Original Research Article

LONG-TERM EFFECT OF DIFFERENT CROPPING SYSTEMS ON SOIL PHYSICO-CHEMICAL PROPERTIES OF SOIL

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ABSTRACT

Rice (*Oryza sativa* L.)-wheat (*Triticum aestivum* L.) is a dominant cropping system in northwestern India, mainly in the Punjab region. Puddling practices in rice result in degradation of the structure and physico-chemical properties of soil. The present study was conducted in an ongoing long-term experiment at the research farm of the School of Organic Farming, Punjab Agricultural University, Ludhiana, to compare the effect of different cropping systems on soil physico-chemical properties. The ten cropping systems in randomized block design (RBD) were selected, viz. rice-wheat (CS_1), maize-wheat (CS_2), basmati rice-wheat-cowpea green manure (CS_3), maize-mustard-cowpea green manure (CS_4), maize-potato-spring groundnut (CS_5), maize-peas-spring groundnut (CS_6), maize+ cowpea (fodder)-maize fodder-oats fodder-sathi maize fodder (CS_7), sorghum multicut fodder-barseem fodder (CS_8), maize (cobs/fodder)-potato-onion (CS_9), and baby corn-potato-okra (CS_{10}). Significantly lower soil pH was reported in CS_4 and CS_8 compared to other cropping systems. Soil EC was significantly higher in CS_5 and CS_{10} while lowest in CS_4. Soil organic carbon (SOC), aggregate-associated carbon (AAC), and mean weight diameter (MWD) were significantly higher in CS_7 and CS_4. Soil bulk density (BD) and penetration resistance (PR) were significantly higher in CS_1 and lowest in CS_4. SOC was 19% higher in CS_7 and BD was 16% lower in CS_4 compared to CS_1. Soil porosity and water-stable aggregates (WSA) were also found significantly higher in CS_4 and CS_7 whereas lowest in CS_1. The increase in soil depths significantly increased the BD and PR, whereas decreased the soil EC, SOC, porosity, MWD, WSA, and AAC. The cropping systems (CS_4, CS_7, CS_8, CS_6, CS_5, CS_3) with green manure/legume/fodder crops in rotation resulted in better physico-chemical properties by adding more organic matter in the soil compared to cereal-cereal rotations.

Keywords: cropping systems, bulk density, soil organic carbon, mean weight diameter, penetration resistance, green manure

1. INTRODUCTION

Rice-wheat is a widely adopted cropping system in northwestern India, especially in Punjab, Haryana, and Uttar Pradesh, because of favourable climatic conditions, availability of high-yielding rice varieties, and groundwater for irrigation (Ambast et al., 2016). After the green revolution, the rice-wheat cropping system raised food-grain production many times, but currently it is deteriorating soil and water resources and endangering the sustainability of this system (Chuhan et al., 2012). Puddling is a land preparation practice that increases water use efficiency and reduces percolation losses in rice (Singh et al., 2001; Singh et al., 2011).

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Continuous intensive puddling practices for a long time form the hardpan in the sub-surface, which adversely affects the growth of other subsequent crops after rice by restricting the root development, nutrient uptake, and the exchange of air with the atmosphere (Singh et al., 2009; Kumar et al., 2020). Continuous cereal-cereal crop rotations, removal of crop residues, and other inappropriate tillage practices cause depletion of nutrients and degradation of soil structure (Mamta et al., 2020, Hiltbrunner et al., 2013). Cereal-cereal crop rotations are more exhaustive than cereal-legume and cereal-oilseed rotations (Kumar et al., 2012). The soil becomes looser and more porous with the addition of a higher amount of biomass (Alam and Salahin, 2013) from the diversity of crops. The quality of organic matter is more important than its quantity for improving the physical condition of the soil (Nweke and Nnabude, 2015). The cropping systems with the inclusion of green manures or legume crops add more soil organic matter as per crop, which further improves soil physical properties (Demir and Isik 2019; Ram et al., 2022) and C sequestration (Acosta-Martinez et al., 2011) depending upon the type and quantity of crop residue added to the soil (Zuber et al., 2015). Significant difference was reported for soil pH (Trehan et al., 2001) and soil EC values (Kumar et al., 2020) from various cropping systems. Lowest pH values were reported from the cropping systems adding higher amount of organic matter (Degu et al., 2019). So, different cropping systems may affect the soil physico-chemical properties differently.

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Soil organic matter (SOM) significantly impacts soil physico-chemical attributes, viz. soil organic carbon, bulk density (BD), and aggregate stability. Biomass products from cereals and legumes contribute a substantial amount of organic carbon to the soil, improving its physical properties and reducing soil deterioration (Jat et al., 2013). Organic matter binds the primary soil particles and maintains the aggregate stability, increases water storage, and improves the physical properties of the soil. The use of various crops add a variety of root and shoot biomass, which creates biopores in the soil profile, further reduces the soil compaction and decreases the soil bulk density (Chen and Weil, 2011), and improves soil aggregation (Ram et al., 2022). Rice grown in rotation with upland crops like maize and mungbean resulted in more SOC content than rice monocropping (Linh et al., 2016). Also, green manuring crops (legumes and non-legumes) add a higher amount of organic matter to the soil and improve soil physical properties like bulk density, total porosity, soil aggregation, etc. Cropping systems with green manuring of sesbania and green gram improved the organic matter status of soil, which improved the aggregation and reduced the bulk density (Kumar et al., 2020). Cover crops (CCs) also improve soil physico-chemical properties (Blanco-Canqui et al., 2011; Cercioglu et al., 2018). The incorporation of legumes as a cover crop improved the total porosity and aggregate stability, and reduced the soil compaction by adding a higher amount of organic matter (Haruna et al., 2020). In this context, there is a need to compare the long-term effects of different cropping systems on soil physico-chemical properties. Therefore, the present study was conducted to compare the cereal-based cropping systems with the inclusion of green manure/legume/ fodder crops to cereals to find their effect on the physico-chemical properties of soil. It may help to promote the rotations of cereal-cereal cropping systems with green manure/fodder/legume crops to sustain the good physical condition of the soil.

2. MATERIAL AND METHODS

2.1 Study site

The presented study was conducted during *kharif* and *rabi* seasons (2020-2021) in an ongoing long-term experiment at the research farm of the School of Organic Farming, Punjab Agricultural University (PAU), Ludhiana, since 2017. The experiment site was located at 30.90’96” N latitude and 75.78’80” longitude with an altitude of 247 m from the Mean Sea Level representative of Indo-Gangetic alluvial plains with average rainfall of 110-271 mm.

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The mean minimum temperature in winter varied from 7.2°C in December 2020 to 10.2°C in February 2021 (weather data 2020-21, PAU, Ludhiana). The basis properties of the soil at the site are given in Table 1.

Table 1 Basic soil properties of the experimental site (0-30 cm soil depth)

Soil property	**Property value**
Soil texture	Loamy sand (80-84% sand, 8-20% silt and 8-10% clay)
Soil pH	7.31-7.70
Electrical conductivity (EC)	0.14-0.22 dSm^{-1}
Soil organic carbon (SOC)	3.9 g/kg (initial)

2.2 Treatment details

The ongoing long-term experiment with ten cropping systems was selected for the present study. The experiment was laid out in a randomized block design (RBD) with four replications having a plot size of 10.4 × 6.4 m². The treatments included ten cropping systems, viz. CS_1: rice-wheat; CS_2: maize-wheat; CS_3: basmati rice-wheat-cowpea green manure (GM); CS_4: maize-mustard-cowpea GM; CS_5: maize-potato-spring groundnut; CS_6: maize-peas-spring groundnut; CS_7: maize+cowpea (fodder)-maize fodder-oats fodder-sathi maize fodder; CS_8: sorghum multicut fodder-barseem fodder; CS_9: maize (cobs/fodder)-potato-onion; CS_{10}: baby corn-potato-okra. The details about crop variety, fertilizer doses, sowing and harvesting time of the crops in different cropping systems are given in Table 2.

Table 2: The details of crop varieties, fertilizer doses applied, sowing and harvesting time of the crops in different cropping systems

Crop	Crop variety grown	*Fertilizer dose, $N:P_2O_5:K_2O$ (kg/ha)	Sowing time	Harvesting time
Rice	PR 124	100:30:30	July 15, 2021	October 20, 2021

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Wheat	HD 2967	120:60:30	November 13, 2020	April 19, 2021
Basmati rice	Pusa basmati 1121	62.5:0:0	27 july, 2021	November12, 2021
Cowpea green manure	CL 367	20:50:0	April 27, 2021	June 6, 2021
Mustard	GL 7	120: 60:30	November 11, 2020	March 24, 2021
Maize	PMH 1	120:60:30	July 21, 2021	October 24, 2021
Potato	Pukhraj	188:65:65	October 19, 2020	January 15, 2021
Spring Groundnut	TG 37 A	15:20:25	March 29, 2021	July 23, 2021
Peas	Pb 89	50:65:0	November 10, 2020	March 22, 2021
Oats Fodder	OL 10	30:20:0	November 13, 2020	March 22, 2021
Sathi Maize Fodder	Sathi maize	120:60:30	April 15, 2021	June 21, 2021
Sorghum multicut Fodder	SL 44	100:20:0	April 23, 2020	-
Barseem Fodder	BL 42	25:75:0	September 24, 2020	April 20, 2021
Onion	Punjab Naroya	100:50:50	January 25, 2021	May 25, 2021
Baby corn	PMH 2	60:0:0	July 27, 2021	September 27, 2021
Okra	Punjab Suhawani	90:0:0	February 25, 2021	May 25, 2021

***** *The nutrient doses were applied as per the recommendations by Punjab Agricultural University, Ludhiana. Urea, diammonium phosphate, and muriate of potash were used as fertilizer sources for N, P_2O_5, and K_2O respectively.*

2.3 Soil sampling, processing and analysis

The soil samples were collected from four soil depths (0-7.5, 7.5-15, 15-22.5, and 22.5-30 cm) under each cropping system after harvesting of *kharif* and *rabi* crops during 2020-21. The collected samples were air-dried, ground, sieved through 2 mm-sized sieves, and stored for analysis. Soil pH and EC were determined using pH and EC meters (Jackson, 1973). Soil organic carbon (SOC) was estimated by the rapid titration method (Walkley and Black, 1934). Undisturbed soil samples were collected with cylindrical iron cores using the core method to determine the soil bulk density (Blake and Hartge, 1986).

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Soil porosity was determined by the indirect method (Hillel 1982) using BD and PD values:

Porosity (%) = {(1- BD/PD)}*100

Aggregate analysis was done using the wet sieving method (Yoder, 1936). Mean weight diameter (Youker and McGuinness, 1957) and water-stable aggregates (Kemper and Rosenau, 1986) were calculated as:

$$\text{MWD} = \sum_{i=1}^{n} di\ x\ wi$$

$$\text{WSA}_{(0.25\ mm)} = \sum_{i=1}^{n} n\ wi\ \text{x } 100$$

Where, n is the number of size fractions, di is the mean diameter of each size range (mm), wi is the weight of aggregates retained in that size range as a fraction of the total dry weight of the sample analyzed (g). Aggregate associated carbon of the aggregates retained on sieve sizes 0.25 mm and 0.1 mm was determined using the rapid titration method (Walkley and Black 1934). Penetration resistance values for all the cropping systems were measured using a hand-held digital cone penetrometer (Naderi-Boldaji et al., 2009) after the harvesting of *rabi* and *kharif* crops.

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2.4 Statistical analysis

The data was subjected to statistical analysis by using randomized block design-two-way analysis of variance (ANOVA) in SPSS v 25.0 (SPSS Inc, Chicago, USA). Tukey's honest significant difference at p=0.05 level of significance was used to compare the treatment and depth-wise means of different cropping systems.

3. RESULTS AND DISCUSSION

3.1 Soil pH and soil electrical conductivity (EC)

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The pooled data pertaining to soil pH in different cropping systems at different soil depths is presented in Figures 1a and 1b respectively. It depicted that different cropping systems and soil depths significantly (p=0.05) affected the soil pH. Comparing all the cropping systems, CS_8 had significantly the lowest pH (7.31) followed by CS_4 (7.37). With the increase in soil depth, it increased significantly in the range of 7.43-7.64. The lowest soil pH in CS_4 and CS_8 is attributed to more decomposition of organic matter added through crop residue comapred to other cropping systems. Rice-wheat cropping system (CS_1) had a lower pH than CS_2, which might be due to submergence in rice as reported by Kumar *et al* (2020). The lowest pH in surface soil resulted from N fertilization, which released more H+ ions during the process of nitrification, in which released nitrate might combined with cations leached from topsoil to subsoil, as these cations were removed and replaced by H+ ions, and declined the soil pH (Cui *et al*, 2022) in surface soil layers.

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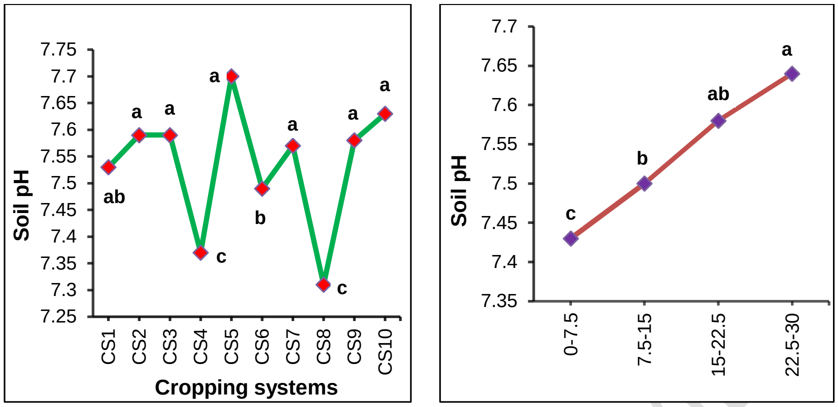

Fig. 1 Effect of (a) cropping systems and (b) soil depths on soil pH
Dissimilar letters indicate the significant difference at p=0.05 by Tukey's honest significant difference

The pooled data pertaining to soil EC in different cropping at different soil depths is presented in Figures 2a and 2b respectively. Soil EC varied in the range 0.14-0.22 dsm^{-1} (Figure 2a) in different cropping systems and 0.17-0.22 dsm^{-1} at different soil depths (Figure 2b). Significantly lowest soil EC was observed in CS_7 followed by CS_8 with values of 0.14 and 0.17 respectively. It was significantly higher by 58% in CS_{10}, CS_5, and by 50% in CS_3, CS_6 than in CS_7 respectively. It decreased significantly with increase in soil depth as also reported by Kumar et al., (2020).

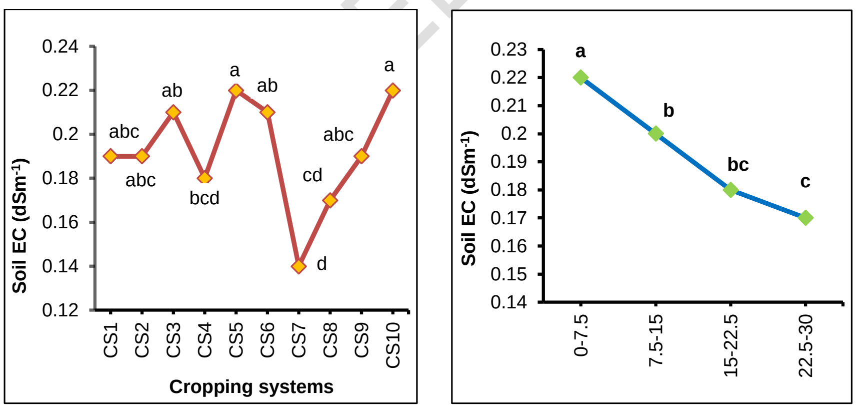

Fig. 2 Effect of (a) different cropping systems and (b) soil depths on soil EC
Dissimilar letters indicate the significant difference at p=0.05 by Tukey's honest significant difference

3.2 Soil organic carbon (SOC) and mean weight diameter (MWD)

The pooled data for SOC and MWD influenced by different cropping systems at different soil depths is given in Table 3. It was reported that in five years (2017-2021), SOC increased from an initial value of 3.9 to 5.0 g/kg. SOC was significantly (p=0.05) higher in CS_7 (5.45 g/kg), at par with CS_4 (5.37 g/kg), followed by CS_6 (5.19 g/kg) and CS_8 (5.10 g/kg). The lowest SOC was noticed in CS_1 (4.59 g/kg) and CS_{10} (4.65 g/kg). The highest SOC and MWD in CS_7 resulted from the addition of a higher amount of plant biomass of fodder crops due to higher plant development in both aerial parts and in the roots. Also, a mixture of fodder crops adds more diversified organic residue in the soil which provides favourable conditions for microorganisms and increases carbon accumulation in the soil (Blanco-Canqui and Jasa, 2019; Demir and Isik, 2019). It was also reported by Velso et al., (2020) that the more the presence and diversity of roots, the higher the exudates of organic compounds which serve as a source of soil carbon. In CS_4, there was an additional effect from incorporation of maize crop residue and green manuring of cowpea which added more organic matter to the soil and built up the SOC. Comparing legume-based cropping systems (CS_6, CS_5), the additional effect of two legume crops (peas and spring groundnut) in CS_6 resulted in significantly more SOC than in CS_5. In the cropping systems with potato as a *rabi* crop, CS_5 showed more SOC than CS_9 and CS_{10} due to comparatively more amount of organic matter added from the legume crop in CS_5. Rice-wheat (CS_1) and maize-wheat (CS_2) had comparatively less SOC than CS_3, as over the five years there was no additional source of organic matter to the CS_1 and CS_2, while in CS_3 green manuring was practiced every year before sowing of basmati rice. Depth-wise, SOC decreased significantly from 5.35 to 4.58 g/kg at 0-7.5 cm to 2.5-30 cm soil depths respectively. A decrease in SOC with an increase in soil depth was reported (Kumar *et al*. 2020) because of less organic matter addition in lower layers of soil.

MWD was significantly highest in CS_7 with a mean value of 0.342 mm at par with CS_4 (0.329 mm) while lowest in CS_1 (0.182 mm). MWD was higher by 87%, 67%, 65%, and 62% in CS_7 than in CS_1, CS_2, CS_{10}, and CS_9 respectively. Lower MWD in CS_9 and CS_{10} was caused by intensive tillage in potato crop, which caused the removal of organic matter and decreased soil aggregation. In rice-based cropping systems, CS_3 (0.205 mm) was at par with CS_1 (0.182 mm), whereas, In the legume-based cropping systems, CS_6 had 29.64% higher MWD than in CS_5. MWD decreased significantly with an increase in soil depth having mean values of 0.330, 0.257, 0.215 and 0.182 mm at 0-7.5, 7.5-15, 15-22.5 and 22.5-30 cm respectively. It was observed that the cropping systems (CS_4, CS_5, CS_6, CS_7, CS_8) with green manure/legume/fodder crops in rotation resulted in higher values for both SOC and MWD compared to other cropping systems. Higher SOC levels increased the MWD in the respective cropping systems as more organic matter addition binds the soil mass together and increases the MWD of soil aggregates. It is also supported by the positive correlation between SOC and MWD (Figure 7b). Haruna et al., (2020) reported that green manure incorporation in maize crops for 2 years increased the SOC by 0.22%. Similarly, in CS_1, tillage operations for rice puddling destroyed the soil structure and decreased the soil aggregation. Reichert et al., (2022) reported that physical disruption by tillage implements breaks the aggregates, favours more oxidation of organic carbon, and hence reduces soil aggregation. However, fodder crops showed better aggregation, because of more root biomass and aerial parts of the fodder which added organic matter to the soil and provided humic substances as binding agents for aggregate stabilization (Horrocks et al., 2019).

Table 3 Effect of different cropping systems on SOC and MWD

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Cropping systems	SOC (g/kg)				Mean*	MWD (mm)				Mean*
	Soil depth (D), cm					Soil depth (D), cm				
	0-7.5	7.5-15	15-22.5	22.5-30		0-7.5	7.5-15	15-22.5	22.5-30	
CS_1	4.89	4.77	4.47	4.24	4.59^{f}	0.226	0.201	0.160	0.143	0.182^{d}
CS_2	5.17	4.92	4.72	4.44	4.81^{e}	0.277	0.234	0.200	0.176	0.222^{cd}
CS_3	5.22	5.07	4.85	4.54	4.92^{d}	0.247	0.219	0.190	0.164	0.205^{cd}
CS_4	5.77	5.53	5.28	4.88	5.37^{a}	0.472	0.324	0.283	0.238	0.329^{a}
CS_5	5.27	5.05	4.75	4.54	4.90^{d}	0.317	0.235	0.195	0.160	0.226^{cd}
CS_6	5.61	5.26	5.13	4.78	5.19^{b}	0.427	0.302	0.239	0.205	0.293^{ab}
CS_7	5.88	5.61	5.39	4.93	5.45^{a}	0.492	0.348	0.282	0.247	0.342^{a}
CS_8	5.59	5.17	4.92	4.72	5.10^{c}	0.350	0.250	0.219	0.176	0.249^{bc}
CS_9	5.08	4.86	4.65	4.39	4.74^{e}	0.251	0.238	0.198	0.158	0.211^{cd}
CS_{10}	5.01	4.79	4.52	4.29	4.65^{f}	0.251	0.221	0.193	0.165	0.207^{cd}
Mean*	5.35^{a}	5.10^{ab}	4.87^{ab}	4.57^{b}		0.331^{a}	0.257^{b}	0.216^{c}	0.183^{d}	

**Means followed by different letters are significantly different at p=0.05 by Tukey's honest significant difference*

3.3 Aggregate associated carbon (AAC)

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The pooled data pertaining to AAC in soil aggregate sizes of 0.25 mm and 0.1 mm in different cropping systems at different soil depths is presented in Figure 3a and 3b respectively. In 0.25 mm sized aggregates, AAC was significantly (p=0.05) higher in CS_4, which was 11%, 18% and 64% higher than CS_8, CS_7 and CS_1 respectively. The lowest AAC was reported in CS_1 (2.28 mg/g) followed by CS_{10} (2.59 mg/g). Comparing the maize-based cropping systems, the incorporation of green manures/fodder/legume crops in rotation resulted in more AAC in CS_4, CS_6, and CS_7 than in CS_2, and CS_9. In rice-based cropping systems, CS_3 with the incorporation of cowpea as green manure resulted in 39.04% more AAC than CS_1. For aggregate size 0.1 mm, AAC was statistically non-significant (p=0.05) in CS_8, CS_4 and CS_7 but significantly higher than CS_1, CS_2, CS_3, CS_9, and CS_{10} (Figure 3a). The AAC content in CS_8 was higher by 14%, 16%, and 20% than in CS_9, CS_2, and CS_{10} respectively. Significantly lowest AAC was reported in CS_1 with a mean value of 2.48 mg/g which was lower by 17.9%, 17.3% and 14.5% than in CS_8, CS_4 and CS_7 respectively. AAC in CS_5 was significantly higher by 6.4% and 5.5% than in CS_9 and CS_{10} attributed to legume crop in CS_5.

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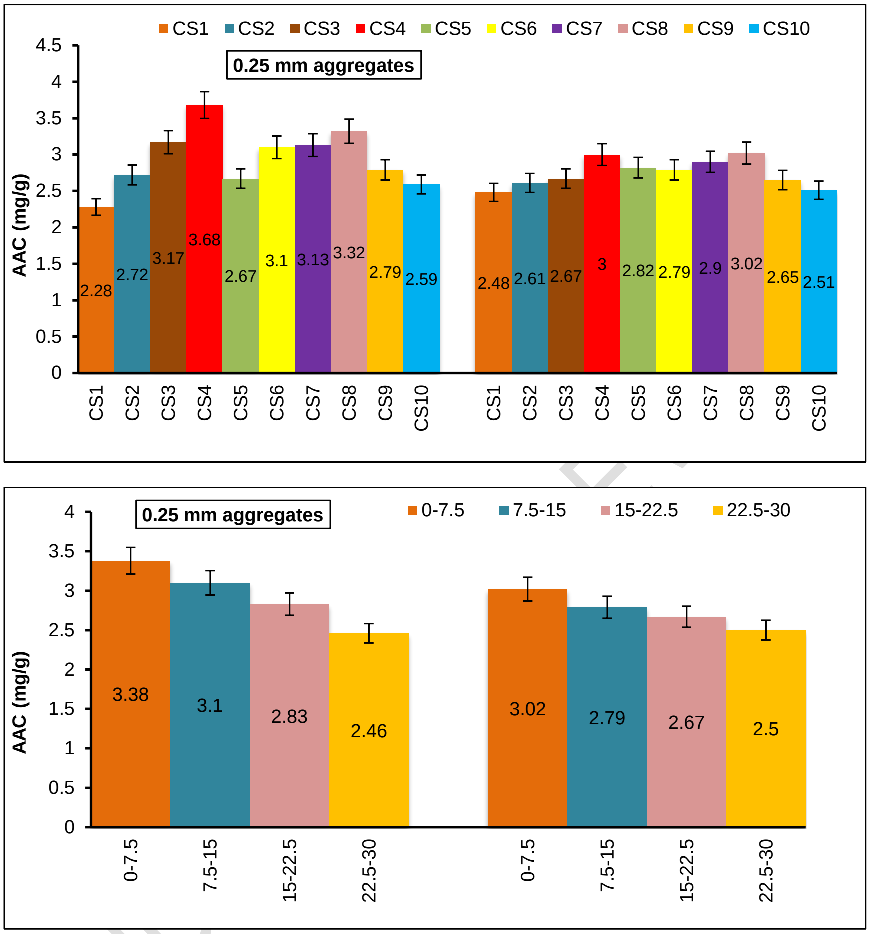

Fig. 3 Effect of (a) cropping systems (b) soil depths on aggregates associated carbon

**Vertical bars and dissimilar letters indicate the significant difference at 5% levels of significance*

Depth-wise results for AAC in 0.25 mm and 0.1 mm sized soil aggregates were also significant at given soil depths (Figure 3b). For both soil aggregate sizes, AAC decreased significantly (p=0.05) from surface soil depths to sub-surface. It was higher by 38% and 21% in 0-7.5 cm than in 22.5 cm soil depth for 0.25 mm and 0.1 mm sized soil aggregates respectively.

3.4 Soil bulk density (BD)

The pooled data pertaining to soil bulk density in different cropping systems at different soil depths is given in Table 4. Significantly lowest BD was reported in CS_4 followed by CS_8, CS_7, CS_6 and CS_5 with mean values of 1.41, 1.49, 1.52, 1.54 and 1.55 g/cm^3 respectively. The highest bulk density was reported in CS_1 (rice-wheat) at par with CS_3 with mean values of 1.66 and 1.64 g/cm^3 respectively. The lowest BD in CS_4 might result from the soil incorporation of maize residue after harvesting of cobs every year, and the coarse nature of this residue decreased the BD. Additionally to it, cowpea was also incorporated as a green

Table 4 Effect of different cropping systems on soil bulk density

Cropping systems	**Soil depths (cm)**				**Mean***
	0-7.5	7.5-15	15-22.5	22.5-30	
CS_1	1.61	1.65	1.68	1.72	1.66^a
CS_2	1.54	1.59	1.63	1.66	1.60^{abc}
CS_3	1.57	1.62	1.68	1.70	1.64^{ab}
CS_4	1.32	1.41	1.46	1.48	1.41^f
CS_5	1.47	1.53	1.58	1.60	1.55^{cde}
CS_6	1.45	1.53	1.59	1.62	1.54^{cde}
CS_7	1.42	1.48	1.58	1.62	1.52^{de}
CS_8	1.37	1.46	1.56	1.57	1.49^e
CS_9	1.49	1.56	1.61	1.63	1.57^{cd}
CS_{10}	1.52	1.57	1.62	1.65	1.59^{bcd}
Mean*	1.47^c	1.54^b	1.60^a	1.62^a	

**Means followed by different letters are significantly different at p=0.05 by Tukey's honest significant difference*

manure from the last five years in CS_4, which added comparatively higher amount of organic matter to the soil. However, higher BD in rice-wheat (CS_1) was caused by puddling in rice carried out every year which might reduced the macroporosity in upper surface layers and resulted in compaction in subsurface layers as also reported by Linh et al., (2016). Intensive tillage practices in potato crop resulted lower BD in CS_9 and CS_{10} as tillage loosened the soil and resulted less BD than in CS_1. The cropping systems having green manure/fodder/legume crops in rotation resulted in lower BD due to the addition of higher organic matter which added less dense organic components on decaying of roots and crop residues in the soil compared to the mineral constituents of the soil (Beutler et al., 2017; Santos et al., 2020). BD increased significantly with an increase in soil depths in all the cropping systems. Depth-wise, it varied in the range of 1.47-1.62 g/cm^3, reported to be lower in surface soil layers compared to sub-surface soil. It was higher by 10% in 22.5 cm soil depth than in 0-7.5 cm due to less organic matter addition in lower layers. The decrease in

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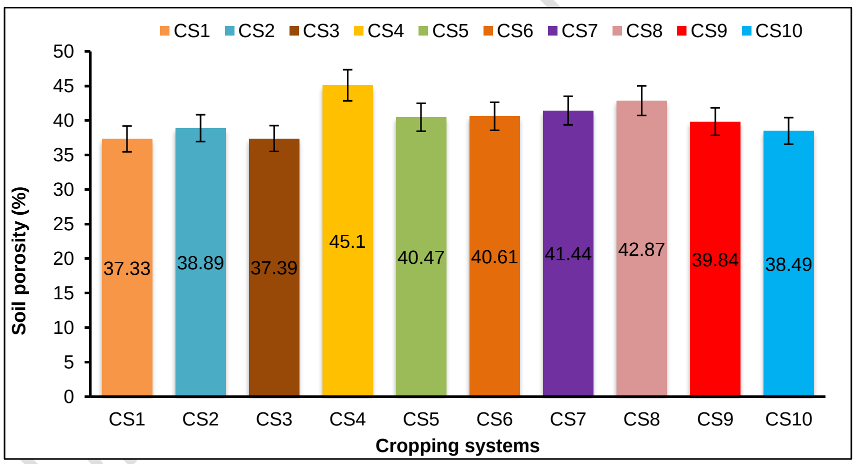
BD with increased SOC through the addition of organic matter from green manure or fodder crops (Table 3), can be explained by the negative correlation between SOC and BD (Figure 7a).

3.5 Soil porosity

The pooled data for soil porosity in different cropping systems at different soil depths is presented in Figure 4a and 4b respectively. Significantly highest porosity was obtained in CS_4 at par with CS_8, followed by CS_7 and CS_6 with mean values of 45.10, 42.87, 41.44 and 40.61% respectively. More addition of organic matter from plant biomass increased the soil aggregation, decreased the BD and hence, increased the soil porosity in CS_4 by 5.2%, 8% and 21% compared to CS_8, CS_7 and CS_1 respectively. Rice-wheat (CS_1) cropping system resulted in the lowest porosity with a mean of 37.33% which was lower by 17%, 13% and 10% than in CS_4, CS_8 and CS_7 respectively. This was due to hardpan formation at the subsurface, which reduced the porosity due to increased compaction in rice-wheat (CS_1) cropping system. Higher porosity in CS_7 and CS_8 is supported by Reichert et al., (2022), who found that fodder crops increased the porosity by improving the proportion of macro aggregates. Soil porosity decreased significantly with an increase in soil depth with mean of 42.95%, 40.79%, 38.91% and 38.31% at 0-7.5, 7.5-15, 15-22.5 and 22.5-30 cm soil depths respectively (Figure 4b).



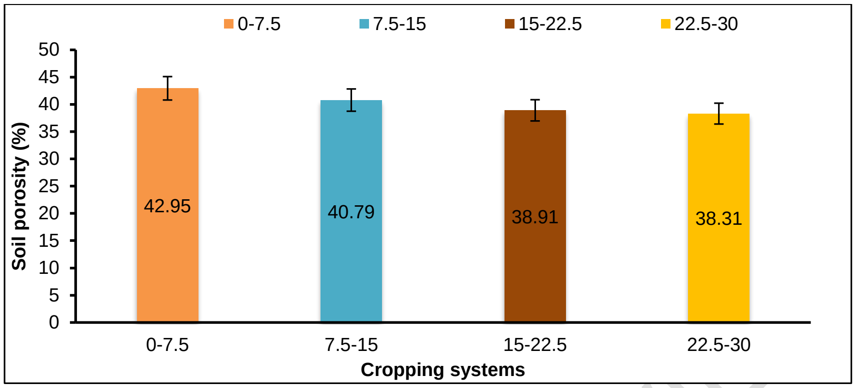


Fig. 4 Effect of (a) cropping systems and (b) soil depths on soil porosity

**Means followed by different letters are significantly different at p=0.05 by Tukey's honest significant difference*

3.6 Water stable aggregates $_{(0.25\ mm)}$ (%):

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The pooled data for water-stable aggregates in 0.25 mm sized soil aggregates in different cropping systems at different soil depths are shown in Figure 5a and 5b respectively. WSA were reported to be significantly higher (p=0.05) in CS_7 at par with CS_4, and CS_8 with mean values of 38.32, 37.42 and 35.11% respectively. However, the lowest WSA was reported in rice-wheat (CS_1), which was lower by 40% than in CS_7. Comparing rice-based cropping systems, WSA increased by 19% in CS_3 compared to CS_1. It was found by Linh et al., (2016) that puddling destroyed the soil aggregation in rice monocropping compared to the rice-mungbean-rice cropping system. Higher SOC levels in CS_7 and CS_4 resulted in more WSA while puddling in rice destructed the soil aggregates and reduced the WSA. It decreased significantly with an increase in soil depth with a higher value (39.54%) in 0-7.5 cm soil depth and then decreased to 30.7, 27.29, and 24.22% at 7.5-15, 15-22.5 and 22.5-30 cm soil depths respectively.

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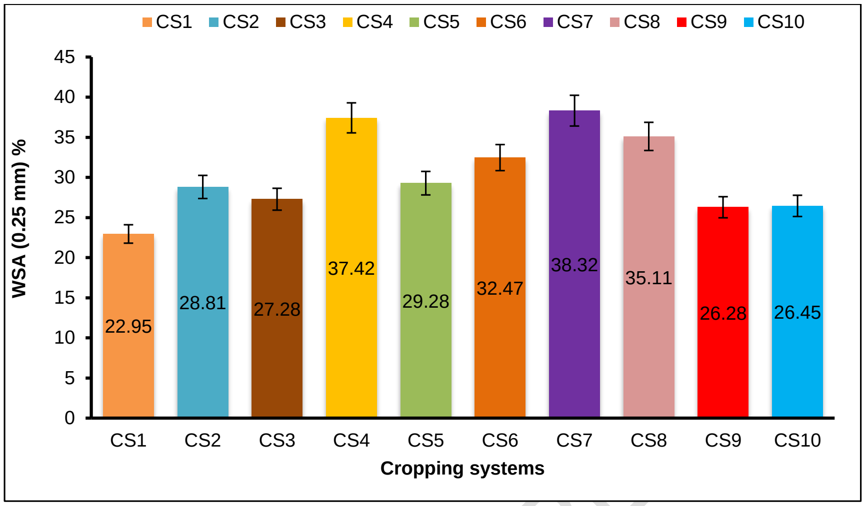

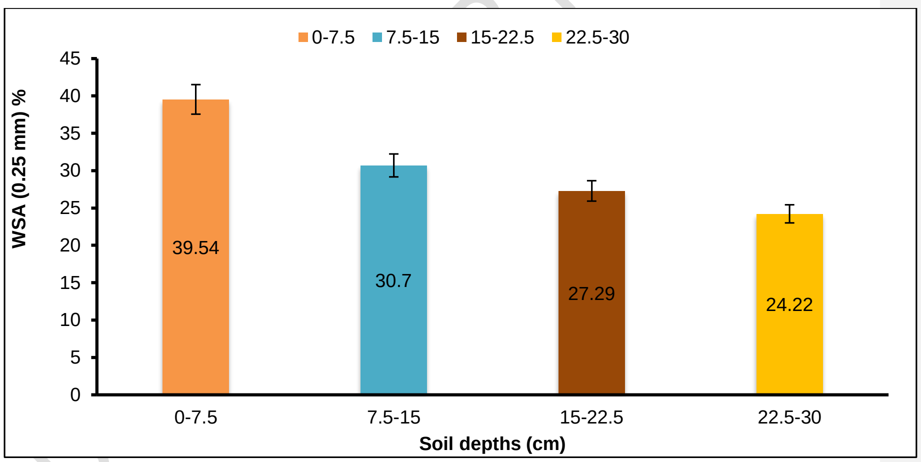

Fig. 5 Effect of (a) cropping systems and (b) soil depths on water stable aggregates

**Vertical bars and dissimilar letters indicate the significant difference at 5% levels of significance p=0.05 by Tukey's honest significant difference*

***3.7 Penetration resistance (PR)*:**

The data for penetration resistance as affected by different cropping systems is presented in Figure 6. It revealed that the highest PR was recorded in the rice-wheat (CS_1) cropping system followed by CS_2 and CS_3. However, CS_4 and CS_7 showed lowest PR compared to other cropping systems. In 0-10 cm soil, PR varied in the range of 30-350 kPa in different cropping systems. At a subsurface soil depth of 10-20 cm, PR increased to the maximum value in the range of 330 to 512 kPa in CS_4 and CS_1 respectively. Below 20 cm, a steep decrease in PR (512 to 445 kPa) in CS_1, and a slight decrease were reported in CS_2, CS_3 and CS_{10}. However, in CS_4 it increased up to 382 kPa with an increase in soil depth. PR was found to be significantly higher in CS_1 at 15-20 cm soil layer, which might resulted from hard pan formation due to puddling in rice whereas, in CS_3, this effect was somewhat overcome by cowpea green manuring. CS_4 and CS_7 showed lower penetration resistance which might be due to higher SOC and lower BD levels (Table 3 and 4 respectively). The cropping systems with green manure/legume/fodder crops in rotation showed less penetration resistance than in CS_1. An increase in BD increased the cohesion of the soil particles, decreased the porosity and increased the risk of soil compaction which led to an increase in PR. The results were also supported by the positive correlation between BD and PR (Figure 7 d), which showed that penetration resistance increased with an increase in soil bulk density. Cima et al., (2015) reported that rice rotation with other upland crops decreased the bulk density and increased the porosity which further decreased the penetration resistance compared to rice monoculture. It was also reported by Doan et al., (2005) that legume-based cropping systems decreased the soil compaction.

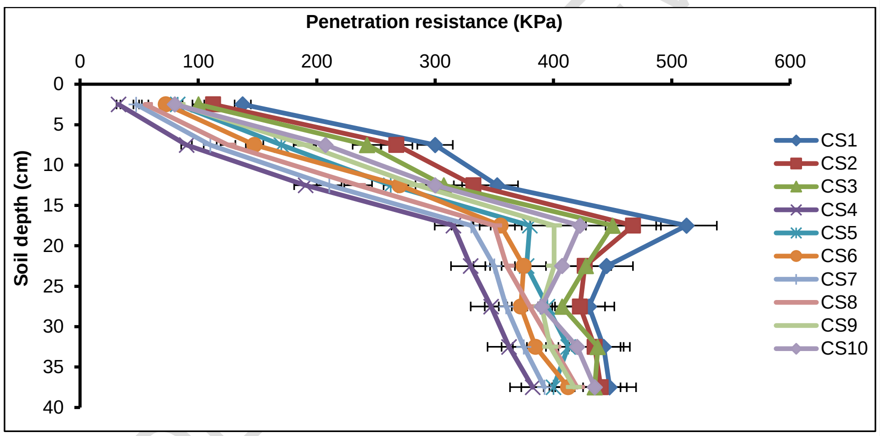

Fig. 6 Effect of different cropping systems on penetration resistance

3.8 Correlation between soil physico-chemical properties

The linear correlation between SOC and MWD, MWD and WSA shows the direct relationship (Figure 7b, 7c respectively) and indicates that more addition of organic matter increased the SOC content which increased the MWD and WSA. However, SOC and BD were inversely related (Figure 7a), which indicated that an increase in SOC reduced the BD. BD was directly related to PR (Figure 7d), indicates that increase in BD increases the PR.

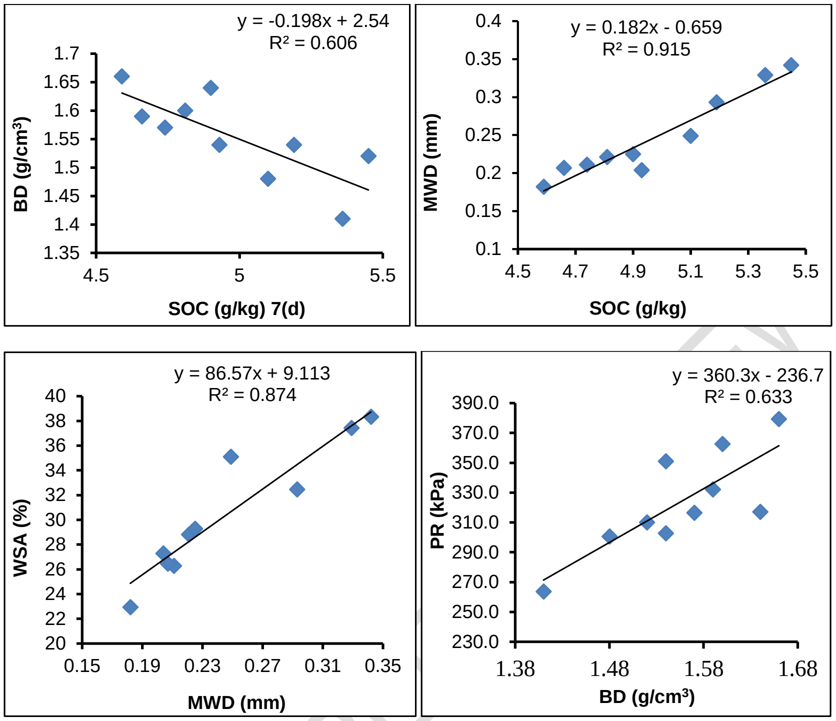

Fig. 7 Relationship between (a) SOC and BD, (b) SOC and MWD, (c) MWD and WSA (d) BD and PR.

4. CONCLUSION

Rice-wheat cropping system resulted in higher bulk density, high penetration resistance, less SOC, MWD and porosity due to hardpan formation in the sub-surface. However, the inclusion of cowpea as green manure in rotation with basmati rice had more SOC, AAC, and less PR than the rice-wheat cropping system. Also, among maize-based cropping systems, CS_4, CS_7, CS_8, CS_6, and CS_5 resulted in better soil physico-chemical properties compared to CS_1, CS_2, CS_9 and CS_{10}. The presence of green manures/fodder/legume crops in CS_4, CS_7, CS_8, CS_6, and CS_5 added a higher amount of root and shoot biomass in the soil, increased the SOC, MWD, porosity, WSA, and reduced the bulk density and penetration resistance. In this way, it was concluded that there is a need to include green manure/fodder/legume crops in rotation as these add a higher amount of crop residue or organic matter in the soil and improve the soil physico-chemical properties compared to cereal-based cropping systems.

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