higher carbon pool index and carbon management index (Lal et al., 2019). The carbon pool index and carbon management index were also improved by the integration of crop residues in the ZT system (Layek et al., 2018). The existence of micro-aggregates inside of bigger macro-aggregates acts as a barrier to keep microbes from destroying SOC. Conservation agriculture controlled microclimatic conditions encourage the formation of larger macro-aggregates (Singh et al., 2023). It has been widely argued that applying CA methods is a productive means of raising carbon management index in a variety of ecological regimes. According to Layek et al. (2022), carbon management index is a helpful indicator for tracking soil quality, measuring soil

C-accumulation, and contrasting the results of different farming techniques. Higher carbon management index values signify a considerable improvement in soil quality and SOC through crop rotation or management measures, resulting in higher root attributes and yield (Li et al., 2023a).

According to the current study, P management techniques had a significant influence on the carbon management index within 0–15 cm of depth. The P_{50}+PSB + AMF+2FSP practice had the highest carbon management index and carbon pool index values when compared to other practices. It could be caused by the concurrent application of P, which showed an affirmative correlation with enhanced carbon management index in the top soil layer. This suggests that there has been a significant build-up of SOC in the upper soil layers as a result of increased biomass production and a constant supply of biomass, crop residues, and root exudates to the soil. The large input of organic matter results in increased carbon fractions, which in turn expand the soil's carbon pool (Choudhary and Rahi, 2018; Li et al., 2023b). According to numerous researchers, P-fertilization strategies, which control soil carbon storage and improve the carbon pool index and carbon stability, are responsible for the increased carbon inputs that result in this augmentation (Li et al., 2024).

4.8. Phosphorus nutrient budgeting

Given that the majority of Indian soils have a low to medium phosphorus supply; P fertilization techniques for the maize-wheat rotation require further consideration due to the low use efficiency of applied P. With an average effectiveness of only 10–15 %, availability of P to plants is a serious limitation in the majority of arable soils worldwide (Harrier and Watson, 2003; Kumar et al., 2014, 2015). Furthermore, the prohibitive expenses associated with phosphate fertilizers impede farmers with limited resources from implementing the recommended P dosages (Choudhary et al., 2008; Bai et al., 2017). Therefore, we must create effective P management strategies, such as foliar-P fertilization in MWR, which may be one of the creative interventions for ensuring sustainable food and nutritional security in the current socio-agro-economic scenario, especially under CA-based crop management, in order to improve P-use efficiency with high economic returns (Choudhary et al., 2018, 2020). Application of 60 kg phosphorus per hectare is generally advised; this is significantly less than the amount of P taken by wheat and maize crops, particularly in cases where crop residues are not recycled back into the soil (Bijay-Singh, 2004). As a result, native soil-P consistently serves as the only source of P supply for the nation's widely used agricultural systems (Sarkar et al., 2014), which worsens the soil's P status and crop productivity (Choudhary et al., 2018, 2020). In order to evaluate the effectiveness of different crop establishment methods and P-fertilization techniques under MWR, phosphorus nutrient budgeting was carried out in the current study.

The current study indicated that, in PRBZT plots where crop residues were preserved, there was a larger uptake of phosphorus and an actual balance; in FBCT plots, where no residues were retained, the lowest values were reported. Actual phosphorus addition and uptake was shown to be highest under P_{50}+PSB + AMF+2FSP treatment, where the yields were highest, and lowest under control (P_0), where the yields were lowest, among P-fertilization techniques. It shows that where residues were kept along with the integrated application (P_{50}+PSB + AMF+2FSP) of 50 % P as soil applied-P, microbial inoculants and foliar applied-P, uptake and actual addition of P increased. This is because there is less P fixation, more solubilisation and mobilisation, and synergistic effects, which improve plant acquisition and uptake (Harrier and Watson, 2003; Kumar et al., 2015; Bai et al., 2017; Rafiullah et al., 2018). It is already well known that P interacts positively and synergistically with N and K. On the other hand, actual P balance was greater and positive than projected P balance using other crop establishment and tillage management approaches, while expected negative P balance was found to be quite high under PRBZT–PRTZT plots in all treatments. This could be because crop residues were added, which greatly increased the soil's SOC and available-NPK (Bajpai et al., 2006; Govaerts et al., 2007). The study of P-fertilization practices revealed that the highest expected deletion was observed under no P treatment, and the highest actual P addition observed with P_{50}+PSB + AMF+2FSP treatment. This variation can be accredited to the positive affirmative effect of applying P through multiple sources, which results in an efficient use of applied P (Harrier and Watson, 2003; Bai et al., 2017). Therefore, compared to other treatments where the complete dosage of P was supplied as basal to the soil, P_{50}+PSB + AMF+2FSP treatment showed reduced P fixation, ehncaced root growth and higher system productivity.

5. Policy and recommendations

Promote the widespread adoption of CA practices across South Asia to increase the sustainability of agricultural production systems. Policy should focus on integrating zero tillage, residue retention, microbial inoculants, and optimized nutrient management to enhance the soil health, use efficiency of resources, and food security while minimizing environmental impact. Encourage the adoption of double zero tillage practices, PRBZT for key cropping systems such as maize-wheat. This method has demonstrated higher productivity, better root architecture, improved soil health, and higher carbon sequestration potential. Provide incentives such as subsidies, training, and equipment support for farmers to transition from conventional tillage to CA based tillage practices. Promote P-fertilization strategies that incorporate biofertilizers like PSB, AMF and foliar application of P to reduce dependency on synthetic fertilizers. Recommend the use of 50 % P + PSB + AMF +2 foliar P sprays to optimize fertilizer use, reduce environmental impact, and achieve nutrient efficiency. Implement soil conservation measures to improve SOC, microbial activity, and aggregate stability, particularly with PRBZT system. Provide incentives such as carbon credits for ecosystem services to farmers adopting practices that enhance soil quality and health. Promote water-saving techniques like residue retention and double zero tillage to increase water-use efficiency and productivity, particularly in resource-constrained and semi-arid regions. Provide financial and technical support for farmers practicing mulching and residue retention at rates of 6 t ha^{-1} to improve water productivity. This could involve government led programs that distribute mulching materials or equipment. Develop training programs for farmers on the benefits of CA and integrated nutrient management using biofertilizers and P foliar sprays. Launch educational campaigns, workshops, and extension services to build smallholder farmers' capacity to implement conservation practices effectively, in partnership with local agricultural universities and research institutions. Support ongoing research and monitoring to assess the long-term effects of CA and integrated nutrient management on soil health, carbon sequestration, and productivity. Establish collaborative projects between government, research institutions, and agricultural organizations to refine practices and ensure scalability across diverse agro-climatic zones in South Asia (Supplementary Fig. 6). These policies will enhance food security; resources-use efficiency, carbon pools, and promote sustainable agricultural practices.

6. Conclusions

In summary, the study highlights the effectiveness of CA based double ZT PRBZT system combined with P_{50}+PSB + AMF+2FSP fertilization within the MWR on South-Asian Inceptisol soils. The approach proved superior in supporting crop growth, enhancing root structure, improving resource-use efficiency, and boosting soil's physical, chemical, and biological properties. It also optimized carbon and phosphorus fractions, promoting a balanced phosphorus budget and minimizing phosphorus loss. The practice contributes to better carbon sequestration and higher SOC levels, improving soil health and resilience to climate change. Notably, optimized phosphate fertiliser management across both crops resulted in a 34.7 % reduction in fertilizer-P use, compared to other treatments, while maintaining a positive phosphorus budget and improving resource-use efficiency.

For farmers in North India's Indo-Gangetic Plain Region, adopting the PRBZT system combined with optimized phosphate fertilizer management is recommended for enhancing root architecture, resource efficiency, and soil health sustainably. This practice directly contibute to achieve SDG 2 (Zero Hunger), SDG 13 (Climate Action) and SDG 15 (Life on Land) thereby advancing ecosystem resilience and productivity.

CRediT authorship contribution statement

M.N. Harish: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Data curation. **Anil K. Choudhary:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Data curation, Conceptualization. **Anchal Dass:** Project administration, Methodology, Data curation. **V.K. Singh:** Project administration, Methodology, Data curation. **G.A. Rajanna:** Writing – review & editing, Writing – original draft. **R.S. Bana:** Writing – review & editing, Data curation. **V. Paramesh:** Writing – original draft, Methodology, Data curation. **T. Varatharajan:** Validation, Data curation. **Ingudam Bhupenchandra:** Validation, Methodology, Data curation. **R. Sadhukhan:** Writing – review & editing. **Adarsh Kumar:** Writing – review & editing, Writing – original draft. **K. S. Sachin:** Writing – review & editing, Data curation. **K.G. Teli:** Writing – review & editing, Data curation. **S.R.K. Singh:** Writing – review & editing. **A.A. Raut:** Writing – review & editing. **M.S. Sannagoudar:** Writing – review & editing. **L. Muniyappa:** Software, Data curation. **H. P.N. Prasad:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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Data availability

The authors do not have permission to share data.

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