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Tillage-based nutrient management practices for sustaining productivity and soil health in the soybean-wheat cropping system in Vertisols of the Indian semi-arid tropics

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To achieve higher crop production in a soybean-wheat cropping system, comprehensive knowledge of soil fertility status and its variability is crucial. However, a significant gap exists between the potential and actual productivity of this system in the Vertisols of Indian semi-arid tropics. Therefore, 2 years of field research were conducted to investigate how different crop management practices affect soil fertility in this cropping system. The trial was conducted using a randomized complete block design (RCBD) with five crop management practices: CAO (conservation tillage + organic nutrient and weed management), CAC (conservation tillage + chemical nutrient and weed management), CTC (conventional tillage + chemical nutrient and weed management), OCT (conventional tillage + organic nutrient and weed management), and PoPs (package of practices). Results showed that CAO significantly ($p < 0.05$) increased soil organic C (6.8 g kg^{-1}), available N (129.5 mg kg^{-1}), P (11.0 mg kg^{-1}), K (232.6 mg kg^{-1}), Fe (9.17 mg kg^{-1}), and Mn (10.48 mg kg^{-1}) at topsoil (0–15 cm) and deeper layers (15–60 cm). In contrast, CAC had significantly ($p < 0.05$) higher soil availability of Ca (5,072 mg kg^{-1}) and Mg (901 mg kg^{-1}) and Cu (0.84 mg kg^{-1}). On the other side, PoPs resulted in the highest S (10.05 mg kg^{-1}) and Zn (0.85 mg kg^{-1}) availability in the topsoil. Our results evidently suggested S and Zn availability as key indicators of soil health sustenance in the present agroecosystem. Notably, CAC had significantly ($p < 0.05$) higher system productivity (4.62 t ha^{-1}) than the other treatments, showing a 14.0, 6.3, and 18.2% increase over CAO, CTC, and OCT, respectively. Based on the results, it is recommended that CAC is a better option for achieving higher system productivity, while CAO is the best option for ensuring long-term sustainability of soil fertility. The findings of this study could be useful for farmers and agricultural researchers in designing efficient crop management practices to improve the productivity and sustainability of soybean-wheat cropping system in arid to semiarid ecology.

KEYWORDS
conservation agriculture, nutrient availability, organic farming, soil depth, sustainability

1. Introduction

The soybean-wheat cropping system is one of the 30 prevalent cropping systems in India and is mostly practiced in the semi-arid tropics including the states of Madhya Pradesh, Maharashtra, and Rajasthan (NMOOP, 2014). This cropping system gained importance in the 1980s when soybean was introduced as a *kharif* (rainy season) crop in the wheat-based cropping systems of India with assured canal irrigation (Ramesh et al., 2017). Soybean and wheat have been vital in addressing food and nutrition security in India (NAAS, 2017). However, system productivity of this cropping system has remained low compared to the national average over the years (Choudhary et al., 2018), particularly in the semi-arid tropical zone of Rajasthan, India. Due to the irrigated ecology, this system productivity is not constrained by soil moisture stress, which is otherwise observed in many parcels of India (Dev et al., 2022; Garg et al., 2022). One of the major factors constraining the productivity of the soybean-wheat cropping system in India is depleted soil fertility and quality (Behera et al., 2007); while the other factors include diseases and pests (Ramesh et al., 2017) and heat stress and/or weather aberrations (Lenka et al., 2016). Soil fertility has deteriorated continually due to mismanagement practices, soil disturbances, and higher nutrient exhaustion caused by high-yielding, input-responsive cultivars of cereals and pulses that have been released since the 1960s (Debnath et al., 2020, 2022). The problem lies in the fact that farmers intensively practice farming in India without appropriate crop management practices, as they are more concerned with monetary returns than caring for soil health (Roos et al., 2018; Sharma et al., 2021). This lack of attention to soil health is adversely affecting crop production, productivity, and the sustainability of soil in the region.

One potential solution to this challenge is to adopt appropriate land management practices that include adequate nutrient management and minimum soil disturbance. The current over-reliance of farmers on inorganic fertilizers to boost crop production without incorporating organic amendments can cause irreparable damage to soil properties and negatively impact the soil environment (Devi et al., 2013). Using a combination of organic and inorganic sources of nutrients can improve soil physicochemical properties, promote the growth of beneficial soil microorganisms, and maintain soil nutrient balance in the cropping system (Zhao et al., 2023). On the other side, conventional tillage practices performed over an extended period can lead to physical degradation of the soil, reduce organic carbon and microbial biomass, and ultimately reduce desirable yield (Singh et al., 2009; Bhan and Behra, 2014). In constrast, adopting conservation tillage practices can efficiently manage the soil for resource efficiency and higher productivity (Carpenter-Boggs et al., 2003; Jayaraman et al., 2021a,b).

There is a growing agreement among experts that conservation tillage practices, such as minimum tillage and residue mulch, have significant benefits for soil health. For instance, minimum tillage leads to improved soil water and carbon storage, better aggregate stability, and increased saturated hydraulic conductivity while reducing bulk density compared to conventional tillage (Jalota et al., 2001; Hati et al., 2015; Dal Ferro et al., 2023). In addition, retaining crop residues in the field has a direct or indirect positive impact on soil quality by reducing soil erosion, conserving soil moisture, maintaining hydrothermal conditions, and increasing soil porosity and infiltration (Zhu et al., 2023). Crop residues also provide energy for the growth and activity of microbes, which increases soil microbial biomass and carbon substrate for microbial biomass (Govaerts et al., 2007; Kätterer and Bolinder, 2023). Therefore, combining conservation tillage with inorganic and organic plant nutrients has the potential to improve soil fertility and crop productivity, which could lead to sustainable development opportunities for a nation like India.

The current fertilization practices in India focus solely on the nutrient needs of the succeeding crops, disregarding the residual effect of applied nutrients on the previous crops. Achieving a balance in nutrient application is crucial for optimizing the output of any cropping system. Globally most of the studies under conservation agriculture were conducted in combination with inorganic nutrients application only. However, there is lack of clear understanding on how conservation agriculture behaves under organic nutrient managements in terms of soil quality improvement and crop yield sustainability. While there have been previous studies on nutrient and tillage management practices in rice-rice (Yadav et al., 2017), rice-wheat (Jha et al., 2023; Dhaliwal et al., 2023a) and maize-wheat (Pramanick et al., 2022; Rani et al., 2023) cropping systems in India, their integrative effect on soil properties and system productivity in soybean-wheat cropping systems remains unexplored. To address these gaps, a two-year field investigation was carried out to examine the impact of conservation, organic, and conventional crop management practices on (i) soil physical and chemical properties, (ii) yield and system productivity, and (iii) key drivers of system productivity in soybean-wheat cropping systems. This study is intended to design efficient crop management practices to improve the productivity and sustainability of soybean-wheat cropping system in the semi-arid to arid ecology of India and many other parcels of the world with similar agroecology.

2. Materials and methods

2.1. Study site characteristics

A two-year field study was conducted at the Agricultural Research Station, Agriculture University, Rajasthan, India (25°10' N, 75°50′ E, and 267 m above msl) from 2018–19 to 2019–20 (Figure 1). The site experiences a subtropical climate with extremely warm and dry summers (April to June) and wet monsoons (July to September) during the soybean season and cold and harsh winters (November to January) during the wheat growing period. The mean maximum temperature ranges between 40 to 48.4°C during May–June, and the mean minimum temperature ranges between 2.0 to 8.5°C during December–January. The study area receives an annual rainfall of 660.6 mm, with the majority falling between the months of June–September. The

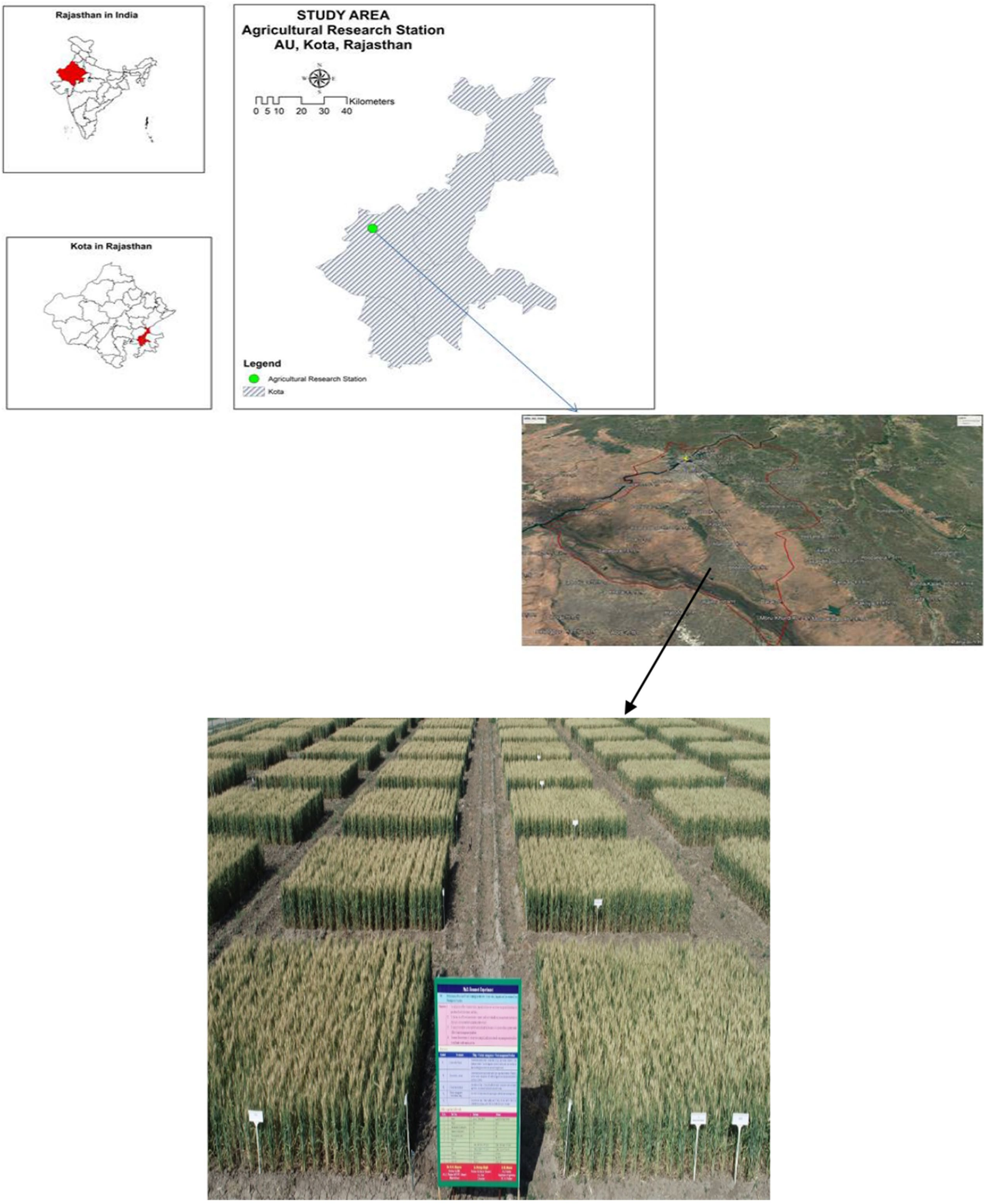

FIGURE 1
Location of the experimental site in the semi-arid tropics of India (Rajasthan).

experimental soil was moderately deep, well-drained, black Vertisols (United States Department of Agriculture classification), clay-loam in texture (sand 25.86%, silt 35.10%, and clay 38.94%), with neutral in soil reaction (7.41). The pre-crop topsoil (0–15 cm) contained organic C (5.1 g kg^{-1}), available N (104.5 mg kg^{-1}), P (9.4 mg kg^{-1}), K (196.0 mg kg^{-1}), S (7.5 mg kg^{-1}), and DTPA-extractable Zn (0.66 mg kg^{-1}), Fe (6.80 mg kg^{-1}), Cu (0.61 mg kg^{-1}), and Mn (7.21 mg kg^{-1}).

2.2. Treatments and experimental design

The study implemented various combinations of conservation tillage, organic, and chemical management practices, including nutrient and weed management, in a soybean-wheat cropping system. The treatments consisted of five scenarios, namely T1-conservation organic (CAO), T2-conservation chemical (CAC), T3-conventional chemical (CTC), T4-organic management + conventional tillage (OCT), and T5-package of practices (PoPs), which were randomly assigned in a randomized complete block design (RCBD) with four replications (Table 1). The plot size for each treatment was 389 m2 (48 m x 8.10 m). Before sowing the crops each year, well-decomposed farmyard manure (FYM) was incorporated into the soil based on the treatment requirements. The total N content in FYM was determined by Kjeldahl digestion following the distillation method (Jackson, 1973), and the FYM was also analyzed for total P, K, S, and Zn, Cu, Fe, and Mn contents through digestion with an HNO_3:$HClO_4$ (4:1) mixture and subsequent determination by vanadomolybdophosphoric acid, flame photometric method, and atomic absorption spectrophotometric method, respectively (Manna et al., 2012). The mean nutrient contents of FYM were analyzed as follows: N (0.50%), P (0.26%), K (0.50%), S (0.03%), Zn (24.80 ppm), Fe (173.90 ppm), Cu (5.15 ppm), and Mn (97.45 ppm). a slightly alkaline pH (7.41).

2.3. Crop management

Table 1 presents the agricultural techniques employed for cultivating the test crops, soybean and wheat, during the 2018–19 and 2019–20 seasons. In the rainy (*kharif*) season, soybean (cv. RKS 45) was sown using a seed drill in mid-July at a spacing of 30 cm (intra-row) x 10 cm (intra-plant) with a seed rate of 80 kg ha^{-1} and harvested in the last week of October. The experimental site was then irrigated for field preparation and sowing of the succeeding wheat crop in the winter (*rabi*) season. Wheat (cv. Raj 4,079) was sown at a spacing of 22.5 cm x 5 cm with a seed rate of 100 kg ha^{1}. Seeding was completed using a seed drill in the first week of December and harvested during the first week of April. Other crop management practices were carried out according to the assigned treatments (Table 1). During the 2018 *kharif* season, one life-saving irrigation was applied at the pod-filling stage [77 days after sowing (DAS)], while no irrigation was applied during the 2019 *kharif* season due to sufficient moisture availability at critical stages of soybean growth. However, during the *rabi* season, four irrigations were applied to the wheat crop at its critical growth stages during the experiment. For soybean, the total quantities of N, P, K, and S were applied as a basal dose, whereas for wheat, 100% of P, K, Zn, and 50% of N were applied at the time of sowing, and the remaining 50% of N was applied after the first irrigation (24 DAS) during the experiment.

2.4. Soil sampling and analysis

Composite soil sampling, involving four depth intervals (0–15, 15–30, 30–45, and 45–60 cm), was done form each plot using a soil auger with 6.0 cm internal diameter after harvest of each crop. The samples were dried in shade and then ground and passed through a 2.0 mm sieve for further laboratory analysis. The soil was analyzed for pH and electrical conductivity (EC; 1,2.5 w/v; Jackson, 1973), organic C (SOC; Walkley and Black, 1934), cation exchange capacity (CEC; Jackson, 1973), and exchangeable Ca and Mg (Jackson, 1973). The soil was also analyzed for also available nutrients like N (Subbiah and Asija, 1956), P (Olsen et al., 1954), K (Schollenberger and Simon, 1945), S (Chesnin and Yien, 1950), Zn, Fe, Cu, and Mn (Lindsay and Norvell, 1978). Bulk density (BD) of experimental site was measured using a core sampler (Blake and Hartge, 1986), and the soil porosity was calculated by the following equation:

$$\text{Porosity}\,(\%) = 1 - \frac{\text{Bulk Density}}{\text{Particle Density}} \times 100$$

2.5. Yield and system productivity of cropping system

At maturity, soybean and wheat crops were harvested manually for economic yield, and the equivalent yield and system productivity were calculated using the following equations:

$$\text{Soybean equivalent yield of wheat}\left(\text{tha}^{-1}\right) = \frac{\text{Yield of wheat}\left(\text{tha}^{-1}\right) \times \text{MSP of wheat}\left(₹\text{t}^{-1}\right)}{\text{MSP of soybean}\left(₹\text{t}^{-1}\right)}$$

System productivity was calculated by adding the soybean yield and soybean equivalent yield of the wheat for the respective years.

$$\text{System productivity (SEY)} = \frac{\text{Yield of soybean}\left(\text{tha}^{-1}\right) \times \text{MSP of soybean}\left(₹\text{t}^{-1}\right)}{\text{MSP of soybean}\left(₹\text{t}^{-1}\right)} + \frac{\text{Yield of wheat} \times \text{MSP of wheat}\left(₹\text{t}^{-1}\right)}{\text{MSP of soybean}\left(₹\text{t}^{-1}\right)}$$

The minimum support price (MSP) was for soybean (₹ 34,000 t^{-1} and ₹ 37,000 t^{-1}) and wheat (₹ 18,400 t^{-1} and ₹ 19,250 t^{-1}) during the year 2018–19 and 2019–20, respectively. 1 USD ($) = 82 INR (₹).

2.6. Statistical analysis

The data presented in this study were pooled from both years and analyzed using two-way analysis of variance (ANOVA) in Statistical Analysis Software v9.4 (SAS Institute, 2016; Supplementary Table S1) and R statistical software (R Core Team, 2016). The relationship between various treatment scenarios and variables was calculated, and the variables were classified based on stability and mean (Yan and Kang, 2002). The effect of different treatments on soil chemical properties was analyzed using a biplot analysis through principal component (PC) with the support of R Studio (RStudio Team, 2014). A Pearson's correlation matrix (correlogram) was constructed to determine the degree of correlation between the tested soil variables.

3. Results and discussion

3.1. Soil physical properties

It was observed that the effects of different management practices on soil bulk density (BD), particle density (PD), and porosity under

TABLE 1 Details of tillage, weed and nutrient management imposed in the present experiment.

	Season/crop	T_1: Conservation organic (CAO)	T_2: Conservation chemical (CAC)	T_3: Conventional chemical (CTC)	T_4: Organic management + conventional tillage (OCT)	T_5: Package of practices (PoPs)*
Tillage	*Kharif* / Soybean	One ploughing and direct sowing through seed drill, previous crop biomass retention (wheat @ 2.5 t ha^{-1})	Same as in T_1	One summer ploughing, two ploughing with planking and sowing through seed drill	Same as in T_3	Same as in T_3
	Rabi / Wheat	One ploughing and direct sowing through seed drill previous crop biomass retention (soybean 1.5 t ha^{-1})	Same as in T_1	three ploughing, sowing of wheat was completed through seed drill	Same as in T_3	Same as in T_3
Weed management	*Kharif* / Soybean	Non-chemical methods, i.e., dust mulch at 20 DAS under cultural method and hand weeding at 35 DAS under mechanical method.	Chemical method: a ready mixed herbicide *viz.* sodium acilfluorfen 16.5% + clodinafop propargyl 8% EC (165 + 80 g *a.i.* ha^{-1}) as sprayed at 25 DAS in soybean	Same as in T_2	Same as in T_1	Same as in T_2
	Rabi / Wheat	Non-chemical methods, i.e., dust mulch at 20 DAS under cultural method and hand weeding at 35 DAS under mechanical method.	Chemical method: a ready mixed herbicide *viz.* clodinafop-propargyl 15% WP + metsulfuron methyl 1% WP (48 + 4 g *a.i.* ha^{-1}) was sprayed as PE at 32 DAS in wheat crop	Same as in T_2	Same as in T_1	Same as in T_2
Nutrient management	*Kharif* / Soybean	Organic source N:P: K, 30:40:40 FYM 6 t ha^{-1} + PSB 600 g ha^{-1}	FYM + Fertilizer N:P: K, 30:40:40 FYM 5 t ha^{-1} + (Urea 11 + SSP 200 + MOP 25 kg ha^{-1})	FYM + Fertilizer N:P:K, 30:40:40 FYM 5 t ha^{-1} + (Urea 11 + SSP 200 + MOP 25 kg ha^{-1})	Organic source N:P:K:S, 30:40:40:30 FYM 6 t ha^{-1} + PSB 600 g ha^{-1}	FYM + N:P:K:S 20:40:40:30 FYM 10 t ha^{-1} + (Urea 65 + SSP 250 + MOP 67 + Elemental S 2.2 kg ha^{-1})
	Rabi / Wheat	Organic source N:P:K 180:40:30 FYM 36 t ha^{-1} + PSB 600 g ha^{-1}	FYM + Fertilizer N:P:K 180:40:30 FYM 5 t ha^{-1} + PSB 600 g ha^{-1} + (Urea 337 + SSP 250 + MOP 50 kg ha^{-1})	FYM+ Fertilizer N:P:K 180:40:30 FYM 5 t + PSB 600 g + (Urea 337 + SSP 250 + MOP 50 kg ha^{-1})	Organic source N:P:K 180:40:30 FYM 36 t ha^{-1} + PSB 600 g ha^{-1}	Fertilizer N:P:K:Zn 120:40:30:25 PSB 600 g ha^{-1} + (Urea 260.9 + SSP 250 + MOP 50 + $ZnSO_4.7H_2O$ 25 kg ha^{-1})

*T_5 – Incorporation of FYM@10 t ha^{-1} for package of practices once in a 3 year thus, applied only during experiment initiation *kharif* 2018.

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the soybean-wheat cropping system were non-significant (p > 0.05; Table 2). However, the conservation organic crop management practice resulted in a reduction of BD (1.2 Mg m−3) and subsequently increased soil porosity (51.8%) at the topsoil (0–15 cm). Previous studies have shown that minimum tillage and the application of organic manures for many consecutive years can reduce soil bulk density and increase porosity (Govaerts et al., 2009; Gathala et al., 2011). Soil bulk density is an important indicator of changes in soil physical condition and water holding capacity due to different tillage practices (Jin et al., 2007). Alam et al. (2014) observed a significant reduction in soil bulk density under zero tillage, minimum tillage, conventional tillage, and deep tillage when compared to initial values, which supports the results of our study.

3.2. Soil physico-chemical properties

Unlike soil physical properties, tillage and crop management practices had significant influence ($p<0.05$) on soil physico-chemical properties involving pH, EC, and SOC (Figures 2A–C). Conservation organic (CAO) and OCT resulted in lowering pH towards neutrality. Similarly organic management (CAO and OCT) significantly reduced EC as compared to CTC and PoPs. There was an increasing trend in pH and along the soil depths, irrespective of the treatments. Averaged across the depths, although CAO and OCT recorded higher CEC but remained at par with other treatments (Figure 2D). SOC showed a depleting trend along with increasing soil depth across the treatments (Figure 2). At 0–15 cm, the highest SOC was recorded under conservation organic (6.8 g kg^{-1}) followed by organic management + conventional tillage (6.6 g kg^{-1}), and the least was observed in the package of practices (5.6 g kg^{-1}). A similar trend was also noticed for other soil depths. Averaged over the soil depths, conservation organic (CAO) recorded 16.3% higher SOC as compared to PoPs over 2 years of experimentation.

Organic carbon in soil ecosystem is mostly controlled through a complex interaction between soil edaphic factors and land husbandry (Yadav et al., 2020). Residues and dead-decaying debris of crops are the main contributor to the organic carbon accumulation in the soil (Lal, 2004). Previous reports indicated that SOC can be increased by reduced tillage (Neugschwandtner et al., 2014) and by crop residues retention (Hati et al., 2015). Onward 60 cm depth, significant increase in SOC under CAO might be due to relatively high quantity of organic inputs through FYM and minimal soil disturbance resulting better permanency of soil organic matter (Hati et al., 2015; Mohanty et al., 2020; Yadav et al., 2020). A likewise increment in SOC under OCT again suggests that SOC accrual was chiefly governed by FYM addition rather than by tillage practices. Earlier, Meena et al. (2019) also demonstrated that FYM addition can significantly increase SOC content in the soil. Apart from increasing SOC, continuous addition of high quantity of FYM can also decrease soil pH (Hao and Chang, 2002; Rayne and Aula, 2020) by lowering the conductance, which corroborates our observation. On the other side, increase in CEC under CAO and OCT may be attributed to the presence of organic matter in manure that decomposes to increase the negatively charged sites on carboxyl and phenolic hydroxyl groups (Hao and Chang, 2002; Miller et al., 2016).

TABLE 2 Physical properties of soil as influenced by tillage, nutrient and weed management practices.

Treatments	Bulk density (g cm^3)	Particle density (g cm^3)	Porosity (%)
CAO	1.20 [a]	2.49 [a]	51.78 [a]
CAC	1.26 [a]	2.55 [a]	50.59 [a]
CTC	1.28 [a]	2.58 [a]	50.37 [a]
OCT	1.23 [a]	2.53 [a]	51.43 [a]
PoPs	1.30 [a]	2.60 [a]	49.98 [a]

Values followed by letter in common do not differ significantly ($p<0.05$) as per Tukey's HSD test.

3.3. Availability of primary nutrients

Tillage and crop management had a significant ($p < 0.05$) impact on the availability of primary nutrients (N, P, and K) as shown in (Figures 2E–G). The CAO crop management treatment had the highest availability of primary nutrients across all soil depths and was significantly ($p < 0.05$) higher than the PoPs treatment. Compared to PoPs, the CAO and CAC treatments showed about a 10.0% increase in N availability. Nitrogen availability decreased across all treatments from 126.2 (0–15 cm) to 89.9 mg kg−1 (45–60 cm). Similarly, compared to CTC and PoPs, conservation tillage with organic and chemical management greatly increased the availability of P (7.9 to 14.7%) and K (5.5 to 7.4%). This is further illustrated in the biplot analysis (Figure 3). Additionally, the availability of P and K decreased with increasing soil depth across all treatments. On the other hand, a strong positive correlation between SOC and the availability of primary nutrients was observed (Figure 4).

The higher availability of N, P, and K in conservation tillage with organic and inorganic nutrient and weed management may be attributed to the increased supply of organic matter and improved soil ecosystem for nutrient cycling. Organic manures, in general, act as slow-release fertilizers, and their decomposition leads to an enhanced availability of nutrients (Mandal et al., 2000; Meena et al., 2019). Previous studies have shown that combining N fertilizer with quality crop residues can have a positive interactive effect on mineral N (Gentile et al., 2008). In contrast, straw incorporation in soil has been found to increase microbial biomass and N mineralization, leading to a higher nutrient supply in soil (Eagle et al., 2000; Choudhary et al., 2018; Dhaliwal et al., 2023b). These observations suggest that both organic and inorganic nutrient management can increase nutrient availability in soils, supporting our findings. Additionally, changes in SOC due to tillage practices can influence N content, with conventional tillage resulting in greater losses due to frequent tillage, higher leaching, and mineralization losses (Lal, 1997; Cui et al., 2023). This may explain the lower N availability observed under CTC.

Again, higher availability of N and P was observed in surface soil under zero tillage and minimum tillage. The build-up of available P in soil is attributed to its constrained downward movement, as reported in previous studies (NzeMemiaghe et al., 2022). The higher availability of K and P under conservation and organic management practices might be attributed to reduced fixation or solubilization of fixed forms due to the higher prevalence of organic acids as well as mineralization of added organic manure, as reported in previous investigations (Yadav and Kumar, 2002; Berner et al., 2008; Mahanta and Rai, 2008; Elayarajan et al., 2015; Meena et al., 2019). Moreover, mobilization of non-exchangeable K into the soil solution might have increased its

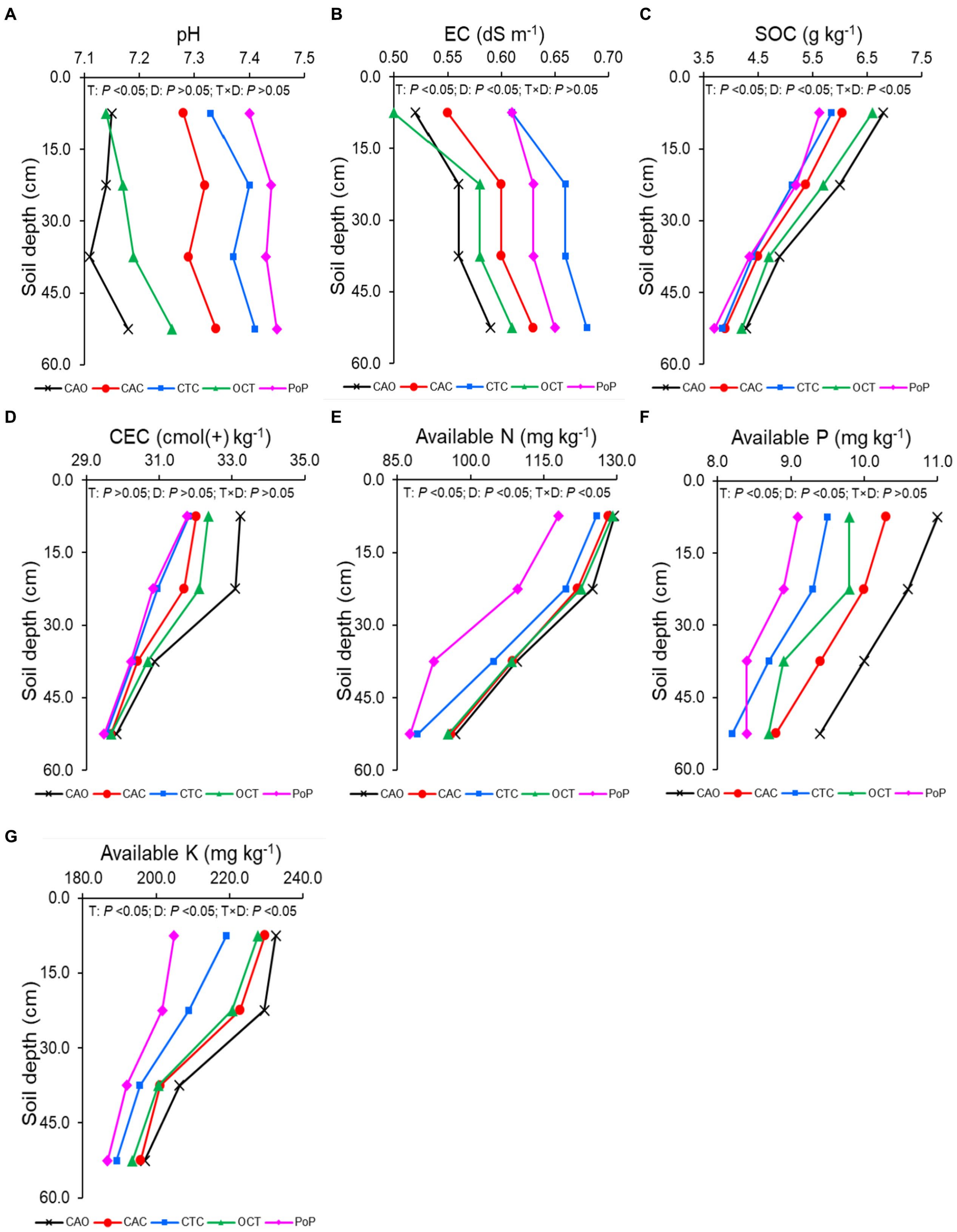

FIGURE 2
Depth-wise variation in the soil physico-chemical properties [**(A)**-pH; **(B)**-EC; **(C)**-SOC and **(D)**-CEC] and availability of primary nutrients [**(E)**-available N; **(F)**-available P and **(G)**- available K] as influenced by tillage, nutrient and weed management practices. Statistical significance ($p < 0.05$) was tested for treatment (T), soil depth (D) and treatment × soil depth (T × D). EC: electrical conductivity; SOC: soil organic C.

availability in the soil under conservation and organic management practices (Venkatesh et al., 2017). Simultaneous increase in soil organic carbon and availability of nutrients with crop residue amendments has also been reported in soybean (Singh and Rai, 2004) and is in line with our observation on positive correlation between SOC and primary nutrients.

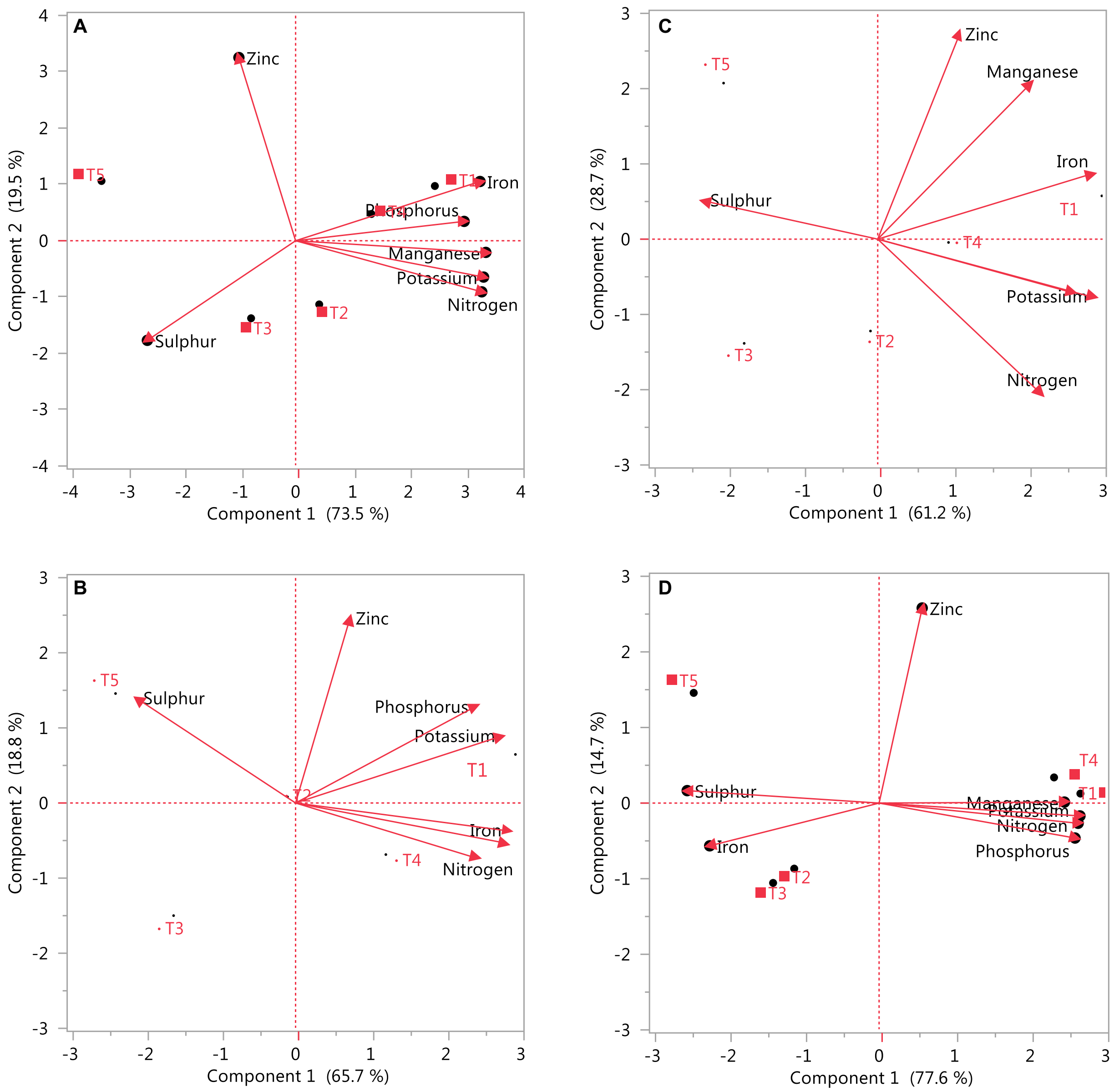

FIGURE 3
PCA biplot analysis of treatment effects (tillage, nutrient and weed management) on soil chemical properties. **(A)** 0–15 cm; **(B)** 15–30 cm; **(C)** 30–45 cm; **(D)** 45–60 cm. The abbreviation section includes key to the label of treatments.

3.4. Availability of secondary- and micro-nutrients

The availability of Ca, Mg, S, (Figures 5A–C) and micronutrients (Figures 5D–G - available Zn, Fe, Cu, and Mn) at different soil depths was significantly ($p < 0.05$) affected by tillage and crop management practices (Figure 5). The CAC treatment showed the highest availability of exchangeable Ca and Mg, which was significantly ($p < 0.05$) higher than the CAO and OCT treatments. Conversely, S availability was comparable between CAC and PoPs but remained significantly ($p < 0.05$) higher than the other treatments. Notably, the least availability of secondary nutrients was observed in OCT. Zinc availability was significantly ($p < 0.05$) higher with PoPs, followed by CAO (Figure 5). Furthermore, Fe and Mn availability increased by 6.5 and 17.3%, respectively, with CAO compared to PoPs management. However, Cu availability was significantly ($p < 0.05$) higher with CAC than the other treatments. Similar to primary nutrients, the availability of secondary and micronutrients also decreased with increasing soil depth across all treatments. Apart from the availabilities, a close view of the biplot graphs revealed distinct position of S and Zn across the soil depths (Figure 3).

Overall, the availability of secondary and micronutrients in the soil was greatly improved by the addition of nutrients from organic and inorganic sources, as well as by tillage practices that affected both the quantity and mineralization of nutrients in the soil. Our results support the findings of Gadana et al. (2020), who also reported a positive impact of soil management practices on exchangeable cations and soil micronutrients. Crop residue retention and the addition of organic manure and mineral fertilizers provided an added advantage for better microbial growth, which accelerated nutrient mineralization and led to enhanced nutrient availability (Kiboi et al., 2021). It is worthy to note that the availability of secondary nutrients remained

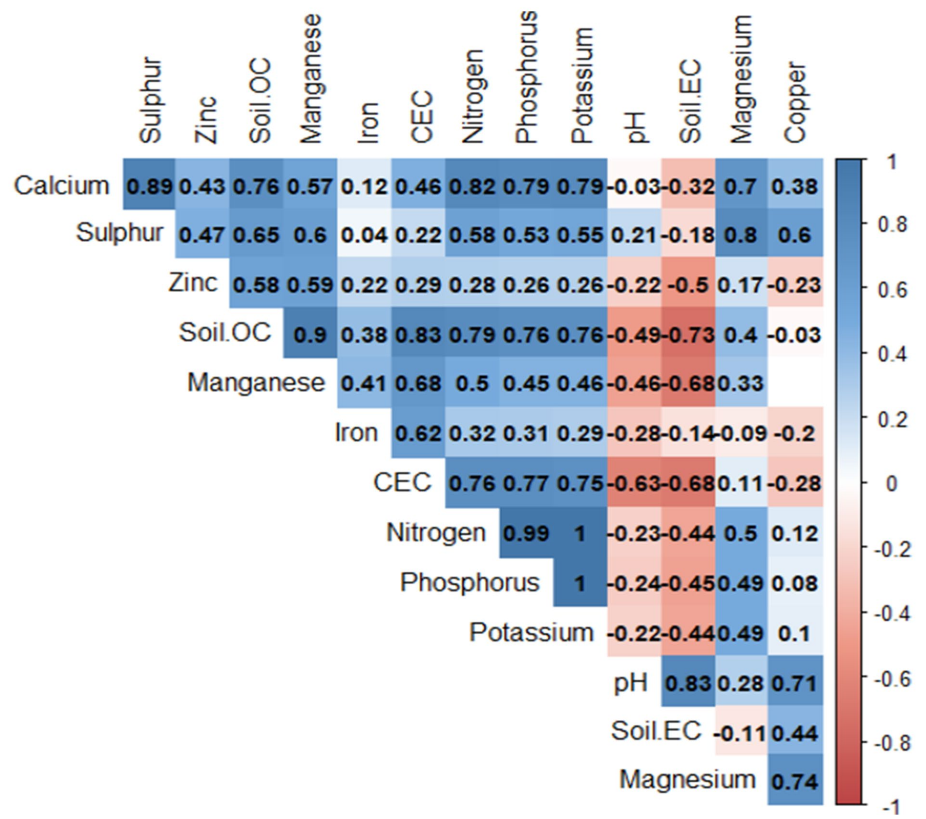

FIGURE 4
Correlogram (Pearson) of different soil fertility parameters as affected by tillage, nutrient and weed management practices.

high for the treatments receiving chemical fertilizers in conjunction with manure. In this study, we used single superphosphate as the P source, which contains a fairly high quantity of Ca and S (Barker, 2019). Therefore, the increased availability of these nutrients in chemically fertilized plots is not surprising.

Regardless of the management practices, the soil in this study showed high availability of micronutrients in comparison to the critical limits identified for Indian soils (Katyal and Sharma, 1991; Debnath et al., 2022), which contrasts with the marginal to medium status of available Fe and Zn and the medium to high status of available Mn and Cu concentration in farmed Vertisol parcels in India (Somasundaram et al., 2009). Therefore, conservation tillage coupled with organic nutrient management may be a sustainable practice to maintain the availability of micronutrients in the soils of this region. However, their removal from crop biomass with continuous cropping may decrease their phytoavailability in soils in the future. Periodical soil testing may thus help to decipher their depletion in soil so as to undertake appropriate remedial measures. Distinct position of S and Zn in biplots suggests their role as key indicators of sustaining soil health in the soybean–wheat systeam in arid ecology. Therefore, periodic monitoring of their availability remains indispensable to avoid yield trade-offs due to their short supply.

Compared to the 30–45 cm depth, a slightly higher availability of micronutrients was observed at the 45–60 cm depth, possibly due to leaching from the upper layer and accumulation at a later soil depth. However, this effect was absent for secondary nutrients, suggesting their leaching into deeper soil layers. This indicates that the leaching of micronutrients into deeper soil layers was possibly prevented by the formation of organo-mineral complexes or chelation due to organic inputs and increased soil organic matter (SOM). The higher availability of Zn with PoPs and CAO may be due to Zn application and organic matter addition, respectively. Our results also suggest that conservation tillage had a significant effect on Fe availability. Similarly, Jayaraman et al. (2021b) reported that available Fe concentration was relatively higher under no-till than conventional tillage in vertisols of Central India. The hierarchical clustering analysis of different soil properties suggests that organic matter addition has significantly improved the availability of Cu and Mn (Figure 6).

3.5. System productivity of cropping system

The soybean-wheat cropping system registered the maximum system productivity (SEY) in CAC with a yield of 4.62 t ha^{-1}, which was significantly higher by 13.96 and 18.17% compared to CAO and OCT, respectively (Table 3). However, SEY of CAC and PoPs was statistically similar. Although nutrient availability increased with organic nutrient management combined with conservation or conventional tillage practices, it did not enhance SEY. This suggests that other factors may have influenced the yields of different treatments. Kravchenko Alexandra et al. (2017) also reported yield penalties of 10–30% under organic management during the initial years. Effective weed management and timely availability of nutrients to the crop under CAC could be the prominent reasons for comparatively higher yields. Tillage

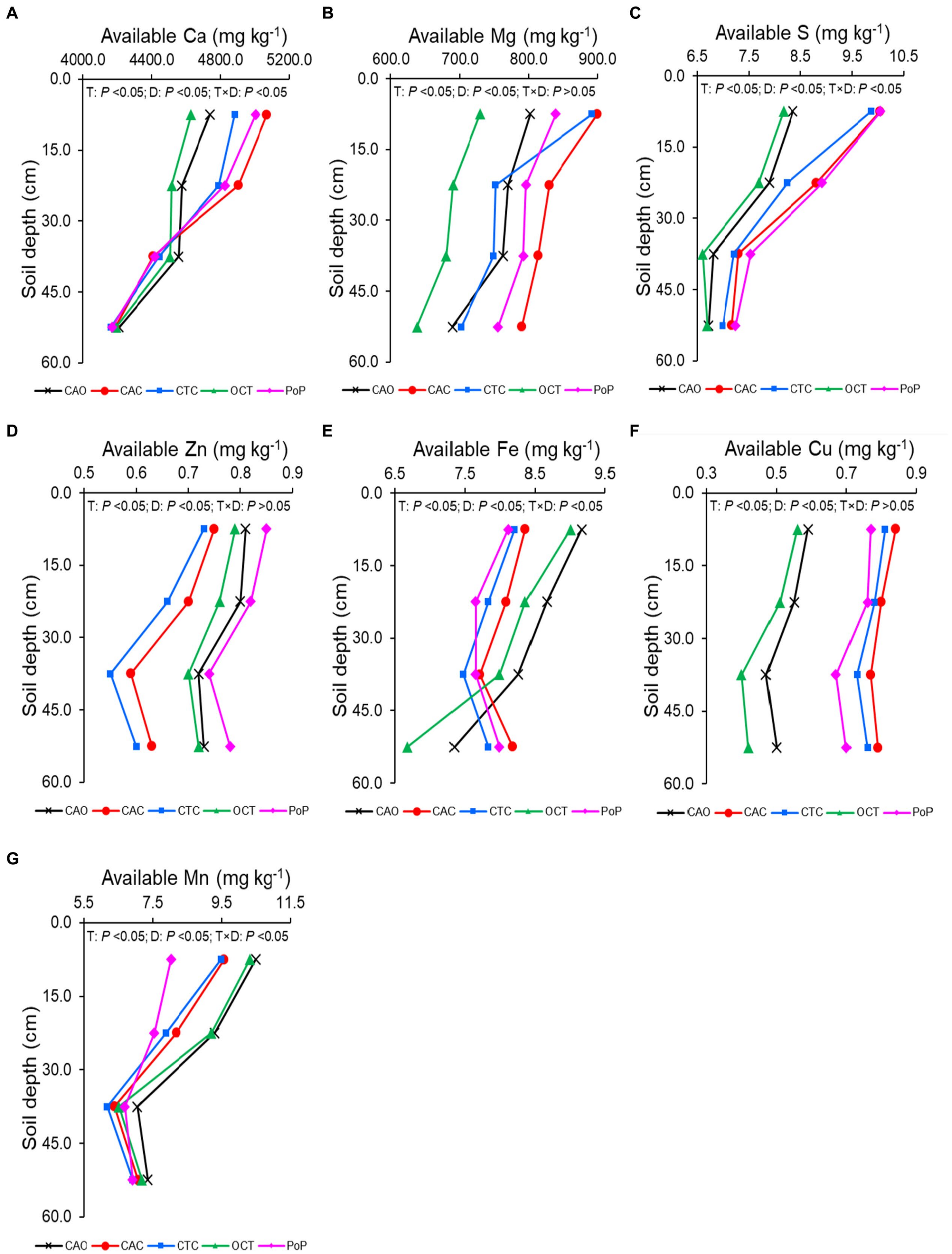

FIGURE 5
Depth-wise variation in the availability of secondary [**(A)**-available Ca; **(B)**-available Mg and **(C)**- available S] and micro-nutrients nutrients as [**(D)**- available Zn; **(E)**-available Fe; **(F)**- available Cu and **(G)**-available Mn] influenced by tillage, nutrient and weed management practices. Statistical significance ($p < 0.05$) was tested for treatment (T), soil depth (D) and treatment × soil depth (T × D).

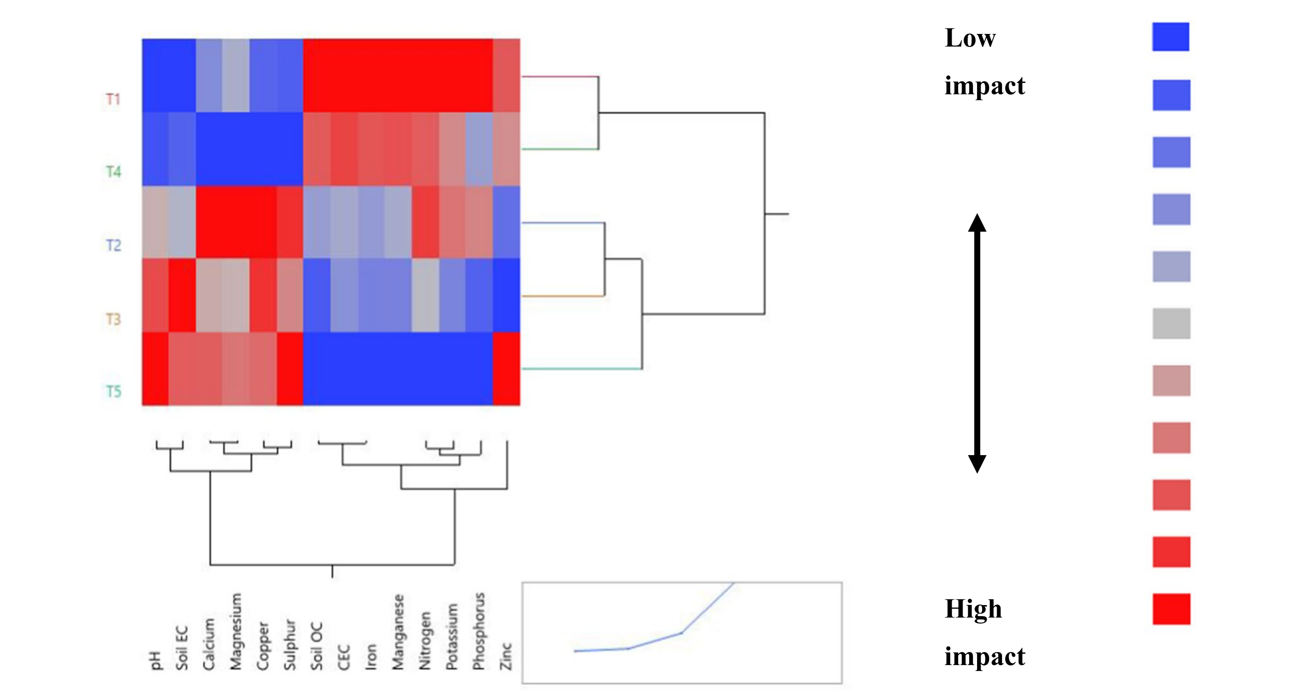

FIGURE 6
Hierarchical clustering of different soil chemical properties as affected by tillage, nutrient and weed management practices.

TABLE 3 Yield and system productivity of soybean-wheat cropping system as influenced by tillage, nutrient, and weed management practices.

Treatments	Soybean seed yield (t ha^{-1})	Wheat grain yield (t ha^{-1})	System productivity (t ha^{-1})
CAO	1.64	4.55	4.05
CAC	1.85	5.21	4.62
CTC	1.77	4.86	4.34
OCT	1.56	4.41	3.91
PoPs	1.85	5.09	4.55
SEm±	0.05	0.15	0.09
CD ($P < 0.05$)	0.15	0.43	0.27

SEm±: Standard error ($n = 4$). CD: Critical difference.

operation, nutrient management, and leguminous crops can significantly influence crop yields in a cropping system (Alam et al., 2020). Meena et al. (2022a, 2022b) also reported that CAC evolved as a better crop management practice under the soybean-wheat cropping system, producing the maximum economic yield of soybean over a regime of practice involving the recommended package of practices: conventional tillage + chemical, conservation tillage + organic, and conventional tillage + organic nutrient management.

4. Conclusion

Our study highlights the importance of the soybean-wheat cropping system for improving soil fertility and ensuring sustainable yields. Organic nutrient and weed management, combined with conservation or conventional tillage, improved soil fertility attributes such as SOC, N, P, K, Ca, Mg, Zn, and Fe but had no significant impact on soil physical characteristics. However, the effects of these management practices on soil fertility attributes were predominantly limited to topsoil (0–15 cm) alone. Our results clearly demonstrated that SOC accrual in the soil was primarily governed by organics addition rather than by tillage practices. Again, the results elucidated S and Zn as key indicators of sustaining soil health in the soybean–wheat systeam of arid ecology and therefore, warrants periodic monitoring of their availability to circumvent yield trade-offs, if there be any, due to their deficiency. The highest system productivity was achieved through the use of chemical herbicides and fertilizers in conjunction with conservation tillage (CAC), which is likely due to effective weed control and instantaneous nutrient availability. Nevertheless, adoption of conservation tillage with organic nutrients and weed management technology can be a long-term strategy for sustaining soil fertility under soybean-wheat cropping system in arid to semiarid ecology, which may help ensuring global food security in the future.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

SN: implementation of field experiment, observation recording, monitoring, and other management practices related to study. SS:

designed the study and guidance. AR, BM, DJ, SD, and DS: manuscript writing, edition and statistical analysis and interpretation of data; DJ and SM: editing and interpretation of results. SY, PV, UD, JM, and SN: technical help, contributed in sample analysis, soil analysis, and drafting. PS: conceptualize the study and guidance during study. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2023.1234344/full#supplementary-material

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