Original Research Article

EFFECT OF ORGANICALLY GROWN CROPPING SYSTEMS ON SOIL PROPERTIES AND CORRELATION OF ORGANIC CARBON WITH SOIL PROPERTIES AND CARBON POOLS

ABSTRACT:

Organic agriculture is gaining vital significance, particularly for its benefits in crop diversity, sustainability, and its role in enhancing soil organic carbon. 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 physical and chemical properties in vertisols. The experiment was laid out in a Randomized Block Design (RBD) with seven treatments consisting of cropping systems: T1: cotton (sole), T2: cotton + sunhemp (2:1), T3: cotton + blackgram (2:1), T4: soybean + pigeonpea (3:1), T5: blackgram - chickpea (rabi), T6: greengram + sorghum (2:1), and T7: sunhemp (sole) which replicated three times. Nutrients were supplied through FYM and vermicompost (50% N from each) with phosphorus compensated through PROM (Phosphate Rich Organic Manure).

The results showed that the Cotton + Sunhemp system recorded the lowest bulk density (1.42 Mg m^{-3}), maximum hydraulic conductivity (0.76 cm hr^{-1}), and mean weight diameter (0.73 mm). 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 Cotton + Sunhemp system also showed significant improvement in soil organic carbon (6.09 g kg^{-1}). The highest available nitrogen (209.27 kg ha^{-1}), available phosphorus (22.28 kg ha^{-1}), and available potassium (354.26 kg ha^{-1}) were observed in the Soybean + Pigeonpea system. These findings highlight the potential of intercropping systems under organic management in enhancing soil health and carbon pools such as very labile C (4.04 g kg^{-1}), labile C (1.29 g kg^{-1}), and less labile C (0.93 g kg^{-1}) were highest in surface soil (0-20 cm) under the Cotton + Sunhemp system, while non-labile C (5.13 g kg^{-1}) was highest in sole Cotton. The active pool contributed 44.96% and 45.54% of total organic carbon in surface (0-20 cm) and subsurface (20-40 cm) soils, respectively, whereas the passive pool contributed 55.04% and 54.46%, respectively. Overall, higher carbon pools were observed in surface soil compared to subsurface soil, with the passive pool dominating the active pool (CNL > CVL > CL > CLL).

Keywords: Soil properties, Carbon pools, *Organic carbon, Organicfarming, Sustainable agriculture*

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1. INTRODUCTION:

Organic agriculture is a holistic production management system that promotes and enhances agro ecosystem biodiversity, biological cycles and soil biological activities. Organic farming is one of the ways to promote self-sufficiency and food security. The primary goal of organic agriculture is to optimize the health and productivity of interdependent communities of soil life, plants, animals and people (Scialabba and Hattam, FAO, 2002).

Soil carbon is an important part of the terrestrial carbon pool and soils of the world are potentially viable sinks for atmospheric carbon (Lal, 1995). Soil organic carbon (SOC) stock is comprised of labile or actively cycling pools and stable, resistant/ recalcitrant pools with varying residence time (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 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 compoundsand 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. The direct effects related to the uptake of plant nutrients and absorption of humic substances by plants influence their metabolism. The indirect effects include the augmentation of beneficial microbial population and their activities such as organic matter decomposition, biological nitrogen fixation and improvement in the physical properties of soil.

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 and augment the available pool of nutrients and conserve more water, maintain soil quality. The use of compost improves physical, chemical and biological property of soil and physical properties by declining bulk density and increasing soil water holding capacity. Vermicompost has incredibly high porosity, aeration, drainage and water-holding capacity. They have an enormous surface area, providing strong absorbability and maintaining the flow of nutrients. Vermicompost contains enzymes like amylase, lipase, cellulase and chitinase to support the breakdown of organic matter and liberate nutrients.

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 properties and correlation of organic carbon with 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

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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 analysed after harvest of crops.

The representative soil samples were taken from 0-20 cm depth. The soil samples were air-dried in shade and pulverized using a mortar and pestle and then homogenized through a 2 mm sieve. For mean weight diameter analysis, 8 mm size aggregates were retained on the sieve and used. For analysis of organic carbon, the soil was passed through a 0.5 mm sieve. The sieved soil was preserved in plastic bags and labelled properly for subsequent analysis.

The experiment was laid out in Randomized Block Design (RBD) with seven treatments shown below in treatment details which replicated three times.
List 1- Selected treatments

	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
Estimated 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

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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

Estimated using 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 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, and a recovery factor of 1.298. The total SOC pool was divided into four sub-fractions: very labile (Pool I: CVL), labile (Pool II: CL), less labile (Pool III: CLL), and non-labile (Pool IV: CNL). 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

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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.

Table 2. Effect of organically grown intercropping systems on soil physicalproperties

	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	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

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3.1.1 Bulk Density

The effect of different cropping systems on bulk density was found significant as presented in Table 2. 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 result was reported byHugar and Soraganvi (2014), Manchala (2017),Khuspure*et al.* (2018) andGawande *et al.* (2024).

3.1.2 Hydraulic conductivity

The hydraulic conductivity of soil as influenced by organically grown cropping systems was found statistically significant as presented in Table 2. It ranged from 0.69 to 0.76 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 organic manure 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), Khuspure*et al.* (2018) and Gawande *et al.* (2024).

3.1.3 Mean Weight Diameter

The MWD of soil in various treatments varied from 0.67 to 0.73 mm under various organic cropping systems (Table 2). From the data it is noticed that MWD was found significantly higher in the treatment Cotton + Sunhemp followed by sole Sunhemp and Soybean + Pigeon pea intercropping system over 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). reported that the higher MWD with the increase in organic carbon content in the soil.

3.2 Effect of organically grown intercropping systems on soil chemical properties

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	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

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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 under various cropping systems where a reduction in soil pH can be observed due to the incorporation of the leguminous crop. The result is in conformity with the findings of Bahadur *et al.* (2012), Bama *et al.* (2017) and Gawande *et al.* (2024).

3.2.2 Electrical Conductivity

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 crops and leaching of soluble salts. In addition to this, the organics on decomposition release various organic acids which helps to solubilize the salts present in soil and a slight reduction in EC may be observed. The findings coincide with the results reported by Bahadur *et al.* (2012), Bama *et al.* (2017) and Gawande *et al.* (2024).

3.2.3 Organic carbon

The data in Table 3 reveals that organic carbon content in soil increased from an initial 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 in soil. A relatively higher proportion of carbon 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 of Gabhane*et al.* (2013), Rakhonde*et al.* (2021)and Gawande *et al.* (2024).

3.2.4 Calcium carbonate

The data 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), Mubark and Nortcliff (2010).

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 $CaCO_3$, variation in its amount in 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 involve 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 significantly 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 due to organic material can be attributed to greater multiplication of soil microbes, 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 nutrients. The findings conform with the results reported by Bama *et al.* (2017), Choudhury *et al.* (2018),Rakhonde*et al.* (2021) and Gawande *et al.* (2024).

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

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intercropping system (22.28 kg ha^{-1}) which was observed 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 have 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), Choudhury *et al.* (2018) Hadke*et al.* (2020) and Gawande *et al.* (2024).

3.2.7 Available Potassium

There was an increment in available potassium in soil due to the addition of plant biomass. 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 by Gabhane*et al. (*2013), Jayakumar and Surendran (2017), Choudhury *et al.* (2018),Rakhonde*et al.* (2021)and Gawande *et al.* (2024).

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3.3 Effect of organically grown intercropping systems on soil biological properties

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

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 emanated 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 varied 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 found 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 on the metabolism of soil microorganisms and due to the increase in microbial growth with the addition of carbon substrate. Similar results were confirmed by Venkatesh *et al.* (2012), Parihar *et al.* (2018),Rakshitha*et al.* (2023) and Ankit *et al.* (2024).

3.4 Effect of organically grown intercropping systems on carbon pools

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

3.4.1 Very Labile Carbon

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

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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 (VLC) 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 were confirmed by Babu*et al.* (2020).

3.4.2 Labile Carbon

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 significant 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 turns 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 (Chan *et al.*, 2001 and Babu*et al.,* 2020).

Adoption of Cotton + Sunhemp*intercropping* 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. This pool 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),(2018),Balpande*et al.* (2020) andBabu*et al.* (2020).

3.4.3 Less labile Carbon

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} (Table 5). 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 line with Babu*et al.* (2020).

3.4.4 Non - Labile Carbon

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 of 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 registered at 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) andBabu*et al.* (2020).

3.4.5 Total Organic Carbon

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 T2 > T7 > T4 > T3 > T6 > T5 >T1 respectively (Table 5). A build-up of the higher amount of TOC in surface

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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).

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

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	

The different soil carbon pools were analysed and per cent contribution of each pool was calculated against total organic carbon. The data pertaining to per cent contribution is reported 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 per cent contribution of the non-labile pool was noticed in the treatment of Cotton + Sunhemp (39.39%) whereas the highest per cent 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 per cent 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 per cent contribution of the very labile pool was noticed in the treatment of Cotton + Sunhemp intercropping system. The

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contribution made by very labile are more or less similar at both depths. The scrutiny of the data concerning the per cent 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 the treatment of Cotton + Sunhemp 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 includes 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) and in order of C_{NL}> C_{VL}> C_L >C_{LL}.

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3.5 Correlation of carbon pools 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 that the significance of organic carbon in concern to organically grown intercropping 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. Result is match with 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% singificant, ** 1% significant, NS: Non-Significant

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4. CONCLUSION

The study reveals the significant impact of organically grown intercropping systems, particularly the T2: Cotton + Sunhemp combination, on various soil carbon pools and other soil properties, contributing to improved soil quality, fertility, and overall soil health.

Soil Physical Properties: Bulk density was lowest in Cotton + Sunhemp (1.42 Mg m^3) and highest in Soybean + Pigeon pea (1.43 Mg m^3). Hydraulic conductivity was highest in Cotton + Sunhemp (0.76 cm/hr). Mean weight diameter was highest in Cotton + Sunhemp (0.73 mm).
Soil Chemical Properties: Soil pH and electrical conductivity remained mostly unchanged. Organic carbon increased from 5.29 g kg^{-1} to 6.09 g kg^{-1}, highest in Cotton + Sunhemp. Calcium carbonate reduced significantly, with Cotton + Sunhemp showing the highest reduction (3.48%). Available nitrogen increased, with Soybean + Pigeon pea having the highest value (209.27 kg ha^{-1}). Available phosphorus was highest in Soybean + Pigeon pea (22.28 kg ha^{-1}), followed by Cotton + Sunhemp (20.62 kg ha^{-1}).
Available potassium increased, with Soybean + Pigeon pea (354.26 kg ha^{-1}) showing the highest value.
Soil Biological Properties: CO2 evolution was highest in Cotton + Sunhemp (35.4 mg 100 g^{-1} soil). Dehydrogenase activity was highest in Cotton + Sunhemp (47.66 µg TPF g^{-1} 24 hr^{-1}).

Soil Carbon Pools: Cotton + Sunhemp had the highest very labile, labile, and less labile carbon pools. Active carbon pool contributed 45% in surface soil (0-20 cm) and 45.54% in subsurface soil (20-40 cm). Passive carbon pool contributed more in both soil layers, with the highest in surface soil.
Organic carbon is positively and significantly correlated with key soil properties such as CO2 evolution and dehydrogenase activity, indicating its role in enhancing biological activity. It has a negative correlation with bulk density and calcium carbonate, suggesting that higher organic carbon improves soil structure. Organic carbon also shows a positive correlation with very labile, labile, and less labile carbon pools, but a negative correlation with non-labile carbon, emphasizing its influence on active carbon fractions in organically grown intercropping systems.

Thus, based on the data generated during the course of investigation, it can be concluded that the different organically grown cropping systems played a vital role in enhancing soil properties and carbon pools. However, organically grown T4: Soybean + Pigeonpea have found to be beneficial in improving availability of nutrients. However, T2: Cotton + Sunhemp and an application of T7: sole Sunhemp recorded significant results in carbon pools and other properties of soil. Hence, T2: Cotton + Sunhemp and T4: Soybean + Pigeonpea were found to be suitable under organically grown intercropping systems to obtain higher productivity, improved soil properties and enhanced carbon pools under semi-arid agro ecosystems.

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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	VLC	LC	LLC	NLC	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					
VLC	-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				
LC	-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			
LLC	-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		
NLC	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% singificant, ** 1% significant, NS: Non-Significant

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