Original Research Article

EFFECT OF ORGANICALLY GROWNCROPPING SYSTEMS ON SOIL PROPERTIES AND THEIR CORRELATION WITH CARBON POOLS

ABSTRACT:

Organic agriculture is gaining significance for its benefits in crop diversity, sustainability, and soil organic carbon enhancement.Considering these advantages, a study was conducted during Kharif 2021-22 at the Research Farm, Centre for Organic Agriculture Research and Training, Department of Agronomy, Dr. Panjabrao Deshmukh Krishi Vidyapeeth, Akola, to evaluate the effect of organically grown cropping systems on soil organic carbon dynamics and soil properties in vertisols. The experiment, laid out in a Randomized Block Design (RBD), included seven treatments: T1 (sole Cotton), T2 (Cotton + Sunhemp, 2:1), T3 (Cotton + Blackgram, 2:1), T4 (Soybean + Pigeonpea, 3:1), T5 (Blackgram - Chickpea), T6 (Greengram + Sorghum, 2:1), and T7 (sole Sunhemp), replicated three times. Nutrients were supplied through FYM and vermicompost (50% N each), with phosphorus supplemented by Phosphate Rich Organic Manure (PROM).Results indicated that the T2: Cotton + Sunhemp system recorded the lowest bulk density (1.42 Mg m^{-3}), highest hydraulic conductivity (0.76 cm hr^{-1}), and mean weight diameter (0.73 mm), reflecting improved soil structure.Also, soil pH (8.04-8.11) and electrical conductivity (0.13-0.15 dS m^{-1}) decreased compared to initial values (8.12 and 0.16 dS m^{-1}).The T2: Cotton + Sunhemp system also showed significant improvement in soil organic carbon (6.09 g kg^{-1}) and reduction in calcium carbonate 3.69% to 3.48%.Nutrient availability wassignificantly highest in the T4: Soybean + Pigeonpea system, with available nitrogen (209.27 kg ha^{-1}), phosphorus (22.28 kg ha^{-1}), and potassium (354.26 kg ha^{-1}).CO_2 evolution (35.4 mg 100 g^{-1} soil) and Dehydrogenase activity (47.66 µg TPF g^{-1} 24 hr^{-1}) was significantly highest in T2: Cotton + Sunhempsystem.The T2: Cotton + Sunhemp system also showed the highest organic carbon (6.09 g kg^{-1}), with very labile C (4.04 g kg^{-1}), labile C (1.29 g kg^{-1}), and less labile C (0.93 g kg^{-1}) being highest in surface soil (0-20 cm). Non-labile C (5.13 g kg^{-1}) was highest in T1: sole Cotton.Correlation analysis highlighted the importance of organic carbon, showing positive relationships with hydraulic conductivity, mean weight diameter, CO_2 evolution, and dehydrogenase activity, while negatively correlating with bulk density and calcium carbonate. The study concludes that organically grown cropping systems, particularly T2: Cotton + Sunhempsystem, significantly enhance soil health, carbon sequestration, and nutrient availability, supporting sustainable agriculture.

Keywords: Soil organic carbon, Soil properties, Carbon pools, Cropping system,Organicfarming,Soil health,Nutrient dynamics, Sustainable agriculture

1. INTRODUCTION:

Intensive farming practices have led to a decline in soil fertility and organic carbon levels, particularly in India's cotton and pulse crop areas, where over-reliance on chemical fertilizers and poor organic matter management have worsened soil quality (Wani, 2003).

Despite the significance of organic practices in improving soil carbon dynamics, there is limited research on their impact, especially in semi-arid regions (Avasthe*et al.,* 2016). This study aims to fill this gap by evaluating the effect of organically grown cropping systems on soil properties and their correlation with carbon pools, focusing on how organic inputs like FYM, vermicompost, and crop residues influence soil quality and carbon sequestration.

Soil carbon is an important part of the terrestrial carbon pool and soils of the world are potentially viable sinks for atmospheric carbon (Lal, 2015).Soil organic carbon (SOC) stock is comprised of labile or actively cycling pools and stable, resistant/recalcitrant pools with varying residence times (Chan *et al*., 2001). Parton *et al.* (1987) defined soil labile carbon as the fraction of soil organic carbon with a turnover time of less than a few years as compared to recalcitrant carbon with a turnover time of several thousand years.The labile C pool of total organic carbon (TOC) has been the main source of nutrition which influences the quality and productivity of the soil (Chan *etal*., 2001). Highly recalcitrant or passive C pool is slowly altered by microbial activities and due to this nature, it may not be a good soil quality parameter but contributes towards overall TOC stock. Labile organic carbon is constituted of amino acids, simple carbohydrates, a fraction of microbial biomass and other simple organic compounds and it changes substantially after disturbance and management (Chan *et al*., 2001).

Farmers have been using organic manures for a long time. Organic manures provide humic substances and other metabolites for maintaining soil productivity. Organic matter directly or indirectly influences the growth of crops (Ampong*et al*., 2022). The earthworm casting which acts as super manure could be used to improve soil conditions. The vermicompost application is one of the useful methods to renew the depleted soil fertility, augment the available pool of nutrients, conserve more water and maintain soil quality (Weber *et al*., 2007).

A cropping system encompasses the spatial and temporal arrangement and management of crops to achieve sustainable productivity. It includes practices like crop rotation, which enhances soil fertility and reduces pests; intercropping, which boosts resource use efficiency and biodiversity; monocropping, which specializes in one crop but may lead to soil degradation; and agroforestry systems, which combine trees with crops and livestock to promote biodiversity and soil health while sequestering carbon. Each system is tailored to specific climatic, soil, and socioeconomic conditions to optimize resources and enhance sustainability (Veste *et al*., 2024).

2. MATERIALS AND METHODS:

The experiment was conducted on organically certified field at Centre for Organic Agriculture Research & Training (COART), Department of Agronomy, Dr. PDKV, Akola during kharifseason of 2021-22 and analytical work was carried out at Department of Soil Science and Agricultural Chemistry, Dr. PDKV, Akola, with the objective to assess the impact of various organically grown cropping system on soil physical, chemical and biological properties; and correlation of organic carbon withother soil properties and carbon pools. The soil of the experimental field comprised clayey montmorillonite, hyperthermic, vertisols.

The nutrients were supplied through FYM and vermicompost based on nitrogen - 50% N through FYM + 50% N through vermicompost. The compensation of phosphorus was made available through PROM (Phosphate rich organic manure). Application of *Trichoderma, Rhizobium and PSB* was done in all crops as seed treatment. Plant protection schedule was followed organically. Similarly, sunhemp was buried in soil after 35 to 40 days of sowing, while other intercrops were harvested and the residues of the same were incorporated in the soil after harvest. Soil samples were analyzed after harvest of crops.

The representative soil samples were taken from 0-20 cm and 20-40 cm (for carbon pool analysis) depth air-dried under shade and pulverized using a mortar and pestle and then homogenized through a 2 mm meshsieve. For mean weight diameter analysis, 8 mm sized aggregates were retained on the sieve and used. For analysis of organic carbon, the soil was passed through a 0.5 mm meshsieve. The sieved soil was preserved in plastic bags and labelled properly for subsequent analysis.Soil samples for biological parameters were collected 35-40 DAS and immediately analyzed.

The experiment was laid out in Randomized Block Design (RBD) with seven treatments shown below in treatment details which were replicated three times. The experimental data collected pertaining to physical, chemical, biological properties, nutrient analysis and carbon pools were tabulated and analyzed by adopting standard statistical methods of analysis of variance (ANOVA) as given by Gomez and Gomez (1984) and the data has been reported at appropriate places.

List 1.Treatments details

	Cropping Systems		
T1	Cotton	Sole	Arboreum (HDPS)
T2	Cotton + Sunhemp	2:1	Hirsutum and Sunhemp green manuring at 35-40 DAS
T3	Cotton + Blackgram	2:1	Hirsutum and in situ mulching of Black gram (After harvest)
T4	Soybean + Pigeon pea	3:1	In situ mulching of Soybean (After harvest)
T5	Blackgram- Chickpea (*Rabi*)		In situ mulching of Black gram (After harvest)
T6	Greengram + Sorghum	2:1	In situ mulching of Greengram (After harvest)
T7	Sole Sunhemp		Sunhemp was buried at 35-40 DAS.

2.1 Soil analysis

2.1.1 Soil Physical Properties

2.1.1.1 Bulk Density
Determined by the clod coating technique as described by Blake and Hartge (1986).

2.1.1.2 Hydraulic Conductivity
Measured using the constant head method on core soil samples fully saturated with distilled water, as described by Klute and Dirksen (1986).

2.1.1.3 Mean Weight Diameter
Assessed using Yoder’s apparatus method as outlined by Kemper and Rosenau (1986).

2.2 Soil Chemical Properties

2.2.1 Soil Reaction (pH)

Soil pH was determined in soil water suspension (1:2.5 soil:water) by a glass electrode pH meter after equilibrating the soil with water for 30 minutes with occasional stirring (Jackson, 1973).

2.2.2 Electrical Conductivity (EC)

Electrical conductivity was determined in soil water suspension (1:2.5 soil:water) after equilibrating the soil with water and keeping the sample undisturbed till the supernatant is obtained and measured using a conductivity meter (Jackson, 1973).

2.2.3 Organic Carbon

Determined by the Walkley and Black method (Nelson and Sommers, 1982). Ground soil samples passed through a 0.5 mm sieve were oxidized with 1N Potassium dichromate and concentrated H_2SO_4 to generate heat for the reaction. The unused dichromate was back-titrated with 0.5N ferrous ammonium sulfate (FAS).

2.2.4 Calcium Carbonate

Measured using the rapid titration (acid neutralization) method (Piper, 1966).

2.2.5 Available Nitrogen

Determined using the alkaline permanganate method with an automatic distillation system (Subbiah & Asija, 1956).

2.2.6 Available Phosphorus

Determinedusing Olsen's method with 0.5 M sodium bicarbonate (pH 8.5) as an extractant, and Darco-G-60 was used to remove organic matter from the filtrate for UV spectrophotometric analysis (Watanabe & Olsen, 1965).

2.2.7 Available Potassium

Determined by a flame photometer using neutral normal ammonium acetate (pH 7.0) as an extractant (Jackson, 1973).

2.3 Soil Biological Properties

2.3.1 CO_2Evolution

Measured using the alkali trap method (Anderson, 1982). Soil samples were incubated at 28°C for 24 hours in a closed vessel, where CO_2 produced was absorbed in sodium hydroxide and quantified by titration.

2.3.2 Dehydrogenase Activity

Assessed by the triphenyl tetrazolium chloride (TTC) method (Klein *et al.*, 1971). A 1g soil sample was incubated with 0.2 ml of 3% triphenyl tetrazolium chloride (TTC) and distilled water in sealed tubes at 28°C for 24 hours. Methanol was added to extract triphenyl formazan (TPF), and its absorbance was measured at 485 nm using a spectrophotometer.

2.4 Carbon Pools

Soil organic carbon (SOC) was determined using the Walkley and Black (1934) method with 36 N H_2SO_4, implying the recovery factor of 1.298 represents the total SOC pool. The total SOC pool was divided into four sub-fractions: very labile (Pool I: C_{VL}), labile (Pool II: C_L), less labile (Pool III: C_{LL}), and non-labile (Pool IV: C_{NL}). Pools I and II form the active pool, while Pools III and IV constitute the passive pool. The analysis used different acid-aqueous solution ratios (0.5:1, 1:1, 2:1) as described by (Chan *et al.*, 2001) for sub-fractionating SOC.

Table 1. Initial soil properties before start of the experiment

Sr. No.	Properties	Value
1	Bulk density (Mg m^{-3})	1.46
2	Hydraulic conductivity (cm hr^{-1})	0.68
3	Mean Weight Diameter (mm)	0.66
4	pH	8.12
5	Electrical conductivity (dSm^{-1})	0.16
6	Organic Carbon (g kg^{-1})	5.20

7	Calcium carbonate (%)	3.69
8	Available Nitrogen (kg ha^{-1})	194.20
9	Available Phosphorus (kg ha^{-1})	13.37
10	Available Potassium (kg ha^{-1})	334.60

3. RESULTS AND DISCUSSION

3.1 Effect of organically grown intercropping systems on soil physical properties

Soil physical properties have a profound influence on nutrient availability which are important attributes of soil quality. The important physical properties of soil viz., bulk density, hydraulic conductivity and mean weight diameter are generally considered as soil quality indicators. The data regarding the soil physical properties as influenced by organically grown intercropping systems is presented in Table 2.

3.1.1 Bulk Density

The effect of different cropping systems on bulk density was found significant as presented in Table 2and graphically depicted in Fig. 1. It was reduced from 1.46 to 1.42 Mg m^{-3} under various cropping systems. Numerically, lower bulk density (1.42 Mg m^{-3}) was recorded with Cotton + Sunhemp and sole Sunhemp. This might be due to the addition of organics which helps to enhance soil porosity and ultimately helps in aeration and reduced the bulk density. The bacterial glue and other soil particle binding agents derived from added organics decrease the soil bulk density by improving soil aggregation and total porosity. Similar results were reported by Hugar and Soraganvi (2014), who found a decrease in bulk density in soils treated with organic amendments; Manchala (2017) observed reduced bulk density cropping systems, while Khuspure*et al.* (2018) and Gawande *et al.* (2024) also reported lower bulk density values under organic practices.

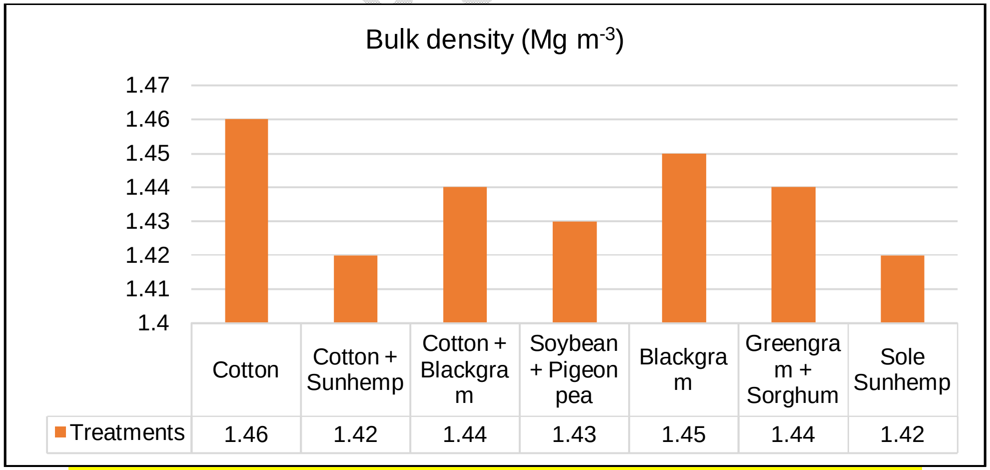

Fig. 1. Effect of organically grown intercropping system on bulk density

3.1.2 Hydraulic conductivity

The hydraulic conductivity of soil as influenced by organically grown cropping systems was foundto be statistically significant as presented in Table 2and graphically depicted in Fig. 2. It ranged from 0.69 to0.76 cm hr^{-1} indicating that the highest (0.76 cm hr^{-1}) hydraulic conductivity was recorded with Cotton + Sunhemp and lowest with sole Cotton (0.69 cm hr^{-1}). Better aggregation and increased porosity due to the addition of organics directly influenced hydraulic conductivity and ultimately soil water dynamics. Hydraulic conductivity was enhanced due to the continuous addition of organics. Similar results were reported by Manchala (2017) who observed improved hydraulic conductivity due to organic amendments attributed to enhanced aggregation; Khuspure*et al.* (2018) and Gawande *et al.* (2024) found significant increases in hydraulic conductivity under organic inputs.

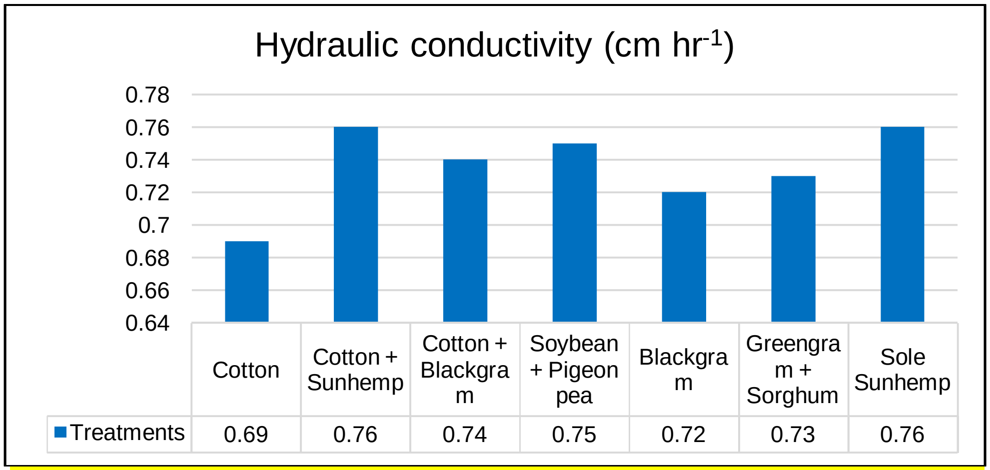

Fig. 2: Effect of organically grown intercropping system on hydraulic conductivity

3.1.3 Mean Weight Diameter(MWD)

The MWD of soil in various treatments varied from 0.67 to 0.73 mm under various organic cropping systems (Table 2and graphically depicted in Fig. 3). From the data it is observed that MWD was found significantly higher in the Cotton + Sunhemp treatment followed by sole Sunhemp and Soybean + Pigeon pea intercropping system overthe rest of the treatments. It was also observed that the MWD was increased with increasing soil organic carbon. Similar results were reported byKhuspure*et al.* (2018)and Gawande *et al.* (2024)whoreported that the higher the MWD the more the organic carbon content in the soil.

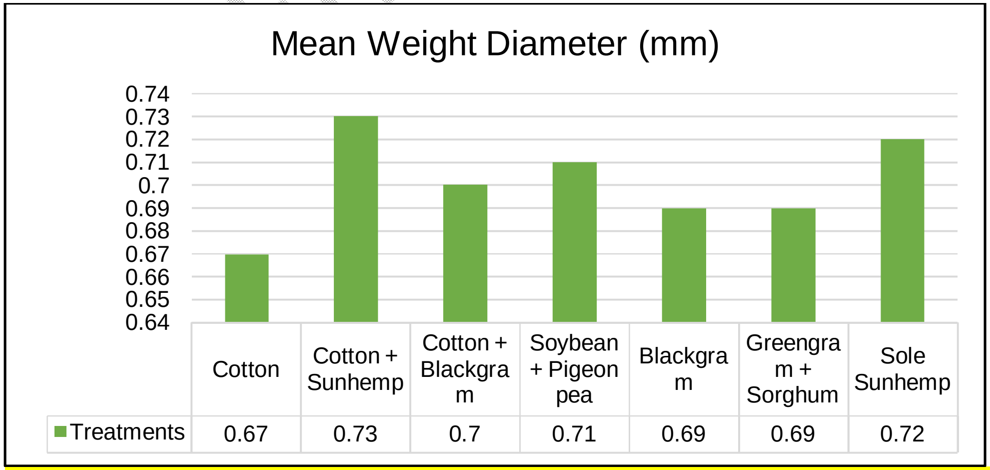

Fig. 3: Effect of organically grown intercropping systems on mean weight diameter

Table 2. Effect of organically grown intercropping systems on soil physical properties

	Treatments	Bulk density (Mg m^{-3})	Hydraulic conductivity (cm hr^{-1})	Mean Weight Diameter (mm)
T1	Cotton	1.46	0.69	0.67
T2	Cotton + Sunhemp	1.42	0.76	0.73
T3	Cotton + Blackgram	1.44	0.74	0.70
T4	Soybean + Pigeon pea	1.43	0.75	0.71
T5	Blackgram- Chickpea (*Rabi*)	1.45	0.72	0.69
T6	Greengram + Sorghum	1.44	0.73	0.69
T7	Sole Sunhemp	1.42	0.76	0.72
	SE(m)±	0.009	0.008	0.012
	CD at 5%	0.028	0.024	0.037
	Initial	1.46	0.68	0.66

Note: SE(m)± = Standard Error of the Mean ± and CD at 5% = Critical Difference at 5% level

3.2 Effect of organically grown intercropping systems on soil chemical properties

3.2.1 Soil pH

The pH of the soil varied from 8.04 to 8.11 over the initial 8.12 (Table 3). There was no significant difference in pH among treatments, which could be attributed to the buffering effect caused due to organic matter and secondly due to the high buffering capacity of the clayey soil. McCauley *et al.* (2017) reported that the addition of soil organic matter pushes the soil solution towards neutral pH. A slight decrease in soil pH was observed under various cropping systems, likely due to the incorporation of leguminous crops. Similar results were reported by Bahadur *et al.* (2012) and Bama *et al.* (2017) observed reduced soil pH due to variouscropping system.

3.2.2 Electrical Conductivity (EC)

The EC of soil varied from 0.13 to 0.15 over the initial 0.16 and was non-significant (Table 3). A slight decrease in soil EC was observed due to the incorporation of leguminous cropsand leaching of soluble salts. In addition to this, the organics on decomposition released various organic acids which helped to solubilize the salts present in thesoilhence, a slight reduction in EC may be observed. Similar results were observed by Bahadur *et al.* (2012) and Bama *et al.* (2017) reported reduced soil EC due to organic amendments and cropping system.

3.2.3 Organic carbon

The data in Table 3 revealed that organic carbon content in soil increased from an initialvalue of 5.29 g kg^{-1} to 6.09 g kg^{-1}. The highest organic carbon was noted in Cotton + Sunhemp (6.09 g kg^{-1}) followed by Sole Sunhemp (5.97 g kg^{-1}). The consistent leaf fall and root activity of cotton till its harvest must have supplied measurable quantity of carbon to the soil. A relatively higher proportion of carbonobserved was due to the supply and the availability of mineralizable and readily hydrolysable carbon resulting from microbial activity because of the addition of FYM, vermicompost and crop residue from intercropping. The increase in organic carbon content under treatments might be due to the direct incorporation of organic matter, better root growth and more plant residue addition. These results are in agreement with the findings ofBandyopadhyay *et al.* (2010),Gabhane*et al.* (2013), Sanchez-Navarro *et al.* (2020),Rakhonde*et al.* (2021),and Gawande *et al.* (2024) reported increased soil organic carbon from organics and cropping system.

3.2.4 Calcium carbonate

Data on regarding to calcium carbonate as influenced by various organic intercropping systems is presented in Table 3. The calcium carbonate in soil reduced from 3.57 to 3.48 % over the initial 3.69 %. The results indicated significant differences and a slight decrease in calcium carbonate under various treatments of intercropping systems where reduction in $CaCO_3$ may be observed due to the incorporation of leguminous crops.The decrease in $CaCO_3$ in the organic treatments might be due to the dissolution of carbonates by the organic acids released during the decomposition of organic materials which might have reacted with $CaCO_3$ to release CO_2 thereby reducing the $CaCO_3$ content in the soil. Similar results were confirmed by Sharma *et al.* (2004) and Mubark and Nortcliff (2010) reported that organic amendments reduced calcium carbonate content by dissolving carbonates through organic acids released during decomposition. The highest reduction in calcium carbonate was found in treatment Cotton + Sunhemp (3.48%) followed by Sole Sunhemp (3.49%) and Soybean + Pigeon pea intercropping (3.51%). The higher amount of $CaCO_3$ was assigned with depth which was indicated by the process of leaching of calcium and subsequently precipitated as carbonate at a lower depth. The leaching of $CaCO_3$ might be due to high permeability and high rainfall. Due to the soluble nature of $CaCO_3$, its concentration can fluctuate at different soil depths (soil profile) (Kumar *et al.,* 2012).

3.2.5 Available Nitrogen

The data in Table 3 showed that the available nitrogen was increased from an initial 194.20 kg ha^{-1} to 209.27 kg ha^{-1} under organically grown cropping systems. The considerable improvement in available nitrogen status was observed in all the treatments which involved the combined application of crop residues and intercropping. This might be attributed to improved microbial activity increased due to the availability of organic matter.Similar results were reported by Singh *et al.* (2015). Also, the increased organic carbon in the present research supports this result.
Available nitrogen was recorded to besignificantly higher in Soybean + Pigeon pea (209.27 kg ha^{-1}) and it was found at par with Cotton + Sunhemp (207.53 kg ha^{-1}), Sole Sunhemp (205.27 kg ha^{-1}) and Cotton + Black gram (204.63 kg ha^{-1}). The increase in available nitrogen could be attributed to greater multiplication of soil microbes due to the presence of organic material, which could convert organic nitrogen into inorganic form. Legumes are advantageous for soils due to their symbiotic relationship with nitrogen-fixing bacteria. Thus, legume intercrops can self-regulate soil nitrogen levels to optimize soil nutrientsavailability. The findings conform with the results reported by Bama *et al.*(2017), Gupta Choudhury*et al.* (2018),Sanchez-Navarro *et al.* (2020),Rakhonde*et al.* (2021), and Gawande *et al.* (2024)reported increased nitrogen availability and improved microbial activity in organic cropping systems.

3.2.6 Available Phosphorus

It is evident from the data as presented in Table 3, that the available P content of the soil under organic cropping systems varied significantly and it ranged from 16.68 to 22.28 kg ha^{-1} indicating that the soil was low in available phosphorus. Significantly higher available phosphorous was recorded in the treatment of Soybean + Pigeon pea intercropping system (22.28 kg ha^{-1}) which was observedto be at par with Cotton + Sunhemp intercropping system (20.62 kg ha^{-1}). The lowest availability of phosphorus was found in sole Cotton. The black soils which had high phosphorus fixation problems are specifically becoming deficient under the intensive cropping systems. Under these circumstances, the crops having a potential of adding considerable biomass through intercropping to the soil have special significance in black soils. The increase in available phosphorus due to legumes can be ascribed to the development of phosphorus-solubilizing organisms in the root zone. The decomposition of leaf litter is useful for a slight reduction in pH which favours the availability of phosphorus in these soils by increasing acidity. The results are in conformity with the findings reported byGabhane*et al. (*2013), Bama *et al.* (2017), Gupta Choudhury*et al.* (2018) Hadke*et al.* (2020), and Gawande *et al.* (2024)who observed increased phosphorus availability in soils with legume-based intercropping, attributed to phosphorus-solubilizing organisms and organic matter decomposition.

3.2.7 Available Potassium

There was an increase in available potassium in the soil due to the incorporation of plant biomass from legume cropping systems. It was found to be increased from an initial value 334.60 kg ha^{-1} to 354.26 kg ha^{-1} under organically grown cropping systems (Table 3). Significantly higher available potassium (354.26 kg ha^{-1}) recorded in Soybean + Pigeon pea intercropping system which was at par with Cotton + Sunhemp (352.03 kg ha^{-1}) and Sole Sunhemp (348.14 kg ha^{-1}). However, the lowest available potassium content was recorded with sole cotton (338.30 kg ha^{-1}). This showed higher available potassium values with slight variation among different treatments because the experimental soil was rich in available potassium and the increase in potassium availability can be attributed to the direct addition of potassium through FYM, vermicompost and incorporation of intercrops and shaded leaf litter of legumes to the available potassium pool of soil, besides the reduction in potassium fixation and release of potassium due to the interaction of organic matter with clay. The results are in conformity with the findings reported byGabhane*et al.* (2013), Jayakumar and Surendran (2017), Gupta Choudhury*et al.* (2018), and Rakhonde*et al.* (2021) who observed increased potassium availability in soils due to organic amendments, while Gawande *et al.* (2024) confirmed similar trends in potassium release through organic matter.

Table 3. Effect of organically grown intercropping systems on soil chemical properties

Treatments		pH	EC (dSm^{-1})	OC (g kg^{-1})	$CaCO_3$ (%)	Available N (kg ha^{-1})	Available P (kg ha^{-1})	Available K (kg ha^{-1})
T1	Cotton	8.11	0.13	5.36	3.57	198.33	16.68	338.30
T2	Cotton + Sunhemp	8.04	0.15	6.09	3.48	207.53	20.62	352.03
T3	Cotton + Blackgram	8.06	0.14	5.72	3.53	204.63	19.67	344.56
T4	Soybean + Pigeon pea	8.06	0.14	5.83	3.51	209.27	22.28	354.26
T5	Blackgram-Chickpea (*Rabi*)	8.09	0.13	5.58	3.56	201.87	18.44	342.23
T6	Greengram + Sorghum	8.08	0.13	5.65	3.55	202.10	18.89	343.84
T7	Sole Sunhemp	8.05	0.15	5.97	3.49	205.27	19.81	348.14
	SE(m)±	0.02	0.005	0.09	0.014	1.54	0.669	3.054
	CD at 5%	NS	NS	0.27	0.043	4.77	2.061	9.410
	Initial	8.12	0.16	5.29	3.69	194.20	13.37	334.60

Note:SE(m)± = Standard Error of the Mean ±, CD at 5% = Critical Difference at 5% level& NS: Non-Significant

3.3 Effect of organically grown intercropping systems on soil biological properties

3.3.1 CO_2 Evolution

The data pertaining to CO_2 evolution as influenced by organically grown cropping systems was found to be significant as presented in Table 4. It ranged from 25.4 to 35.4 mg 100 g^{-1} soil. Significantly higher CO_2 evolution was observed in the treatment Cotton + Sunhemp intercropping system (35.4 mg 100 g^{-1} soil) which resulted at par with Sole Sunhemp (34.9 mg 100 g^{-1} soil) and Soybean + Pigeon pea intercropping system (32.4 mg 100 g^{-1} soil). The increased microbial biomass and metabolically active substances could have resulted in an increased soil respiration rate. Similar findings were reported by Casals *et al.* (2000). These microorganisms decompose the organic matter and make soil a net source of carbon by releasing CO_2 into the atmosphere. The rate of CO_2 evolution release has a linear relationship with the organic carbon content of the soil. The addition of crop residue might release organic acids upon decomposition and further enhance microbial respiration in the rhizosphere (Chi *et al.*, 2012) and Ray *et al.* (2020).

3.3.2 Dehydrogenase activity

The dehydrogenase activity as influenced by organically grown cropping systems was found to be significant as presented in Table 4. It was found to vary from 39.42 to 47.66 µg TPF g^{-1} 24 hr^{-1}. Significantly higher DHA was recorded in the treatment of Cotton +Sunhemp intercropping system (47.66 µg TPF g^{-1} 24 hr^{-1}) which was foundto be at par with Sole Sunhemp (46.98 µg TPF g^{-1} 24 hr^{-1}), Soybean +Pigeon pea (44.62 µg TPF g^{-1} 24 hr^{-1}). The stronger effects of an application of FYM, vermicompost and incorporation of crop residue on dehydrogenase activity might be due to the more easily decomposable components of crop residues and the metabolism by soil microorganisms and due to the increase in microbial growth with the addition of carbon substrate.Similar findings were reported by Venkatesh *et al.* (2012) and Parihar *et al.* (2018), who observed enhanced dehydrogenase activity with organic amendments; Rakshitha*et al.* (2023) and Ankit *et al.* (2024) also confirmed increased microbial growth and DHA due to crop residues and organic inputs.

Table 4. Effect of organically grown intercropping systems on soil biological properties

Treatments		CO_2 evolution (mg 100 g^{-1} soil)	DHA (µg TPF g^{-1} 24 hr^{-1})
T1	Cotton	25.43	39.42
T2	Cotton + Sunhemp	35.37	47.66
T3	Cotton + Blackgram	31.75	43.75
T4	Soybean + Pigeon pea	32.42	44.62
T5	Blackgram- Chickpea (Rabi)	28.08	41.61
T6	Greengram + Sorghum	30.87	42.84
T7	Sole Sunhemp	34.80	46.98
	SE(m)±	1.049	1.036
	CD at 5%	3.231	3.193

Note: SE(m)± = standard error of the mean ± and CD at 5% = critical difference at 5% level

3.4 Effect of organically grown intercropping systems on carbon pools

3.4.1 Very Labile Carbon(C_{VL})

Very labile carbon pool of soils as influenced by organically grown cropping systems was found to be significant as presented in Table 5. The very labile carbon in different treatments varied from 2.90 to 4.04 g kg^{-1} in surface soil (0-20 cm) and 2.84 to 4.02 g kg^{-1} in subsurface soil (20-40 cm). The highest very labile carbon (4.04 g kg^{-1}) was recorded under Cotton + Sunhemp (0-20 cm) intercropping system. This might be due to the provision of more organic matter by Sunhemp which has resulted in a significant increase in the very labile carbon pool. In general, the surface top layer has higher SOC concentration as compared to lower depths. Very labile form of carbon (C_{VL}) i.e., the most easily oxidizable fraction of carbon is more easily decomposable and for this reason, it is related to the supply of organic residues in the soil. The findings are in close conformity with the findings reported by (Chan *et al.* 2001). The lower values of very labile carbon noted under Cotton (T1) may be due to the comparatively lower addition of biomass.Similer result was presentedby Babu *et al.* (2020).

3.4.2 Labile Carbon(C_L)

The labile carbon varied from 0.83 to 1.29 g kg^{-1} in surface soil (0-20 cm) and 0.85 to 1.28 g kg^{-1} in sub-surface soil (20-40 cm). The effect of organically grown cropping system on the labile carbon pool of soils was found to besignificant as presented in Table 5. The highest labile carbon (1.29 g kg^{-1}) was recorded under the Cotton + Sunhemp (0-20 cm). The increase in labile C content with the application of FYM, vermicompost and *in situ* incorporation of legumes could be because of the fresh organic materials in the soils. These stimulate the microbial activity helping SOC decomposition due to rapid excretion of the labile C. Labile soil organic carbon pool is considered as the readily accessible source of microorganisms which turnsthem over rapidly and has a direct impact on nutrient supply. Labile soil organic carbon pool generally includes a light fraction of organic matter, microbial biomass and mineralizable organic matter. The labile C pool of total organic carbon (TOC) has been the main source of nutrition which influences the quality and productivity of soil. Similar findings were reported by Chan *et al.*(2001)and Babu *et al.* (2020) reported that organic amendments improved the labile carbon pool and stimulated microbial activity.

Adoption of Cotton + Sunhempintercropping system can preferentially enhance more labile soil organic carbon and would be a useful approach for characterizing soil organic carbon and hence building soil fertility and nutrient availability to plants. Although, the quantity of labile carbon pool is very low as compared to TOC, it is easily accessible and thus more important from the point of nutrient availability during the crop growth period as compared to total soil organic carbon. Therefore, labile carbon pool helps to understand the availability of nutrients in the soil for uptake by plants. The findings are in close agreement with the results reported by Ghosh *et al.* (2017), Kumar *et al.* (2018),Balpande*et al.* (2020), andBabu *et al.* (2020) reported that organic amendments and intercropping systems enhance labile carbon pools, soil fertility, and nutrient availability.

3.4.3 Less Labile Carbon(C_{LL})

The data in respect of less labile carbon pool in soils as influenced by organically grown intercropping systems was found to be significant as presented in Table 5. The less labile carbon pool ranged from 0.59 to 0.90 g kg^{-1} in surface soil and 0.64 to 0.93 g kg^{-1}. It is evident from the results that the less labile carbon pool of soil was significantly highest in Cotton + Sunhemp (20-40 cm).results reported by Babu *et al.* (2020) found that organic amendments increased the less labile carbon pool, especially in deeper soil layers.

3.4.4 Non - Labile Carbon(C_{NL})

It is observed that the non-labile carbon varied from 4.22 to 5.13 g kg^{-1} in surface soil (0-20 cm) and 4.05 to 4.94 g kg^{-1} in subsurface soil (20-40 cm) (Table 5). The effect of organically grown cropping system on the non-labile carbon pool in soils was found significant. Non-labile carbon pool was noted significantly higher in Cotton (T1) over the rest of the treatments. Among all treatments, the lower value of non-labile carbon was recorded in Cotton + Sunhemp (4.05 g kg^{-1}) intercropping system at 20-40 cm depth. The findings are in line with the results reported by Mandal *et al.* (2013), Das *et al.* (2017), and Babu *et al.* (2020)found organic cropping systems increased non-labile carbon pools.

3.4.5 Total Organic Carbon(TOC)

TOC content for all the treatments was high in surface soil (0-20 cm) than in subsurface soil (20-40 cm). TOC in surface and sub-surface soil was in the order $T_2 > T_7 > T_4 > T_3 > T_6 > T_5 > T_1$ respectively (Table 5). A build-up of the higher amount of TOC in surface soil over sub-surface soil is attributed to the accumulation of organic matter from root biomass and leftover crop residues in the former that decreased with soil depth. The addition of root biomass and root exudates results in such variation in soil depths (Kaur *et al.,* 2008) and Babu *et al.* (2020).

Table 5: Effect of organically grown intercropping systems on soil carbon pools and total organic carbon

Treatments		Very labile (g kg^{-1})		Labile (g kg^{-1})		Less labile (g kg^{-1})		Non-labile (g kg^{-1})		Total OC (g kg^{-1})	
		0-20 cm	20-40 cm	0-20 cm	20-40 cm	0-20 cm	20-40 cm	0-20 cm	20-40 cm	0-20 cm	20-40 cm
T1	Cotton	2.90	2.84	0.83	0.88	0.59	0.64	5.32	5.14	9.64	9.50
T2	Cotton + Sunhemp	4.04	4.02	1.29	1.28	0.90	0.93	4.04	3.85	10.27	10.09
T3	Cotton + Blackgram	3.50	3.46	1.00	0.94	0.77	0.84	4.69	4.51	9.96	9.75
T4	Soybean + Pigeon pea	3.54	3.53	1.05	1.02	0.80	0.85	4.65	4.42	10.04	9.82
T5	Blackgram-Chickpea (Rabi)	3.15	3.13	0.84	0.85	0.62	0.65	5.20	4.85	9.81	9.48
T6	Greengram + Sorghum	3.36	3.34	0.93	0.94	0.68	0.69	4.92	4.61	9.90	9.57
T7	Sole Sunhemp	3.88	3.85	1.11	1.04	0.81	0.91	4.36	4.20	10.16	10.00
	SE (m) ±	0.018	0.016	0.016	0.016	0.015	0.017	0.020	0.020	0.019	0.020
	CD at 5%	0.055	0.050	0.048	0.049	0.047	0.052	0.062	0.061	0.058	0.062

Note: SE(m)± = Standard Error of the Mean ± and CD at 5% = Critical Difference at 5% level

3.4.6 Percent contribution of soil carbon pools to total organic carbon of soil

The different soil carbon pools were analyzed and percent contribution of each pool wascalculated against total organic carbon. The data pertaining to percent contribution isreported in Table 6 for surface soil (0-20 cm) and Table 7 for subsurface soil (20-40 cm).The calculation indicates the higher contribution of non-labile carbon pool to the total organic carbon and it varied from (40.36 to 54.26%) in surface soil (0-20 cm) and (39.39 to 53.12%) in subsurface soil (20-40 cm) under various organically grown intercropping systems. The lowest percent contribution of the non-labile pool was noticed in the treatment of Cotton + Sunhemp (39.39%) whereas the highest percent contribution was found in Cotton (54.26%). Among all the pools, the less labile carbon pool contributed 6.27 to 8.66% (0-20 cm) and 6.87 to 9.02% (20-40 cm). The highest percent contribution was recorded in the treatment of Cotton + Sunhemp intercropping system. The percent contribution of very labile pool varied from 30.72 to 38.67% (0-20 cm) while 30.55 to 39.11% (20-40 cm). The highest percent contribution of the very labile pool was noticed inCotton + Sunhemptreatment. The contribution made by very labile are more or less similar at both depths. The scrutiny of the data concerning the percent contribution of labile pool recorded 8.75 to 12.31% in surface soil (0-20 cm) and 9.45 to 12.48%in subsurface soil (20-40 cm). It is noticed that the highest percent contribution of the labile pool was recorded in Cotton + Sunhemp treatment at both depths.

The average contribution of C_{VL}, C_L, C_{LL}, and C_{NL} towards total organic carbon under different treatments in surface soil (0-20 cm) was 35.06%, 10.13%, 7.43% and 47.34% respectively. The passive pool (C_{LL}+C_{NL}) contributed a relatively higher proportion (55.04%) than the active pool (C_{VL}+C_L) (44.96%). Similarly, the average contribution of C_{VL}, C_L, C_{LL}, and C_{NL} towards total organic carbon under different treatments in subsurface soil was 35.26%, 10.12%, 8.02% and 46.61% respectively. In subsurface soil, the passive pool (C_{LL}+C_{NL}) contributed a relatively higher proportion (54.46%) than the active pool (C_{VL}+C_L) (45.54%). Similar results were reported by Das *et al.* (2017), Kumar *et al.* (2018) Balpande*et al.* (2020), Hadke*et al.* (2020),and Babu *et al.* (2020). also reported similar results in Vertisol.

Passive pool (C_{PP}) dominated active pool (C_{AP}) of C in all the treatments for various soil depths. As the C_{AP} generally included a light fraction of organic matter, microbial biomass and mineralizable organic matter (Chan *et al.,* 2001,Chivhane and Bhattacharyya, 2010) organic intercropping systems can play a pivotal role in enhancing soil fertility, nutrient availability and crop productivity (Bhattacharyya *et al.*, 2007 and Babu *et al.*, 2020). The higher soil organic carbon pool as influenced by the organically grown intercropping system was more in the surface soil (0-20 cm) as compared to subsurface soil (20-40 cm) andwas inthe order of C_{NL}> C_{VL}> C_L >C_{LL}.

Table 6: Percent contribution of soil organic carbon pools to total organic carbon in surface soil (0-20 cm)

Treatments		Active pool (%)		Passive pool (%)	
		Very labile	**Labile**	**Less labile**	**Non labile**
T1	Cotton	30.11	8.58	6.14	55.16
T2	Cotton + Sunhemp	39.35	12.53	8.81	39.32
T3	Cotton + Blackgram	35.12	10.02	7.76	47.09
T4	Soybean + Pigeonpea	35.28	10.47	7.92	46.33
T5	Blackgram- Chickpea (Rabi)	32.15	8.60	6.30	52.95
T6	Greengram + Sorghum	33.98	9.39	6.90	49.74
T7	Sole Sunhemp	38.20	10.97	7.95	42.88
	Average	34.88	10.08	7.40	47.64
	% contribution to TOC	44.96		55.04	

Table 7: Percent contribution of soil carbon pools to total organic carbon in subsurface soil (20-40 cm)

Treatments		Active pool (%)		Passive pool (%)	
		Very labile	**Labile**	**Less labile**	**Non labile**
T1	Cotton	29.91	9.25	6.73	54.11
T2	Cotton + Sunhemp	39.88	12.73	9.20	38.19
T3	Cotton + Blackgram	35.53	9.61	8.60	46.26
T4	Soybean + Pigeon pea	35.93	10.34	8.69	45.04
T5	Blackgram- Chickpea (Rabi)	33.05	8.95	6.85	51.15

T6	Greengram + Sorghum	34.91	9.79	7.17	48.13
T7	Sole Sunhemp	38.48	10.40	9.10	42.02
	Average	35.38	10.15	8.05	46.41
	% contribution to TOC	45.54		54.46	

3.5 Correlation of organic carbon with soil properties and carbon pools

It was observed that the organic carbon was positively and significantly correlated with soil properties shown in table 8. It was noticed that organic carbon has positive and significant correlation with CO_2 evolution and DHA, while it has negative correlation with bulk density and calcium carbonate. The results thus suggested the significance of organic carbon in relation to the organically grown cropping systems. Also, the organic carbon was found to have significant and positive correlation with very labile carbon, labile carbon, less labile carbon and total carbon, whereas it has negative correlation with non-labile carbon.This result is match withSanchez-Navarro *et al.* (2020) and Mir *et al.* (2023).

Table 8: Correlation of organic carbon with soil properties and carbon pools

Sr. No.	A) Soil properties	Organic carbon
1.	Bulk density	-0.703**
2.	Hydraulic conductivity	0.871**
3.	Mean weight diameter	0.747**
4.	Calcium carbonate	-0.822**
	B) Biological parameters	
5.	CO_2 evolution	0.804**
6.	Dehydrogenase activity	0.933**
	C) Carbon pools	
7.	Very labile carbon	0.985**
8.	Labile carbon	0.936**
9.	Less labile carbon	0.928**
10.	Non-labile carbon	-0.970**
11.	Total carbon	0.985**

* 5% significant, ** 1% significant

4. CONCLUSION

The study demonstrated that organic cropping systems significantly improved soil health by enhancing soil organic carbon (SOC) dynamics, soil properties, and nutrient availability. The T2: Cotton + Sunhempintercropping system showed improved physical properties, including reduced bulk density, increased hydraulic conductivity, and mean weight diameter, alongside improved chemical properties such as higher organic carbon and reduced calcium carbonate, along with increased availability of nitrogen, phosphorus, and potassium, particularly in T4: Soybean + Pigeonpeaintercropping system. Biological properties, like dehydrogenase activity and CO_2 evolution, were highest in T2, indicating greater microbial activity. Soil carbon pools were significantly influenced by organically grown intercropping systems, with higher levels of C_{VL}, C_L, and C_{LL} recorded in the T2: Cotton + Sunhemp system, while C_{NL} was highest in the T1: sole Cotton. The active pool contributed 44.96% and 45.54% to total organic carbon in surface and subsurface soils, respectively, while the passive pool contributed 55.04% and 54.46%.Surface soils had greater organic carbon than subsurface soils, with the fractions following the order C_{NL}> C_{VL}> C_{L}> C_{LL}.Correlation analysis revealed positive links between organic carbon and hydraulic conductivity, mean weight diameter, CO_2 evolution, and dehydrogenase activity, while showing negative correlations with bulk density and calcium carbonate.These findings emphasize the role of organic intercropping systems in improving soil health and carbon sequestration.

In conclusion, organically grown cropping systems, particularly intercropping with legumes, significantly enhance soil properties, carbon sequestration, and nutrient availability. These systems improve soil structure, boost microbial activity, and maintain soil fertility, contributing to long-term agricultural sustainability. The findings strongly support the implementation of organic farming practices to enhance crop productivity and build resilient soil ecosystems, contributing to sustainable agricultural development.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declares that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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ANNEXURE

Correlation of organic carbon with soil properties and carbon pools

	BD	**HC**	**MWD**	**pH**	**EC**	**OC**	**$CaCO_3$**	**Avail. N**	**Avail P**	**Avail K**	**CO_2 evolution**	**DHA**	**C_{VL}**	**C_L**	**C_{LL}**	**C_{NL}**	**TC**
BD	1.000																
HC	-0.608 **	1.000															
MWD	-0.497 **	0.695 **	1.000														
pH	0.432 *	-0.676 **	-0.522 **	1.000													
EC	-0.317	0.486 *	0.538 **	-0.401	1.000												
OC	-0.703 **	0.871 **	0.747 **	-0.597 **	0.570 **	1.000											
$CaCO_3$	0.696 **	-0.729 **	-0.742 **	0.601 **	-0.630 **	-0.822 **	1.000										
Avail. N	-0.210	0.630 **	0.587 **	-0.223	0.485 *	0.612 **	-0.584 **	1.000									
Avail P	-0.656 **	0.494 **	0.348	-0.174	0.250	0.581 **	-0.569 **	0.552 **	1.000								
Avail K	-0.530 **	0.515 **	0.536 **	-0.218	0.414	0.663 **	-0.711 **	0.546 **	0.744 **	1.000							
CO_2 evolution	-0.535 **	0.836 **	0.591 **	-0.732 **	0.578 **	0.804 **	-0.623 **	0.406	0.349	0.504 **	1.000						
DHA	-0.661 **	0.802 **	0.747 **	-0.475 *	0.721 **	0.933 **	-0.818 **	0.616 **	0.534 **	0.708 **	0.772 **	1.000					
C_{VL}	-0.698 **	0.867 **	0.718 **	-0.617 **	0.613 **	0.985 **	-0.844 **	0.567 **	0.532 **	0.642 **	0.839 **	0.933 **	1.000				
C_L	-0.667 **	0.808 **	0.730 **	-0.568 **	0.637 **	0.936 **	-0.829 **	0.554 **	0.523 **	0.672 **	0.803 **	0.899 **	0.950 **	1.000			
C_{LL}	-0.669 **	0.872 **	0.759 **	-0.618 **	0.583 **	0.928 **	-0.837 **	0.684 **	0.591 **	0.660 **	0.806 **	0.864 **	0.937 **	0.947 **	1.000		
C_{NL}	0.664 **	-0.839 **	-0.712 **	0.599 **	-0.608 **	-0.970 **	0.833 **	-0.585 **	-0.546 **	-0.648 **	-0.817 **	-0.908 **	-0.98 **	-0.976 **	-0.958 **	1.000	
TC	-0.635 **	0.861 **	0.721 **	-0.564 **	0.498 **	0.985 **	-0.781 **	0.631 **	0.559 **	0.644 **	0.806 **	0.890 **	0.970 **	0.916 **	0.916 **	-0.958 **	1.000

* 5% significant& ** 1% significant