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Preeti, Sunita Sheoran, Dhram Prakash, Ankit, Todarmal, Sonia Rani, Rameshwar Singh, Parmod Kumar Yadav & Rajni Kant Sharma

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Soil carbon, micronutrients and microbiological dynamics under cash crop-based cropping systems in semi-arid National Capital Region of India

Preeti[a,₹], Sunita Sheoran[a,₹], Dhram Prakash[a,₹,*], Ankit[ab,₹], Todarmal[c], Sonia Rani[a], Rameshwar Singh[a], Parmod Kumar Yadav[a], Rajni Kant Sharma[d]

[a]Department of Soil Science, CCS Haryana Agricultural University, Hisar-125004, Haryana, India
[b]Division of Soil and Crop Management, ICAR-CSSRI, Karnal-132001, Haryana, India
[c]Department of Agronomy, CCS Haryana Agricultural University, Hisar-125004, Haryana, India
[d]Department of Chemistry, CCS Haryana Agricultural University, Hisar-125004, Haryana, India
₹Authors contributed equally
*Corresponding Author E-mail address: dhramprakashteotia@gmail.com; sheoransunita27@gmail.com (S.S.),
pritisaini864@gmail.com (P., Preeti), dhramprakashteotia@gmail.com (D.P.),
ankityadav13419@gmail.com (A., Ankit), todarmal.poonia@gmail.com (T.),
sagwalsonia18@gmail.com(S.R.), rssinsinwar@gmail.com (R.S.),
pparmodyadava@rediffmail.com(P.K.Y.), rajniorganic@gmail.com (R.K.S)

*Tel.

Office: +91 1284 297200

Home: +91 1284 297015

Mobile: +91 9779943372

ABSTRACT

Cropping systems and nutrient management practices potentially alter microbiological properties and nutrients bioavailability in soils. This study evaluated the footprints of prevalent cash crops-based cropping systems at farmers' fields (>10 years) on total carbon (TC), total inorganic carbon (TIC), soil organic carbon (SOC), micronutrients as well as biological activities. The soils faced rice-wheat (RW) cropping system exhibited significant accrual in SOC (29.16%) over pearl millet-wheat (PW). Higher dissolved organic carbon (DOC) content was obtained in soils from sugarcane-sugarcane (SS) mono-cropping with a magnitude of 4.75, 9.01, 11.71 and 45.35% with respect to PW, RW, cotton-wheat (CW) and pearl millet-mustard (PM), respectively. Accretion of TIC (4.92 g kg^{-1}) and TC (11.26 g kg^{-1}) contents were acquired in soils experienced PM and SS cropping systems, respectively. DTPA-extractable micronutrients except copper (Cu) were found in higher concentration under RW compared to other cropping systems. In soils of RW cropping system, SOC, microbial biomass carbon (MBC), dehydrogenase activity (DHA) and DTPA-extractable Zn, Mn and Fe were higher by 3.33 to 58.97, 1.94 to 27.40, 23.81 to 51.59, 12.12 to 85.00, 25.73 to 58.05 and 15.17 to 83.44%, over other persisted systems. Despite the lesser chemical fertilization and manure addition, soils faced SS mono-cropping statistically reflected similar values to RW cropping system for most of studied properties. Two main canonical discriminant functions (CDFs), based on SOC, DOC, TIC, TC, DTPA-extractable micronutrients (Mn, Zn, Fe, and Cu), MBC and DHA, clearly differentiated the cropping systems and both CDFs explained 92.3% variance of the total variation. Principal component analysis (PCA) picked out MBC, SOC, pH and EC as most influential variables in evaluating soil status across various cropping systems. Additionally, two principal components (PCs) explained 73.7% of total variance in original dataset, underscored the major factors influencing soil properties under varied cropping techniques. Among the studied cropping systems, RW was found superior in relation to the soil microbial activity and nutrient availability. However, SS mono-cropping also exhibited comparable results to RW and proved better over other aerobic cropping systems, especially in terms of carbon dynamics and microbiological properties of soils.

Keywords: Cropping system, Soil carbon fraction, Biological activity, Micronutrient

Introduction

The RW is a major cropping system in Indo-Gangetic Plains (IGP) of India covering around 10 million hectares area [1] of Punjab, Haryana, Bihar, Uttar Pradesh and Madhya Pradesh; and accounts for 75% of nation's staple food production [2]. However, ceaseless RW cultivation created several issues, including soil degradation, nutrient depletion, declining water table due to over-extraction of groundwater, thus strongly posing a challenge to its sustainability [3-4]. Following RW, PW is the second important food production system and spanning approximately 2.26 million hectares area. Among oil seeds cultivation in India, mustard is the second important crop and is practiced over 5.6 million ha area [5]. The CW cropping system is cultivated in about 3.22 million hectares of Punjab, Haryana and Rajasthan, and has become increasingly significant in north-western IGP because of high profitability [6]. The SS cropping system is notably cultivated on approximately 4.85 million hectares in India and plays vital role in Haryana's agricultural landscape [7]. Cropping systems not only ruminate the agronomic choices of local farmers but also effectively shape the soil functioning, particularly in terms of fertility and organic matter status in soil [8]. In recent past, the emphasis is continuously increasing for sustainable agricultural practices to enhance productivity while ensuring the environmental quality, and ecosystem resilience [9].

The dynamics of SOC in soil is controlled by several components such as land use pattern, cropping systems, management practices and antecedent level of soil health [10-12]. Different cropping systems add on varying rates of organic materials with different chemical composition into soil, thus modulates the soil organic matter (SOM) turnover [13]. Apart from maintaining the soil productivity, SOM dynamism significantly contributes for soil structure formation and biological properties [14]. Therefore, understanding of SOM transformations is essential to plan the sustainable agricultural practices that would improve all the aspects of soil health [15]. In semi-arid regions, the varyingly exacerbation of SOM from agricultural lands contributes about one fifth of total CO_2 release [16]. Further, variations in management practices, moisture regimes, quality of crop residues and rhizo-deposition exert significant alterations in C pools [17]. Therefore, a precise evaluation of carbon (C) pools as source or sink under different land uses or management practices is imperative that ultimately contribute towards international C budgeting [18]. Dissolved organic carbon (DOC) represents the water-soluble fraction of SOC and controls the availability/mobility/leaching processes of nutrients and pollutants in soil [19]. The concentration of DOC in soil is influenced by plant root exudates, carbon inputs, residue decomposition, microbial activity and soil properties [20]. The soil inorganic carbon (SIC) fraction profoundly constitutes about 90 % of total carbon pool especially in arid and semi-arid areas [21] and is susceptible to disturbances such as land use pattern, intensive cropping, soil acidification, and moisture regimes changes [22]. The formation and dissolution of TIC; primarily the carbonate minerals; influence soil pH, buffering capacity, and long-term carbon sequestration [23]. Long-term field experiments advocate that integrating crop diversity, organic amendments, and minimal soil disturbance can significantly improve the TC levels, soil fertility and carbon sequestration potential [24]. Microbial biomass and enzymes activity regulate the transformations and bio-availability of nutrients in soil [25], thus facilitates early reflection of SOM decomposition and considered as most sensitive indicators of alteration in management practices than total SOM [26]. Although the microbial biomass carbon (MBC) is around only 1-3% of total SOC, yet extensively reflects the status of soil microbial activity [25, 27]. The geographical position, weather variables, soil factors and nature of adopted crop species collectively control the MBC dynamics in soil. Among soil enzymes, dehydrogenase activity (DHA) is one of the most valuable indicators for assessing the oxidative status or microorganism's activity in soil [28-29].

Analyzing the nutrient status in soil is helpful to formulate the effective fertilizer and soil management strategies, thereby enhancing agricultural sustainability and economic viability for local farmers [30]. Indiscriminate nutrients application leads to the deterioration of soil functions and ultimately declined the agricultural outputs [31-32]. In recent past, micronutrients deficiency has been considered as major constraint in crop production as well as produce quality especially in neutral to alkaline soils [33]. Through chelation, SOM retards the formation of insoluble precipitates of micronutrients and preserve their availability particularly in alkaline soils [34-35]. [6] monitored the higher SOC (0.56%), DOC (33.17 mg kg^{-1}), MBC (262.04 mg kg^{-1}) and DHA (30.77 μg TPF g^{-1} $24h^{-1}$) under RW cropping system over other studied crop production scenarios in north-western regions of India. Augmented levels of SOC, DTPA-extractable-Mn and Fe under submerged soils of RW cropping system were also documented by [13]. After thirteen years of experimentation, the highest SOC (8.62 g kg^{-1}) and MBC (493 mg kg^{-1}) under basmati-rice-sesbania and maize-mustard-sesbania, respectively, was recorded in organically managed plots over other nutrition and cropping techniques [36].

Aforementioned facts demonstrated that several studies have been done to quantify the left-out footprints of different cropping systems on soil health and confined literature is available on comparative analysis of cropping systems on nutrient dynamics and biological properties. But the relative impact of various cropping systems (RW, CW, PW, PM and SS) on soil micronutrients availability, as well as microbial and enzymatic activities in dry areas are incompletely grasped. For example: parallel analysis of aerobic and anaerobic crop lands with mono-cropping of perennial cash crop especially sugarcane has not been studied yet. Therefore, the studies on alteration in soil properties under different cropping systems would help to overcome this knowledge gap. It was hypothesized that different cropping systems with varying moisture regimes would left out noticeable signature on physico-chemical and biological properties in soils of semi-arid region. Thus, underlying hypothesis suggests that a thorough insight of major cropping systems and their associated management techniques could influence agricultural sustainability via governing the nutrient dynamics in soil. Considering the facts, this study was planned to estimate how different cash crop-based cropping systems and their related management ways at farmers' fields control the footprints of soil C fractions (TC, TIC, SOC and DOC), micronutrients availability (Fe, Mn, Cu and Zn,), soil microbiological activities, and their inter-relationships in semi-arid soils of district Palwal in National Capital Region of India.

Materials and Methods

Details of Study Area

The current evaluation was done for the soils of southern Haryana, India. Specifically, the study locations in district Palwal extend from 28°00'00'' to 28°30'00'' N latitude and 77°05'00'' to 77°37'30'' E longitude, comprising an area of 1359 square kilometres along with an altitude of 195 m. The district experiences distinct seasonal variations in temperature, and mean summer, winter, and annual temperatures are observed as 36, 15 and 34.4 $^{\circ}$C, respectively. The climate of Palwal district is semi-arid with an average annual rainfall of 520 mm.

Details of Sampling Locations

Soil sampling was conducted from 100 geographically distinct farmers' fields, with 20 fields representing each cropping system: RW: rice (*Oryza sativa* L.)-wheat (*Triticum aestivum* L.), CW: cotton (*Gossypium hirsutum* L.)-wheat, PW: pearl millet (*Pennisetum glaucum* L.)-wheat, PM: pearl millet-mustard (*Brassica juncea* L.) and SS: sugarcane-sugarcane mono cropping (*Saccharum officinarum*). A composite soil sample was collected from each field and the field was considered as a unit of replication for statistical analysis. The selection criteria ensured that all sites represented alike physical geographic situations and conventional agricultural practices within system coupled with a regular cropping record of ten years or more. Farmers adopted crop specific nutrition management techniques to fed different crops**.** Rice crop was nourished with 135-180 kg N, 40-60 kg P_2O_5, 30-40 kg K_2O and 15-30 kg $ZnSO_4$ ha^{-1}. In addition to chemical fertilizers, farm yard manure (FYM) @ 10-12 Mg ha^{-1} was applied before rice transplanting in alternate year. Sugarcane crop was fertilized with 130-160 kg N, 30-40 kg P_2O_5, 20-30 kg K_2O and 10-20 kg $ZnSO_4$ ha^{-1} in first year; and 220-

250 kg N, 10-20 kg P_2O_5, 10-20 kg K_2O ha^{-1} in second and third year. In addition, FYM @ 10-12 Mg ha^{-1} was also applied in alternate year. Pearl millet crop was fertilized with 120-160 kg N, 50-60 kg P_2O_5, 20-30 kg K_2O, 10-15 kg $ZnSO_4$ ha^{-1} every year, and FYM @ 8-10 Mg ha^{-1} was applied in alternate years. Cotton crop was dressed with 140-180 kg N, 50-60 kg P_2O_5, 40-60 kg K_2O and 15-25 kg $ZnSO_4$ ha^{-1} yr^{-1}, and FYM @ 10-12 Mg ha^{-1} was applied in alternate years. Soils under wheat crop was treated with 135-180 kg N, 40-60 kg P_2O_5, 30-40 kg K_2O, 15-30 kg $ZnSO_4$ ha^{-1} yr^{-1}, and FYM @ 8-10 Mg ha^{-1} was applied in alternate years. Total 40-60 kg N, 25-35 P_2O_5, 15-20 kg K_2O and 10-15 kg $ZnSO_4$ ha^{-1} every year was given to mustard, and FYM @ 5-7 Mg ha^{-1} was also applied at alternate years. Average doses of chemical nutrient and FYM applied annually in different cropping systems of Palwal are presented in Supplementary table 1. Harvesting of sugarcane was done at maturity, and thereafter ratoon crop was raised for consecutive two years. Irrigation was provided through canal water and groundwater in all the cropping systems. The crops were irrigated as and when required, however, in rice fields, submerged conditions were maintained for initial four to five weeks after transplanting followed by flood irrigation.

Collection of Soil Sampling and Investigation

Soil Sampling

A total of 100 surface soil samples (0-15 cm depth) i.e. 20 samples from each system were collected by choosing different sites for a system and these distinct sampling sites, geographically located in district Palwal (Southern Haryana, India), have been illustrated using Fig. 1. The map of district Palwal was generated by taking the geo-coordinates (latitude and longitude angles) of sampling points through Arc-GIS 10.3 software (https://www.arcgis.com/home/index.html). Followed by harvesting of *Rabi* season crops, soil samples were gathered using a metallic core sampler during the month of May 2023. Each composite sample was composed of three sub-samples obtained from 0.4-hectare field. A pair of composite soil samples were collected per location and separated in two groups. One group of collected samples were naturally dehydrated, powdered, filtered through 2 mm mesh, and shifted in polythene bags under congenial conditions for further soil chemical testing, including the assessment of available Fe, Mn, Zn and Cu concentrations. However, second group constituted fresh and moist soil samples which were kept at 4°C in a deep freezer for determination of microbial biomass carbon and dehydrogenase activity.

Determination of Soil Basic Parameters

Soil reaction ($pH_{1:2}$) was tested using a glass electrode via potentiometric method [37]. Following the settling of suspension, the supernatant was used to measure the electrical conductivity ($EC_{1:2}$) by adopting conductometric method [37]. Soil texture was classified by "feel method", wherein moist soil samples were rubbed to evaluate their texture based on tactile perception.

The SOC content was determined using wet digestion method [38] in which 1N potassium dichromate ($K_2Cr_2O_7$) and concentrated sulphuric acid (H_2SO_4) were used to oxidize the soil organic matter. In presence of diphenyl amine indicator and sodium fluoride, excess of $K_2Cr_2O_7$ was determined by titrating with 0.5N ferrous ammonium sulphate solution.

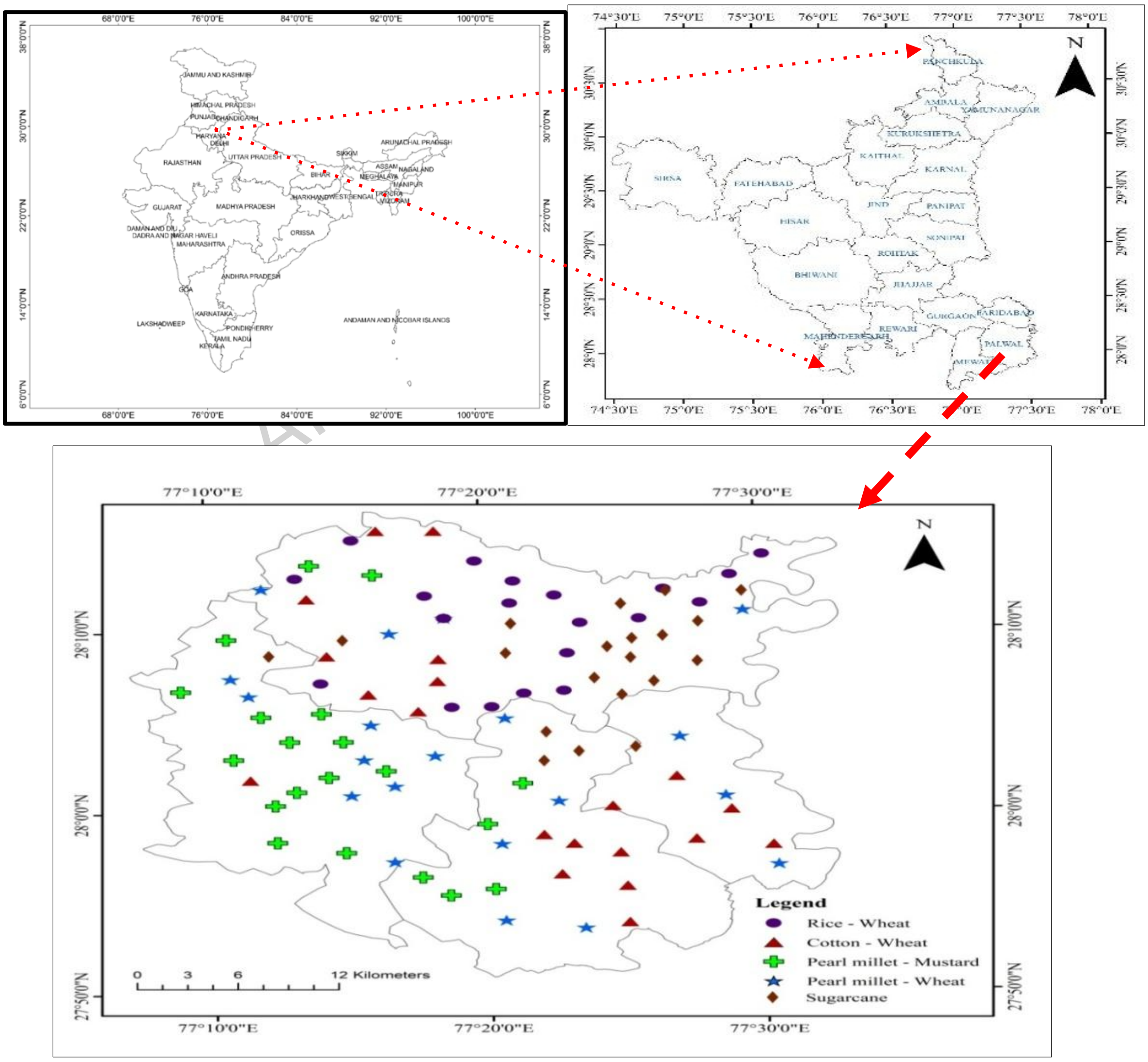

Fig. 1 Locations of soil samples collected from different cropping systems in district Palwal,

Haryana, India

Analysis of Dissolved Organic Carbon, Total Inorganic Carbon, Total Carbon

The DOC content was analysed by following the method proposed by [39]. Ten grams of soil mixed with 50 ml de-ionized water was shaken for one hour in a horizontal shaker followed by centrifugation of suspension for 30 minutes at 800 rpm. Filtered solution was further analyzed in same way as for SOC content.

Total carbon was determined by TOC analyzer Multi N/C 3100 (Analytik Jena) at 1200°C. For TC, 200 to 250 mg of soil was taken in ceramic boat and placed in auto sampler. Readings were noted through multiWin pro software 4.12.1.0 (https://www.analytik-jena.in/products/sum-parameter-analysis/toctnb-analysis/toc-tnb-analyzer-multi-nc-x300-series/). The difference between TOC and TC was considered as TIC.

Analysis of Soil Available Micronutrients (Fe, Zn, Cu and Mn)

The method proposed by [40] was followed for analyzing the DTPA extractable micronutrients. Soil sample was mixed with DTPA extracting solution buffered at pH 7.3 with triethanolamine to prevent dissolution of $CaCO_3$. After 2 hours shaking, the solution was filtered through Whatman no. 42 filter paper. The content of micronutrients was measured in filtrate using their respective cathode lamps on atomic absorption spectrophotometer (AAS).

Characterization of Soil Microbial and Enzymatic Activity

The MBC was measured by adopting the fumigation extraction method proposed by [41]. Ten-gram soil from each moist sample was fumigated with ethanol-free methyl tri-chloride ($CHCl_3$) for 24 hours at 25°C. After fumigation removal, the soil was extracted with 0.5 M K_2SO_4 and then filtered. Similarly, non-fumigated samples were also extracted. Soil MBC was computed by deducting extracted carbon between fumigated and non-fumigated samples, and this difference was multiplied with a transformation factor of K_{EC} (2.64).

The rate of tri-phenyl formazan (TPF) synthesis from tri-phenyl tetrazolium chloride (TTC) was used to estimate the soil dehydrogenase activity [42]. Five grams of soil sample was mixed with 1 ml TTC solution (3%) and 2.5 ml distilled water, and incubated at 37°C for 24 hours. To eliminate the reddish colour, soil was extracted with methanol after incubation. The intensity of red or orange colour was measured at 485 nm using a spectrophotometer.

Statistical Analysis

Twenty geographically distinct fields were selected for each cropping system, and one composite sample per field was taken, thus the field number (n=20 per system) was used as unit of replication for statistical analysis. Mean values for various cropping systems were separated and assessed at 95% confidence interval employing the Duncan's multiple range test (DMRT). The statistical analysis was done with SPSS 16.0 for Windows (SPSS Inc., Chicago, U.S.A) [43]. Discriminant Function Analysis (DFA) was conducted to identify the key soil physico-chemical or biological parameters that effectively differentiate among RW, CW, PW, PM and SS cropping systems. The analysis, performed using [44], facilitated group separation by identifying the most influential variables. The results were visualized in a two-dimensional space, representing the first two canonical discriminant functions (CDFs), which captured the highest proportion of variance among cropping systems. Additionally, Principal Component Analysis (PCA) was utilized to examine the variance explained by the principal components (PCs) using R statistical software [45]. Two most significant PCs, accounting for the greatest variance, were illustrated in a two-dimensional plot, providing insights into the primary factors driving variability among soil properties.

Results

Impact of five major cropping systems (RW, CW, PW, PM and SS), practiced more than 10 years at farmers' fields on soil properties were precisely assessed.

Basic Soil Properties

Soil pH of RW, CW, PW, PM and SS cropping system ranged from 7.01-7.84, 7.01- 8.17, 7.21-8.51, 7.30-8.26 and 7.10-7.90, respectively with mean values as 7.37, 7.54, 7.78, 7.93 and 7.50, respectively (Table 1). Soils under PM cropping system showed higher mean soil pH (7.93) followed by PW cropping system. Numerically, soils experienced RW cropping system, exhibited lowest soil reaction among studied cropping systems. Soils experienced rice and sugarcane-based systems of crop cultivation had significantly lower soil pH as compared to pearl millet-based systems. Soil EC fluctuated between 0.11-0.75, 0.13-0.72, 0.11-0.94, 0.16-1.02 and 0.13-0.90 dSm^{-1} for RW, CW, PW, PM and SS cropping system with a mean of 0.35, 0.41, 0.47, 0.49 and 0.43 dSm^{-1}, respectively (Table 1). Upon examination of data, the lowest soil EC was recorded under RW and highest in PM cultivated soils, however soil EC did not differ significantly among various cropping systems. The SOC content in RW, CW, PW, PM and SS cropping systems varied from 0.45-0.78, 0.29-0.72, 0.27-0.80, 0.29-0.49 and 0.25-0.84 %

with mean values of 0.62, 0.56, 0.48, 0.39 and 0.60%, respectively (Table 2). Significantly raised SOC level was noticed in soils from RW followed by SS and CW cropping system than to soils of PW system. However, soils under PW (0.48%) were significantly superior to accrue SOC than PM cropping system. The soil texture of Palwal district also found varied across different cropping systems. Under RW, PW and SS systems, the soil texture was found sandy loam to sandy clay loam. In contrast, the soils under CW and PM systems exhibit a texture variation from loamy sand to sandy loam.

Table 1. Soil properties (0-15 cm) under different cropping systems of district Palwal, Haryana.

Soil Property	Cropping Systems [Mean (range) ± standard error of mean]				
	PW	PM	RW	CW	SS
Soil $pH_{1:2}$	7.78[a] (7.21-8.51) ±0.07	7.93[a] (7.30-8.26) ±0.06	7.37[b] (7.01-7.84) ±0.04	7.54[b] (7.01-8.17) ±0.07	7.50[b] (7.10-7.90) ±0.06
$EC_{1:2}$ (dSm^{-1})	0.47[a] (0.11-0.94) ±0.06	0.49[a] (0.16-1.02) ±0.06	0.35[a] (0.11-0.75) ±0.05	0.41[a] (0.13-0.72) ±0.04	0.43[a] (0.13-0.90) ±0.05
Texture	Sandy loam to sandy clay loam	Loamy sand to sandy loam	Sandy loam to sandy clay loam	Loamy sand to sandy loam	Sandy loam to sandy clay loam

PW: pearl millet-wheat; PM: pearl millet-mustard; RW: rice-wheat; CW: cotton-wheat; SS: sugarcane-sugarcane. EC: electrical conductivity. Distinct letters connected with mean values of various cropping systems indicates significant difference ($p < 0.05$) and those connected with alike letter are at par ($p < 0.05$) by Duncan's multiple range test (DMRT).

Soil carbon fractions

The DOC content under RW, CW, PW, PM and SS cropping system varied from 23.79-51.65, 18.49-47.56, 28.38-51.63, 12.78-39.50 and 18.65-50.15 mg kg^{-1} with a mean value of 34.42, 33.57, 35.80, 25.80 and 37.65 mg kg^{-1}, respectively (Table 2). The highest (37.50 mg kg^{-1}) and lowest (25.80 mg kg^{-1}) DOC level was obtained in soils under SS and PM cropping system, respectively. Soils of PM cropping were found statistically inferior for DOC content than remainder cropping systems.

The TIC content in various soils extended from 1.10-5.79, 2.47-3.94, 1.54-7.45, 3.14-6.27 and 1.39-5.01 g kg^{-1} and reflected the mean value of 2.40, 3.19, 3.41, 4.92 and 2.93 g kg^{-1} for RW, CW, PW, PM and SS system, respectively (Table

2). Soils from PM cultivation demonstrated significant accrual in TIC content than remainder systems.

The perusal of data in table 2 showed that the TC content ranged from 8.10-17.50, 7.40-11.90, 7.20-17.40, 6.40-13.00 and 6.20-16.50 g kg^{-1} in soils under RW, CW, PW, PM and SS cropping system with corresponding mean value of 11.05, 10.08, 10.09, 10.04 and 11.26 g kg^{-1}, respectively. The TC content among different cropping systems followed the order as: SS>RW>PW≈CW>PM, however did not differ significantly. A polynomial relationship (R^2= 0.527) was observed between SOC and TC under different cropping systems (Fig.2).

Table 2. Carbon content in soils under different cropping systems of district Palwal, Haryana

Soil Property	Cropping Systems [Mean (range) ± standard error of mean]				
	PW	**PM**	**RW**	**CW**	**SS**
SOC (%)	0.48^b (0.27-0.80) ±0.03	0.39^c (0.29-0.49) ±0.01	0.62^a (0.45-0.78) ±0.02	0.56^a (0.29-0.72) ±0.03	0.60^a (0.25-0.84) ±0.04
DOC (mg kg^{-1})	35.80^a (28.38-51.63) ±1.27	25.80^b (12.78-39.50) ±1.26	34.4^a (23.79-51.65) ±1.55	33.57^a (18.49-47.56) ±1.83	37.50^a (18.65-50.15) ±2.01
MBC (mg kg^{-1})	176.00^{ab} (110.48-271.64) ±9.02	150.32^b (94.00-185.42) ±5.18	191.51^a (130.57-294.41) ±9.36	182.70^a(90.47-254.67) ±10.62	187.86^a (77.54-253.14) ±11.45
TIC (g kg^{-1})	3.41^b (1.54-7.45) ±0.31	4.92^a (3.14-6.27) ±0.18	2.40^c (1.10-5.79) ±0.23	3.19^b (2.47-3.94) ±0.07	2.93^{bc} (1.39-5.01) ±0.21
TC (g kg^{-1})	10.09^a (7.20-17.40) ±0.54	10.04^a (6.40-13.00) ±0.36	11.05^a (8.10-17.50) ±0.49	10.08^a (7.40-11.90) ±0.26	11.26^a (6.20-16.50) ±0.60

PW: pearl millet-wheat; PM: pearl millet-mustard; RW: rice-wheat; CW: cotton-wheat; SS: sugarcane-sugarcane. SOC: soil organic carbon; DOC: dissolved organic carbon, MBC: microbial biomass carbon; TIC: total inorganic carbon; TC: total carbon (TC). Distinct letters connected with mean values of various cropping systems indicates significant difference ($p < 0.05$), and those connected with alike letter are at par ($p < 0.05$) by Duncan's multiple range test (DMRT).

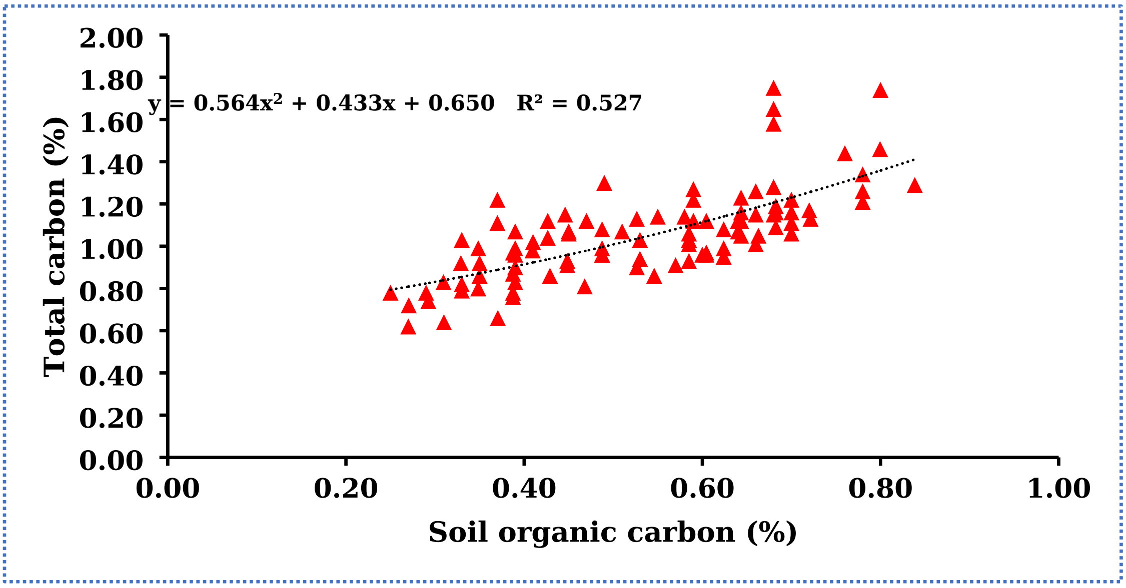

Fig. 2. Relationship between soil organic carbon (SOC) and total carbon (TC) of soils under different cropping systems.

DTPA Extractable Micronutrients (Fe, Zn, Mn and Cu)

Soils withstand RW system exhibited significantly larger concentrations of DTPA-extractable iron (Fe), zinc (Zn), and manganese (Mn) compared to other cropping systems, whereas the DTPA-extractable copper (Cu) content was greatest in the soils of PM cropping (Table 3). Across the cropping systems, available Fe content expanded between 7.13 to 58.16 mg kg^{-1}. Specifically, the Fe concentration varied between 14.71–52.32 mg kg^{-1} in RW, 7.91–58.16 mg kg^{-1} in CW, 10.47–21.36 mg kg^{-1} in PW, 7.13–19.15 mg kg^{-1} in PM and 9.45–24.67 mg kg^{-1} in SS cropping, with respective mean values of 27.02, 23.46, 15.51, 14.73 and 17.53 mg kg^{-1} (Table 3). Data indicated that soils under RW and CW cropping accommodated significantly greater quantity of bio-available Fe than remaining systems. The various systems of crop production followed the descending order for DTPA-extractable Fe concentration as: RW> CW> SS> PW > PM. A polynomial relationship (R^2= 0.348) was observed between SOC and available Fe under studied cropping systems (Fig.3).

Available Zn concentration (DTPA-extractable) in soils fluctuated between 0.30 to 4.12 mg kg^{-1} across different cropping systems. The Zn concentrations ranged from 0.94–4.12 mg kg^{-1} in RW, 0.82–3.67 mg kg^{-1} in CW, 0.77–3.17 mg kg^{-1} in PW, 0.30–1.62 mg kg^{-1} in PM and 0.74–3.47 mg kg^{-1} in SS cropping system, with corresponding mean values of 2.22, 1.98, 1.75, 1.20 and 1.91 mg kg^{-1}, respectively (Table 3). The highest and lowest concentrations of soil available Zn were observed in RW (4.12 mg kg^{-1}) and PM (0.30 mg kg^{-1}) systems, respectively.

The Zn concentration in RW soils was significantly elevated over PW and PM cropping systems. However, bio-available Zn was statistically at par among RW, CW and SS cropping systems. Additionally, the inclusion of mustard in cropping system (PM) exhibited a significant decrease in available Zn as compared to PW system. A polynomial relationship (R^2= 0.596) was acquired between SOC and DTPA-extractable Zn under different cropping systems in semi-arid region of Palwal (Fig.3).

Results indicated that available Cu concentrations in soils expanded between 0.55 to 3.72 mg kg^{-1} across different cropping systems. Specifically, Cu concentrations ranged from 0.55–2.76 mg kg^{-1} in RW, 1.01–3.04 mg kg^{-1} in CW, 0.65–3.32 mg kg^{-1} in PW, 0.46–3.72 mg kg^{-1} in PM and 1.20–3.16 mg kg^{-1} in SS cropping systems, with respective mean values of 1.53, 2.06, 2.01, 2.55 and 1.98 mg kg^{-1} (Table 3). Soils from PM system showed significantly greater values of Cu concentrations over wheat and sugarcane-based cropping. Although Cu level in CW (2.06 mg kg^{-1}) was numerically higher than those in PW (2.01 mg kg^{-1}) and SS (1.98 mg kg^{-1}), but the differences were not statistically significant. Additionally, the RW system reported a significantly lower DTPA-extractable Cu concentration than studied aerobic cropping systems. The SOC and available Cu displayed a weak polynomial relationship (R^2= 0.074) in studied cropping systems (Fig.3).

The concentrations of available Mn (DTPA-extractable) in soils varied from 6.37 to 47.00 mg kg^{-1} in evaluated cropping systems. The Mn concentration ranged from 18.13-47.00 mg kg^{-1} in RW, 6.37-36.93 mg kg^{-1} in CW, 11.97-37.13 mg kg^{-1} in PW, 9.93-28.46 mg kg^{-1} in PM and 8.69-36.92 mg kg^{-1} in SS cropping systems, with respective mean values of 29.95, 23.82, 21.17, 18.95 and 21.85 mg kg^{-1}, accordingly (Table 3). The RW soils evidenced significantly higher soil available Mn concentrations than other studied cropping systems. Relatively, CW soils contained higher Mn concentrations than SS and PW, but, differences were not statistically significant. The order of available Mn concentrations in various cropping systems was as follows: RW> CW > SS > PW> PM. A polynomial relationship (R^2= 0.553) was found between SOC and Mn availability under diverse systems of crop production (Fig.3).

The DTPA-extractable micronutrients (Fe, Cu, Zn and Mn) were significantly affected by the variegated systems of cultivation practices. The highest Zn, Fe and Mn content was observed under RW cropping system having mean values of 2.22, 27.02 and 29.95 mg kg^{-1}, respectively. As per the results achieved, all the soil samples collected from RW, CW, PW and SS cropping systems had sufficient bio-available Zn, Fe, Mn and Cu concentration. However, only 5% of collected soil samples were deficient in available Zn (<0.6 mg kg^{-1}) under PM cropping system. Overall, soil samples under studied cropping systems reflected sufficient amount of available Fe (>4.5 mg kg^{-1}), Mn (>1.0 mg kg^{-1}) and Cu (>0.2mg kg^{-1}).

Table 3. Available micronutrients, microbial biomass carbon and enzyme activity in soils under different cropping systems of district Palwal, Haryana.

Soil Property	Cropping Systems [Mean (range) ± standard error of mean]				
	PW	**PM**	**RW**	**CW**	**SS**
DTPA-Fe (mg kg^{-1})	15.51^{b} (10.47-21.36) ±0.51	14.73^{b} (7.13-19.15) ±0.64	27.02^{a} (14.71-52.32) ±2.15	23.46^{a} (7.91-58.16) ±2.94	17.53^{b} (9.45-24.67) ±0.69
DTPA-Zn (mg kg^{-1})	1.75^{b} (0.77-3.17) ±0.16	1.20^{c} (0.30-1.62) ±0.07	2.22^{a} (0.94-4.12) ±0.17	1.98^{ab} (0.82-3.67) ±0.19	1.91^{ab} (0.74-3.47) ±0.15
DTPA-Cu (mg kg^{-1})	2.01^{b} (0.65-3.32) ±0.17	2.55^{a} (0.46-3.72) ±0.16	1.53^{c} (0.55-2.76) ±0.13	2.06^{b} (1.01-3.04) ±0.13	1.98^{b} (1.20-3.16) ±0.11
DTPA-Mn (mg kg^{-1})	21.17^{bc} (11.97-37.13) ±1.64	18.95^{c} (9.93-28.46) ±1.08	29.95^{a} (18.13-47.00) ±1.52	23.82^{b} (6.37-36.93) ±1.84	21.85^{bc} (8.69-36.92) ±1.44
DHA (µg TPF g^{-1} $24h^{-1}$)	30.23^{bc} (21.70-47.80) ±1.37	32.04^{b} (18.50-43.90) ±1.45	39.67^{a} (20.60-69.40) ±2.65	29.80^{bc} (19.60-40.80) ±1.23	26.17^{c} (15.70-38.70) ±1.22

PW: pearl millet-wheat; PM: pearl millet-mustard; RW: rice-wheat; CW: cotton-wheat; SS: sugarcane-sugarcane. DHA: Dehydrogenase activity. Distinct letters connected with mean values of various cropping systems indicates significant difference ($p < 0.05$) and those connected with alike letter are at par ($p < 0.05$) by Duncan's multiple range test (DMRT).

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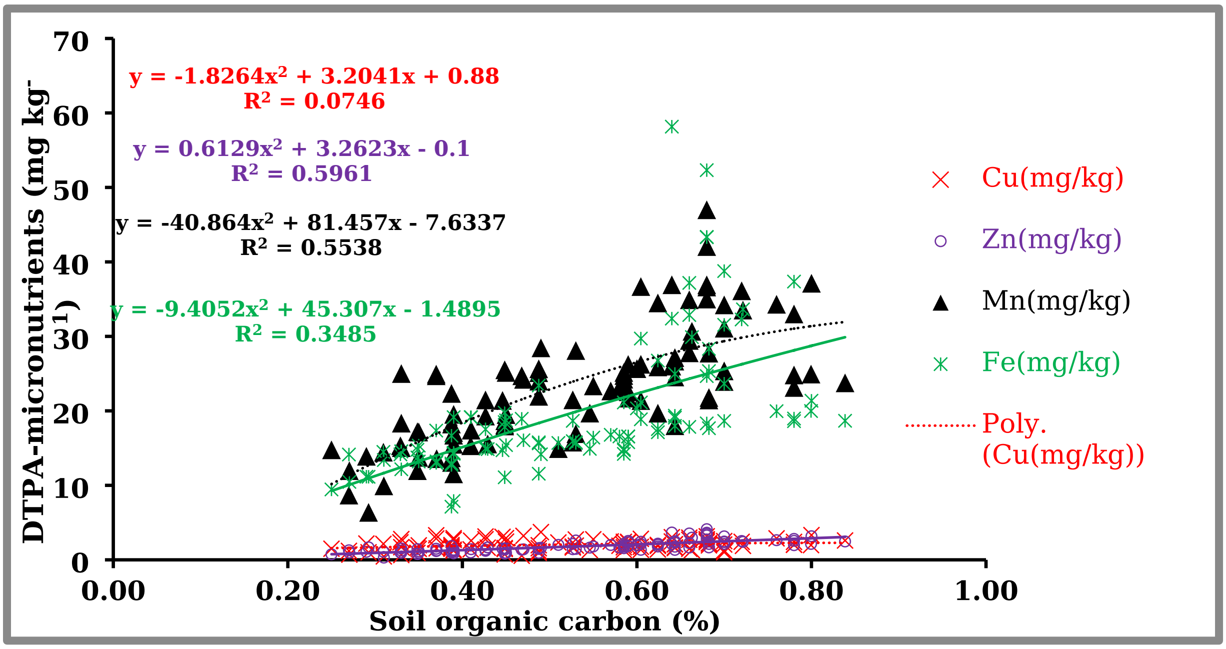
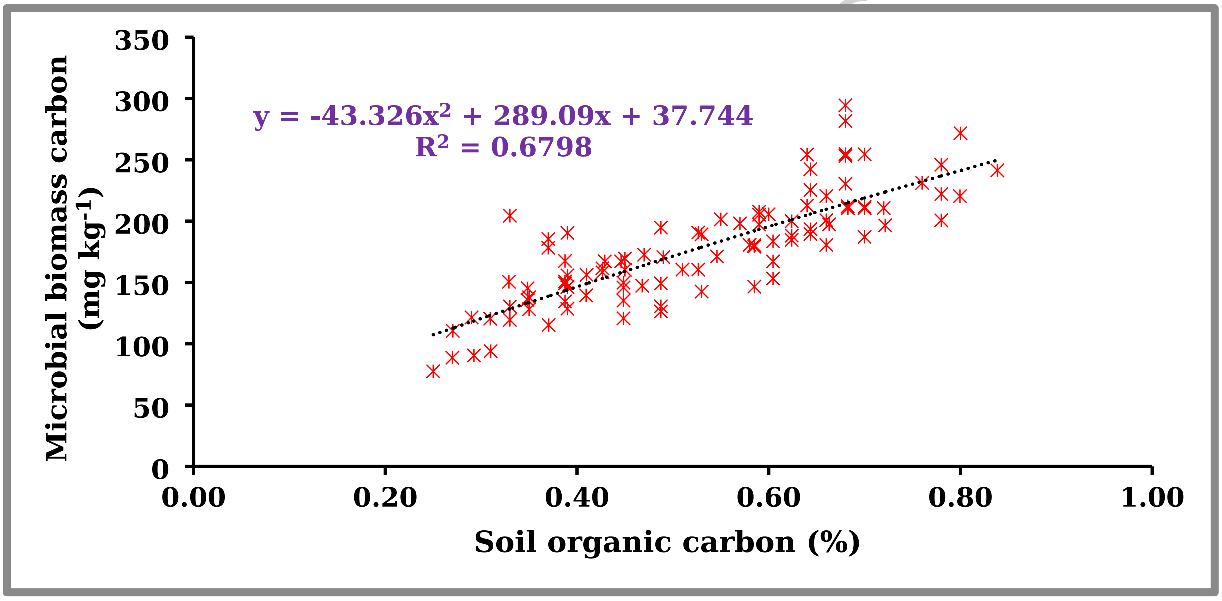


427 **Fig. 3.** Relationship between soil organic carbon (SOC) and available micro nutrients in soils under
428 different cropping systems.



429
430 **Fig. 4.** Relationship between soil organic carbon (SOC) and microbial biomass carbon (MBC) in
431 soils under different cropping systems.

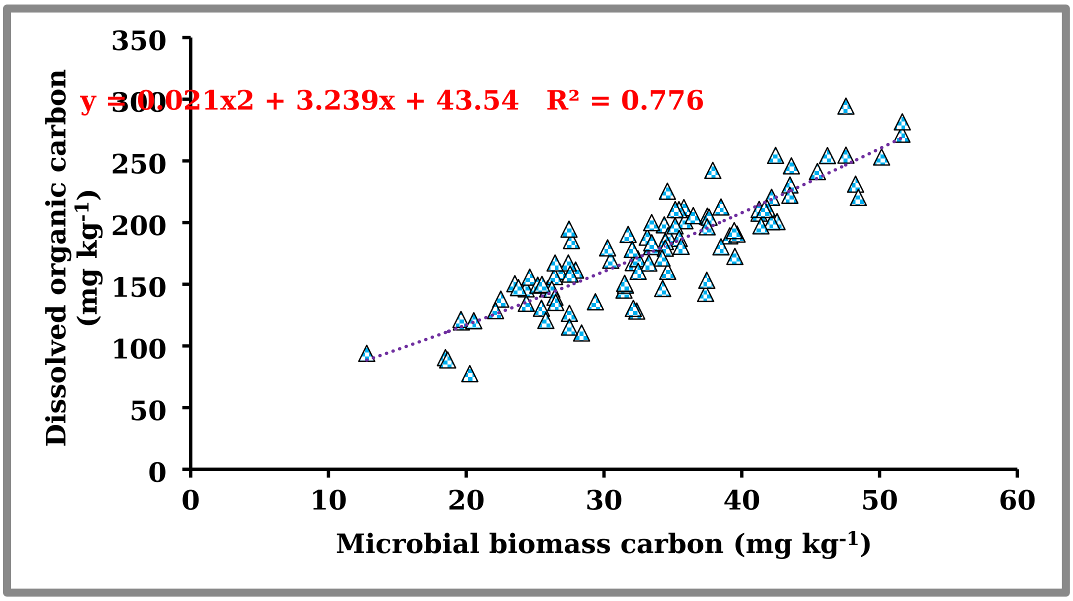


Fig. 5. Relationship between dissolved organic carbon (DOC) and microbial biomass carbon (MBC) in soils under different cropping systems.

Soil Microbiological and Enzymatic Activity

The MBC content in soils under RW, CW, PW, PM and SS cropping system positioned between 130.57-294.41, 90.47-254.67, 110.48-271.64, 94.00-185.42 and 77.54-253.14 mg kg^{-1} with their parallel mean value of 191.51, 182.70, 176.00, 150.32 and 187.86 mg kg^{-1}, respectively. Significantly higher MBC content was observed in soils under RW system over PM cropping, however non-significantly numerically higher over SS, CW and PW cropping. Amidst different cropping systems, MBC content in soils followed the order as: RW>SS>CW>PW>PM (Table 2). A polynomial relationship (R^2= 0.679) of MBC with SOC (Fig.4); and MBC with DOC (R^2= 0.776) was expressed among studied cropping systems (Fig.5).

The DHA activity in RW, CW, PW, PM and SS cropping system ranged from 20.60-69.40, 19.60-40.80, 21.70-47.80, 18.50-43.90 and 15.70-38.70 µg TPF $g^{-1}24h^{-1}$ with the mean value of 39.67, 29.80, 30.23, 32.04 and 26.17 µg TPF $g^{-1}24h^{-1}$, respectively (Table 3). The highest and lowest DHA activity was observed in RW (69.40 µg TPF $g^{-1}24h^{-1}$) and SS (15.70 µg TPF g^{-1} $24h^{-1}$) cropping systems, respectively. The RW cropping system showed significantly higher DHA (39.67 µg TPF $g^{-1}24h^{-1}$) as compared to PM (32.04 µg TPF $g^{-1}24h^{-1}$), PW (30.23 µg TPF $g^{-1}24h^{-1}$), CW (29.80 µg TPF $g^{-1}24h^{-1}$) and SS (26.17 µg TPF $g^{-1}24h^{-1}$) cropping systems. Additionally, soils from PW, PM, and CW; and soils of SS, CW and PW cropping systems did not differ significantly for DHA activity. Numerically, impact of different cropping systems at farmers' fields on DHA levels in soil demonstrated the order as: RW>PM>PW>CW and SS.

Correlation

The correlation matrix provided key insights of interactions among soil physico-chemical properties (pH, EC, TC, TIC, SOC, and DOC), micronutrients availability (DTPA-extractable Cu, Zn, Mn, Fe) and microbial activity indicators (MBC and DHA) (Fig.6). Soil pH was highly positively correlated with TIC ($r=0.73$; $p< 0.05$) and DTPA-Cu ($r=0.76$; $p< 0.05$). Conversely, soil pH showed a non-significant correlation with SOC and DTPA-Fe. Soil EC exhibited weak correlations with most of the variables**,** including negative correlation with SOC, DOC and DTPA-Zn. SOC was strongly positively correlated with TC ($r=0.72$; $p< 0.05$), DOC ($r=0.83$; $p< 0.05$), DTPA-Zn ($r=0.77$; $p< 0.05$), Mn ($r=0.74$; $p< 0.05$) and MBC ($r=0.82$; $p< 0.05$). Similarly, moderate and significant correlation of SOC was found with DTPA-Fe and DHA, however, a non-significant correlation was observed between SOC and TIC. TC showed a highly significant positive correlation with SOC ($r=0.72$; $p< 0.05$), DOC ($r=0.78$; $p< 0.05$), Zn ($r=0.70$; $p< 0.05$), Mn ($r=0.72$; $p< 0.05$), MBC ($r=0.80$; $p< 0.05$) and DHA ($r=0.68$; $p< 0.05$), and also exhibited a positive correlation with soil pH ($r=0.33$; $p< 0.05$), TIC ($r=0.55$; $p< 0.05$), DTPA-Cu ($r=0.59$; $p< 0.05$) and Fe ($r=0.47$; $p< 0.05$). The TIC under divergent cropping systems showed a highly significant positive correlation with soil pH and DTPA-Cu ($r=0.79$; $p< 0.05$). DOC indicated highly positive correlation with TC, SOC, DTPA-Zn ($r=0.82$; $p< 0.05$), Mn ($r=0.73$; $p< 0.05$) and MBC ($r=0.88$; $p< 0.05$). Micronutrients availability was significantly influenced by organic matter, as confirmed by the strong correlations between SOC and DTPA-Zn, DTPA-Mn and DOC and DTPA-Fe. Additionally, DTPA-Zn, Mn and Fe exhibited strong inter-correlations, suggesting the similar geochemical behaviour**.** The DTPA-Cu content under different cropping systems was positively correlated with all the studied soil parameters. Similarly, DTPA-Zn, Mn and Fe were positively correlated with all the studied soil parameters except soil EC. DTPA-Fe and Mn was strongly correlated with SOC, DOC, DTPA-Zn, MBC and DHA. The MBC content showed highly significant positive correlation with TC, SOC, DOC, DTPA-Zn, Mn, Fe and DHA. Likewise, DHA exhibited significant positive correlation with all the studied soil parameters under diverse cropping systems.

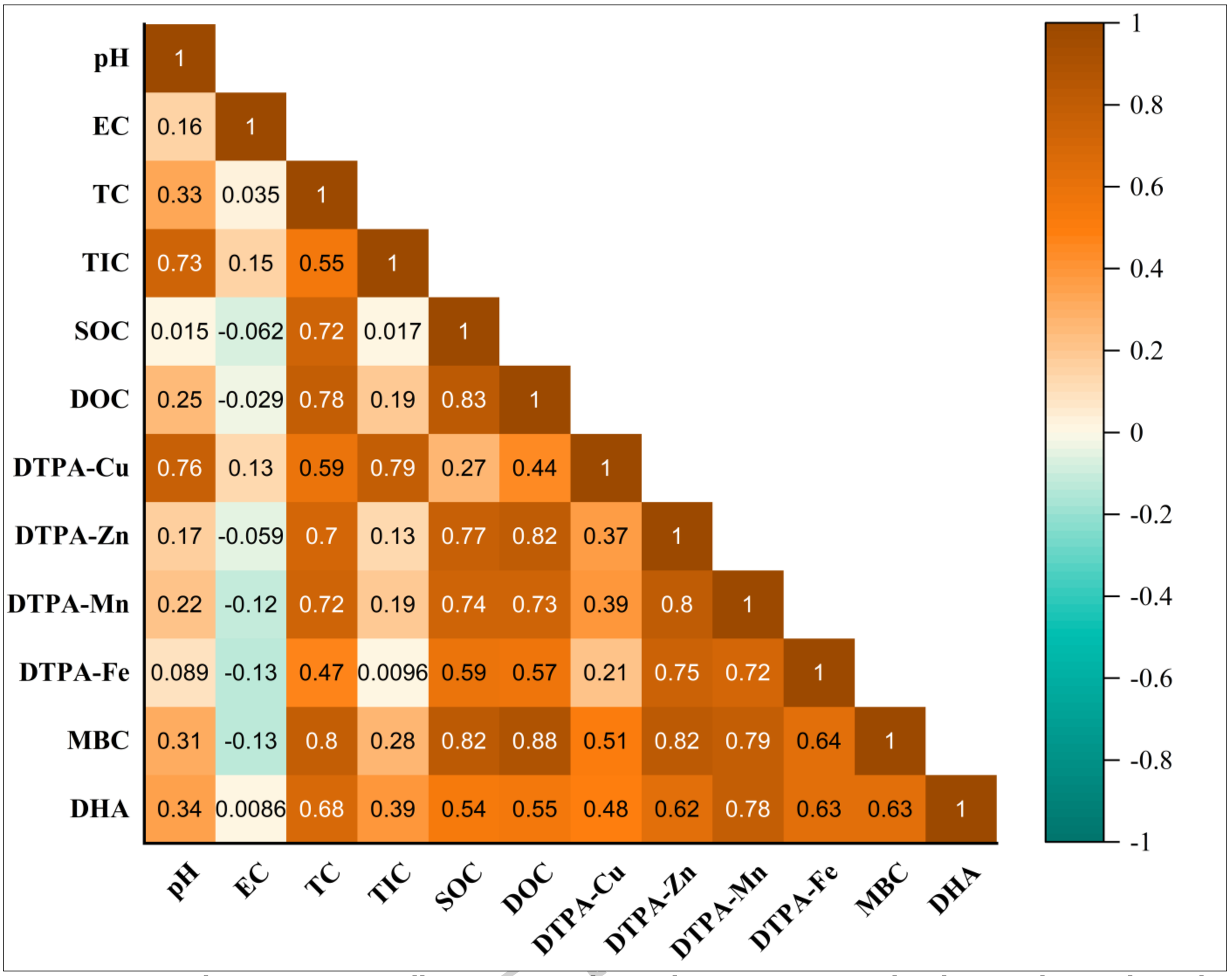


Fig. 6. Correlation matrix illustrating relationships among soil physico-chemical and microbiological properties

Data pooled for soils from different cropping systems. EC = Electrical conductivity, TC: Total carbon; TIC: Total inorganic carbon; SOC: Soil organic carbon; DOC: Dissolved organic carbon; MBC: Microbial biomass carbon; DHA: Dehydrogenase activity. Correlation is significant at p<0.05 level (2-tailed).

Discriminant Analysis (DA) and Data Reduction Technique (Principal Component Analysis (PCA)

The analysis was performed to differentiate the different cropping systems (RW, CW, PW, PM and SS) using soil physico-chemical parameters (pH, EC, TC, TIC, SOC and DOC), micronutrient availability (DTPA-extractable Cu, Zn, Mn, Fe) and biological properties (MBC and DHA) as discriminating variables. The scatter plot presented the canonical discriminant functions (CDF_1 and CDF_2) (Table 4), which explained 67.9 and 24.4% of the total variance, respectively, indicating that these two functions account for a significant proportion of the differences among cropping systems and classified the soils into five groups (Fig.7). Two canonical functions (Function 1, 0.955**, $p < 0.05$, and Function 2, 0.888*, $p < 0.05$) depicted significant correlations among studied variables. The canonical structure matrix indicated that CDFs' soil properties were statistically significant ($p < 0.05$). The identified parameters effectively differentiated the RW and SS cropping systems from pearl millet-based systems (PW and PM) and CW cropping system. However, there was a noticeable overlap in soil characteristics among PW, PM and CW cropping systems, indicated by closely aligned centroids.

Table 4. Canonical discriminant function coefficients for classified groups and structure matrix.

	Standardized canonical discriminant functions		Non- standardized canonical discriminant functions		Structure matrix	
Variable	**Funct.1**	**Funct.2**	**Funct.1**	**Funct.2**	**Funct.1**	**Funct.2**
pH	0.415	-0.272	1.598	8.737	0.238	0.013
EC	0.107	-0.011	0.469	-1.047	0.063	-0.028
TC	-2.017	-0.783	-9.683	-0.051	-0.060	-0.028
TIC	2.112	0.745	21.976	-3.760	0.267	0.111
SOC	-0.313	0.674	-2.561	7.759	-0.213	-0.070
DOC	0.784	-2.435	0.108	5.505	-0.122	-0.213
DTPA-Cu	0.399	-0.183	0.631	-0.338	0.156	0.010
DTPA-Zn	-0.311	-0.074	-0.457	-0.290	-0.153	-0.032
DTPA-Mn	-0.464	0.660	-0.068	-0.109	-0.159	0.110
DTPA-Fe	-0.082	0.515	-0.010	0.097	-0.166	0.147
MBC	-0.032	0.308	-7.809	0.067	-0.103	-0.060
DHA	-0.399	1.159	-0.053	0.007	-0.082	0.2538
Constant			-8.743	8.737		

EC: Electrical conductivity; TC: Total Carbon; TIC: Total inorganic carbon; SOC: Soil organic carbon; DOC: Dissolved organic carbon; MBC: Microbial biomass carbon; DHA: Dehydrogenase activity.

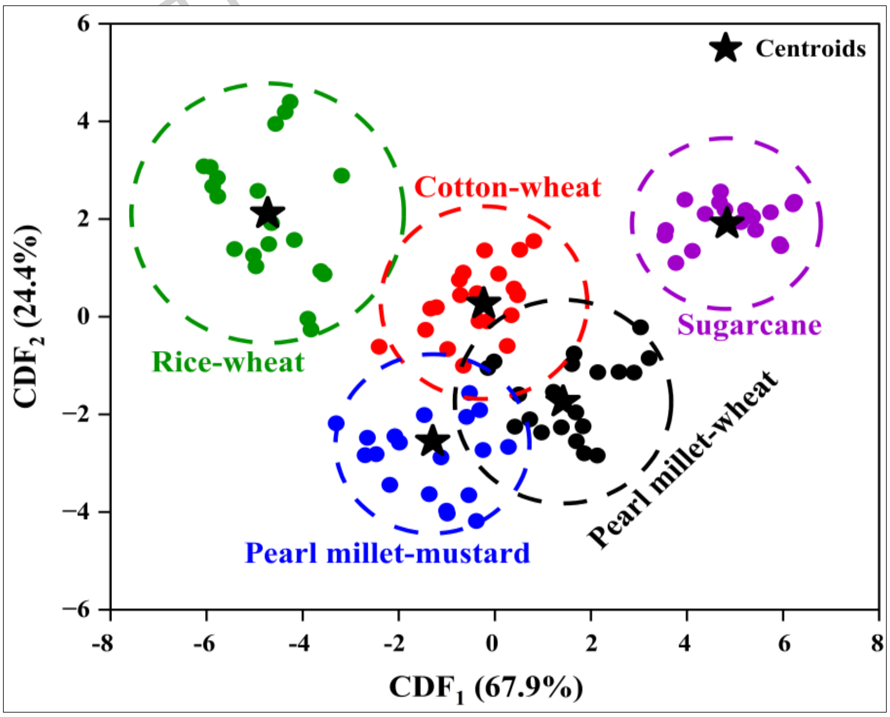


Fig. 7. Canonical discriminant functions (CDFs) plot for separating rice-wheat, cotton-wheat, pearl millet-wheat, pearl millet-mustard and sugarcane-sugarcane cropping systems in Palwal, Haryana.

Further, PCA of different soil properties under studied cropping systems reflected that the first two principal components had eigen value >1(Table 5). The plot represents the locations of various soil variables in orthogonal space (Fig.8). The first principal component (PC_1) accounted for 54.3% of the total variance, while the second principal component (PC_2) provided an additional 19.4%, resulting in a cumulative variance of 73.7% in total data set. The PC_1 and PC_2 had eigen value of 6.51 and 2.33, respectively. For PC_1, MBC, TC, DTPA-Mn and DOC had the highest contributions with loading values of 0.362, 0.347, 0.346 and 0.345, respectively, suggesting their significant role in explaining soil variability, however, soil EC had a negative weighted loading value of -0.014. In contrast, for PC_2, TIC and soil pH were the most influential variables with negative loading values of -0.543 and -0.509, respectively.

Table 5. Loading values of soil properties and the percentage contribution of principal components on the axis recognized by principal component analysis (PCA).

Soil variables	PC1/Dim1			PC2/Dim2	
	Loading values	Contribution of variables (%)		Loading values	Contribution of variables (%)
pH	0.161	2.592		-0.509	25.898
EC	-0.014	0.019		-0.234	5.489
TC	0.347	12.032		-0.08	0.637
TIC	0.164	2.701		-0.543	29.512
SOC	0.319	10.207		0.247	6.081
DOC	0.345	11.901		0.111	1.226
DTPA-Cu	0.245	5.979		-0.447	19.965
DTPA-Zn	0.343	11.775		0.177	3.121
DTPA-Mn	0.346	11.967		0.136	1.843
DTPA-Fe	0.281	7.915		0.233	5.451
MBC	0.362	13.117		0.077	0.597
DHA	0.313	9.794		-0.042	0.18
Eigen value		6.51			2.33
Variability (%)		54.3			19.4
Cumulative variability (%)		54.3			73.7

PC: Principal component; Dim: Dimension; EC: Electrical conductivity; TC: Total Carbon; TIC: Total inorganic carbon; SOC: Soil organic carbon; DOC: Dissolved organic carbon; MBC: Microbial biomass carbon; DHA: Dehydrogenase activity.

The inter-correlation highly weighted loading values of soil variables among different PCs disclosed that MBC in PC_1, and TIC and soil pH in PC_2 with the highest correlation might be selected for MDS. Computed percentage of total variance ranged between 0.26 and 0.74 based on weight of each PC. For three distinct MDSs, the weighted factor followed PC_1 (0.74) >PC_2 (0.26) (Table 5).

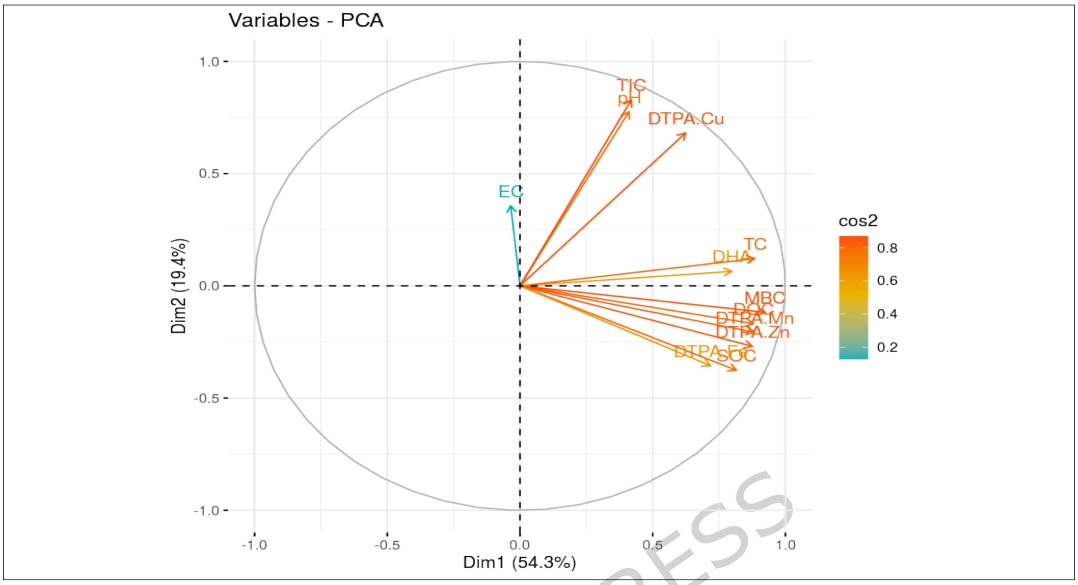


Fig. 8. Principal component analysis (PCA) plot of soil properties comprising pH, electrical conductivity (EC), soil organic carbon (SOC), dissolved organic carbon (DOC), microbial biomass carbon (MBC) and dehydrogenase activity (DHA) in soils experienced rice-wheat, cotton-wheat, pearl millet-wheat, pearl millet-mustard and sugarcane-sugarcane cropping systems of Palwal, Haryana. Dim: Dimension.

Discussion

Land uses and cropping systems play a significant role in nutrient availability via influencing the SOC dynamics, variations in plant-derived carbon inputs, crop management practices, and microbial activity in soil, consequently impacting the overall soil quality [46]. Therefore, a comprehensive knowledge of aerobic and anaerobic agricultural systems is crucial for developing the farming systems that sustain or improve soil health on long term basis. The results achieved during this study are discussed under the following headings:

Basic Soil Properties

Soils under RW cropping system reported the lowest pH compared to the soils of aerobic cropping systems i.e. CW, PW, PM and SS (Table 1). Apart from the released organic acids through organic matter decomposition, evidently higher SOC content under submerged conditions of rice resulted into more decrement in soil pH as compared to aerobic cultivation systems [47]. The lower soil pH might be linked to the specific management practices like high FYM addition in RW (Supplementary table 1, and higher in-situ residue retention in SS system that increases the SOC and MBC in soil (Table 2). Soils faced RW cropping system recorded 14.63, 18.60, 25.53 and 28.57 % lower soil EC compared to the soils under CW, SS, PW and PM cropping systems, respectively. The increased solubility coupled with higher leaching losses of soluble salts under submerged conditions of rice fields might cause the reduction in soil EC as supported by the findings of [48]. However, in aerobic cropping systems, regular incorporation of manures raised the levels of calcium, magnesium and related salts in soils; and further less leaching losses resulted in accumulation of theses salts in soil, ultimately associated with higher soil EC [49]. The semi-arid climatic conditions of the study area having low annual rainfall also restrict the complete leaching of these salts from root zone, especially under aerobic systems, and causes accumulation of these salts in surface soil layer.

Carbon Dynamics

The soil samples from RW system reported 3.33, 10.71, 29.16, 58.97 % higher SOC as compared to SS, CW, PW and PM cropping systems, respectively. Under RW cropping system, 95 and 5% soil samples fall under medium and high category, respectively, and no sample from tested soils was found in low SOC category. The higher SOC in RW cropping system might be a combined effect of anaerobic conditions and frequent addition of organic manure/FYM in higher doses, therefore slow decomposition rates are linked with higher SOC status in these soils [50-51]. The accretion of SOC in SS system is likely due to regular and high-rate addition of organic matter via leaf litter fall, leftover sugarcane tops and below ground biomass. The rate of crop residues decomposition is also regulated by lignin, cellulose, and poly phenols content of the crops that led to the variations in SOC build up [52]. Under PW cropping system, 50, 45 and 5% soil samples exhibited low, medium and high category of SOC, respectively. In CW cropping system, 10 and 90% of studied soil samples were under low and medium category, respectively, and no sample from tested soils showed high SOC category. Similar to SS cropping, considerably higher SOC level of soils under CW over PW cropping might be primarily due to greater above and below ground biomass accumulation in addition to higher FYM (Supplementary table 1) application rates [53]. About 60 and 40% soil samples from PM cropping system fall under low and medium category, respectively. The addition of lower FYM doses coupled with low antecedent soil fertility, associated with sandy texture, collectively reduced the SOC retention in soil [17].

The DOC serves as a vital medium for substance transport and an essential energy source for microbial communities [54]. Regular SS mono cropping reflected higher DOC level in soil followed by PW, RW, CW and PM cropping system. Enhanced DOC in soils of SS cropping might be related to higher retention of low C:N ratio crop residues over longer duration that promotes carbon stocks in soil, and consequently released more labile carbon in soil like DOC [55]. Despite the higher residual retention in CW, less DOC released as compared to SS could be explained by resistant nature of cotton residues like hard twigs with wide C:N ration. In contrast, lesser litter deposition and low humification rate in soils under other aerobic cropping systems might be the possible reason for lower DOC. Furthermore, despite the higher SOC content under RW system, the increased leaching loss due to anaerobic submerged conditions attributed to retain lesser DOC in soil relative to SS cropping system [56]. As per the outcomes of experimental study, 44.28, 54.23, 67.92 and 105% higher TIC content in soils of PM system over PW, CW, SS and RW cropping system, respectively, might be attributed due to the positive relationship of soil pH with calcium carbonate content [57]. The lower TIC content in soils of RW system might be related to the collective impact of higher SOC content and lower soil pH under anaerobic conditions of rice [58]. [59] also reported a negative relation of SIC with SOC. Another reason for lower TIC content in RW system might be the dissolution and leaching of carbonates under flooded conditions of rice [60-61]. Significantly higher TIC content under pearl millet based cropping systems may be associated with low SOC, high pH and lesser N fertilization, in contrast, relatively reduced TIC of CW cropping system is attributed to intensive agricultural management techniques and soil acidification by higher N fertilizer (Supplementary table 1) application [62]. As per the observations of present study, the TC content among various cropping systems did not differ significantly, however, soils from SS mono cropping showed 1.90, 11.60, 11.70 and 12.15% higher TC content over RW, PW, CW and PM cropping system, respectively. The perennial aerobic SS system reflected higher soil TC because of constant organic matter inputs through leaf litter fall and rhizo-deposition over longer time span as compared to other cropping systems [63-65]. Although, SOC content was higher under RW, however, lower TC could be ascribed to more leaching of labile carbon pools under anaerobic condition of submerged rice. Lower TC content in soils of aerobic cropping systems (especially PM and PW) than RW might be linked to the combined impacts of fast SOM decomposition rate, less external nutritional supply through FYM and fertilizers (Supplementary table 1) that ultimately causing lower biomass addition in soils. Thus, cumulative impact of inherent soil fertility, texture, nutritional demand and management practices of specific cropping systems, and existing moisture conditions (aerobic/anaerobic) could lead to the differential level of soil carbon stocks [6,17,66-68].

Micronutrients Availability

The concentrations of bio-available micronutrients (Fe, Zn, Cu and Mn) were significantly impacted by the studied cropping systems and soils of RW cropping system recorded 15.17, 54.14, 74.21 and 83.44 % higher DTPA extractable Fe compared to CW, SS, PW and PM cropping system, respectively. Soil pH, redox potential (Eh) and chelates formation are the major chemical processes which typically regulates the Fe availability [69]. The increased soil available Fe under RW cropping system might be associated with anaerobic moisture regimes, which facilitated the conversion of iron to soluble ferrous (Fe^{2+}) form [11,70]. Increased chelation of Fe associated with higher organic matter under anaerobic rice crop also reduces its losses and enhances its bio-availability for plants [71]. In addition, the decay of crop stubbles further facilitates Fe mobilization and sustained release of available Fe in soil [72]. The lesser availability DTPA-Fe in soils under aerobic cropping systems might be due to high pH (Table 1) and oxidised state of soil system that reduces the Fe solubility and availability. The soils of RW cropping system exhibited 12.12, 16.23, 26.86 and 85.00% higher DTPA extractable Zn concentration compared to CW, SS, PW and PM cropping system, respectively. Similar to Fe, positive correlation of DTPA extractable Zn with SOC content may be the possible reason for its higher levels in anaerobic soils of rice crop [73]. Another probable reason may correspond to the accumulation and recycling of Zn added via organic residues, crop litter and root residues [74]. Furthermore, application of Zn fertilizers in rice crop as common practice by farmers in present investigation also elevated its concentrations [75]. The lowest Zn level in soils under PM cropping system might be due to exhaustive absorption by the pearl millet in addition to less Zn fertilizer application [76]. Soils under RW cropping system exhibited 25.73, 37.12, 41.47 and 58.05% higher DTPA extractable Mn content over CW, SS, PW and PM cropping, respectively. A positive and significant relationship among DTPA-extractable Mn, SOC and clay content of soils increased the DTPA-extractable Mn in rice soils [77]. Substantial increase of soil available Mn with RW system might be ascribed to lower soil pH that increases the solubility and availability of micronutrients in soil as compared to aerobic cropping systems with higher soil pH (Table 1) [78-79]. Prolonged soil flooding or anaerobic conditions in RW system lowered down the redox potential of soil and promotes the conversion of Mn^{4+} to soluble Mn^{2+} ions [80-81]. The higher soil EC of aerobic cropping systems also negatively influence the DTPA-extractable Mn availability [77].

The soils undergone PM system showed 23.79, 26.87, 28.79 and 66.67% higher DTPA-extractable Cu content as compared to CW, PW, SS and RW cropping system, respectively. The lower concentration of available Cu in soils of RW system might be attributed to increased formation of Cu organo-complexes due to higher organic matter content under anaerobic conditions of rice [82-83]. The Cu is recognized to be the most easily bound cation with organic matter among micronutrients [69]. Higher available Cu in aerobic CW system compared to SOM rich RW cropping was also reported by [84]. Significantly lower DTPA-extractable Cu concentration in anaerobic RW system compared to aerobic cropping systems might be due to higher Cu immobilization through sulphide formation (CuS, Cu_2S) because of increased sulphur solubilisation under reduced conditions of rice [85-86]. Further, intensive mining without balanced micronutrients replenishment also reduces the Cu availability under RW system [87]. The relatively higher Cu availability in soils under PM cropping system with low SOC and high pH can be explained by the reduced role of organic matter in Cu immobilization. [88] also demonstrated that soil organic matter act as dominant sink for Cu through complexation; consequently, in soils with low SOC, fewer Cu-organic complexes are formed, leaving a greater proportion of Cu as labile pools despite the high soil pH. Pearl millet roots release phytosiderophores having strong affinity for Cu into the rhizosphere, which mobilize Cu from weakly bound soil pools; and these rhizosphere-mediated mobilisation strategies increase Cu availability in pearl millet soils. [89] also reported that aerobic crops with extensive root systems and high biomass, such as mustard, can mobilize Cu from soil matrices through root exudates and rhizospheric interactions, thus enhancing its bioavailability. Furthermore, mustard residues contributes to higher DTPA-extractable Cu by adding Cu-rich leachates which upon decomposition release Cu into soil [90-91]. The present study also displayed a weak polynomial relationship between SOC and available Cu (R^2= 0.074) in evaluated cropping systems (Fig.3).

Microbiological parameters

Microbial diversity, their populations and activities are controlled by soil parameters (texture, moisture, aeration, manures and fertilizer applications), environmental factors (temperature, rainfall and humidity) and crop production techniques [92]. The MBC content in RW cropping system was 1.94, 4.82, 8.81, and 27.40% higher compared to SS, CW, PW, and PM cropping systems, respectively. The higher SOM accumulation under anaerobic conditions of rice exhibited a highly positive and statistically significant association with MBC and other soil microbiological properties [15, 93, 94, 95]. The incorporation of bio-fertilizers, green manures, and high doses of organic manures associated with slow decomposition rate also enhanced the MBC levels in RW cropping system [96]. The higher MBC level in soils undergoing SS mono-cropping as compared to other aerobic systems might be attributed to higher accumulation of above and below ground biomass [97]. In semi-arid soils, the improvement in MBC level in CW could be associated with accrual of SOC content under intensive nutrient management (Supplementary table 1), and positive relationship of SOC with MBC [98]. The DHA was significantly affected by different cropping systems in accordance with the findings of [99] and soils possessed RW cropping had 23.81, 31.23, 33.12 and 51.58% higher DHA over PM, PW, CW and SS system, respectively. In soils from RW cropping system, the elevated DHA may be connected to higher biomass accumulation as substrate along with moisture conditions that provides favourable environment for microbes' proliferation [81, 100]. [101] also demonstrated a higher DHA level in soils linked with more residue addition because the SOC acts as precursor for enzyme synthesis through increased activity of microbe and encourages physical protection of carbon in soil. Comparatively, lesser DHA in soils under aerobic cropping systems may be related to high pH, less moisture coupled with low SOC content (Table 2). The lowest DHA in SS perennial mono cropping could be collective effects of more nutrients mining by crop; heavy use of pesticides that suppress microbial activity and production of enzymes like DHA; multi ratoon systems without proper soil and nutrient management that might gradually reduce microbial population over time; soil compaction disturbs soil structure and negatively impact microbial habitat and activities [102].

The correlation studies revealed that SOC had robust and positive association with TC, DOC, DTPA-Zn, Mn, MBC, DTPA-Fe and DHA [103-104], however, a weak connection was observed between SOC and TIC. The soil microbiological parameters (MBC and DHA) were highly positive and significantly correlated with soil pH, TC, TIC, SOC, DOC; and have positive significant influence on post-harvest available micronutrients, however, showed non-significant correlation with soil EC.

Analysing the complex interactions of different cropping systems with soil parameters could help better to achieve desired level of crop production and to ensure long-term agricultural sustainability. Especially in areas like Haryana or across India, where intensive farming practices dominate, estimating soil health is crucial for obtaining high yields and readdressing the environmental issues through adopting the standard particle size analysis method which was the limitation of present study. Additionally, this is the first report of the region, so has limitations of initial baseline data for comparison, however, this data would be utilized as a base line data set for the future studies in the region. Among the widely practiced cropping systems, RW system was found superior in relation to the soil microbial activity and nutrient retention. Followed by RW system, SS mono-cropping system also proved better than other aerobic cropping systems, mainly in terms of DOC and soil biological properties. Sustainability facet of RW system needs a multifaceted approach that reviews important issues such as soil degradation, nutrient depletion, declining SOM and subsurface water table. The promotion of sustainable and conservational agricultural practices such as minimal tillage, crop diversification, use of bio-fertilizers, integrated nutrient management, organic farming and judicious residue management must be prioritized that offer promising avenues to reduce environmental harm, improve water use efficiency, maintain soil health and enhance crop production. Need based region-specific research across India's diverse agro-ecological zones can better help to guide for the development of targeted and resilient farming strategies. Ultimately, the integration of conservation-based cropping systems with supportive policy frameworks is incumbent for advancing soil restoration, fostering climate-resilient agriculture and securing long-term food and environmental sustainability.

Conclusions

This study gave prominence that SOC, available micronutrients and microbial characteristics serve as key measures to estimate the footprints of dominant cropping systems (RW, CW, PW, PM and SS mono-cropping) on soil quality and functioning. Soils under RW cropping system exhibited lower soil pH (7.37) and EC (0.35 dS m^{-1}) compared to those under CW, PW, PM and SS systems. The RW cropping system soils demonstrated higher SOC (0.62%), MBC (191.51 mg kg^{-1}) and DHA (39.67 µg TPF g^{-1} $24h^{-1}$), contributing to improved soil fitness. Although the implementation of carbon rehabilitation in RW cropping system has been proven effective in sustaining better soil biological health and micronutrients (Zn, Fe and Mn) availability, but this system is widely recognized to face serious long-term sustainability challenges, particularly related to groundwater depletion and soil degradation. Therefore, despite the relatively favourable impacts, long-term sustainability of RW requires cautious evaluation. Thus, integrated approaches that combine the strengths of different cropping systems together with innovations like direct-seeded rice (DSR), balanced nutrient management and legume-based intercropping, may be under taken to enhance soil health while mitigating environmental trade-offs. This research also provides critical evidence for developing region-specific, sustainable intensification strategies, while highlighting the need for continued investigation of long-term sustainability of RW, SS and CW systems.

CRediT authorship contribution statement

Preeti, Dhram Prakash, Sunita Sheoran, Todarmal, Rajni Kant Sharma - Conceptualization, methodology, investigation, resources, data curation, project administration, formal analysis, writing-original draft preparation, **Preeti, Dhram Prakash, Sunita Sheoran, Ankit, Todarmal, Sonia Rani, Rameshwar Singh and Parmod Kumar Yadav** - software, supervision, validation, visualization, writing-review and editing. All authors have read and agreed to the published version of the manuscript.

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Data availability

The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influence the outcomes or interpretation reported of this manuscript.

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