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Influence of Crops and Different Production Systems on Soil Carbon Fractions and Carbon Sequestration in Rainfed Areas of Semiarid Tropics in India

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Abstract: Organic agriculture's economic benefits and widespread adoption are well documented, but its impact on soil C dynamics in rainfed regions of semiarid tropics is less understood. The use of organic amendments in organic farming not only supply nutrients but also have the potential to contribute to soil carbon sequestration. Carbon storage and various soil organic pools are affected differently by various crops and production systems. A study was conducted with three crops (sunflower, pigeonpea, and greengram) under three production systems (control, organic and integrated) to assess the effect on soil C stocks, carbon sequestration potential, and crop yield. After seven years of experiment, pigeonpea (*Cajanus cajan* L.) cultivation improved soil bulk density, porosity and water holding capacity compared to greengram [*Vigna radiata* (L) Wilczek] and sunflower (*Helianthus annuus* L.). Furthermore, plots under pigeonpea cultivation being on par with greengram had 15.6% higher total C (113.52 Mg C ha^{-1}), 14% higher easily oxidizable organic C (17.5 Mg C ha^{-1}) and C sequestration rate of 1.22 Mg C ha^{-1} yr^{-1} compared to sunflower. Among the three production systems, plots under organic management had significantly lower bulk density and higher water holding capacity and porosity at all of the profile depths compared to integrated production system and control. Similarly, organic production system being on par with integrated production system improved the easily oxidizable, oxidizable and weakly oxidizable organic C fractions at different soil depths compared to control. The C sequestration rate ranged from 0.21 to 0.85 Mg C ha^{-1} yr^{-1} in organic production systems compared to negligible rate (0.01–0.04 Mg ha^{-1} yr^{-1}) in the plots under control. On average, integrated production system being on par with organic management recorded significantly higher pigeonpea equivalent seed yield (886 kg ha^{-1}) compared to control (792 kg ha^{-1}). These results suggest the potential of organic production system in improving soil properties, C sequestration, and crop yields in semiarid rainfed areas.

Keywords: organic production system; pigeonpea; greengram; sunflower; carbon fractions; carbon sequestration potential; rainfed areas

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1. Introduction

Improving soil organic carbon (SOC) is critical for agroecosystem production since SOC influences soil quality and function through changing soil physical, chemical, and biological properties [1–3]. SOC levels are determined by the carbon (C) input and output balance, which is majorly influenced by soil management methods [4]. Crop rotation,

tillage practices, fertilization strategies [5–7], integrated soil fertility management [8,9], practical rates of mineral fertilizers and organic additions [10–12], and conservation tillage approaches [13] can all help to maintain and improve SOC. Agronomic production is greatly influenced by soil quality in dry and semiarid locations, which are characterized by drought-prone soils with low and depleted SOC reserves. SOC is known to influence soil water content, porosity, bulk density, and infiltration in agriculture fields [14]. Soil moisture plays a key role in water-limited arid and semiarid agroecosystems [15]. The improved soil physical properties including soil moisture due to higher SOC will further help in realizing better crop yields particularly in dryland areas.

Soils in India have a poor reserve of carbon and plant nutrients. Rainfed regions of the country contribute almost to 44% of the total food requirement. However, over the years there has been significant reduction in the soil carbon. Changes in SOC caused by management techniques are often sluggish. These changes are minor in comparison to the large SOC pool size, and they vary both geographically and temporally [16,17]. The influence of agricultural management on soil quality can be determined using SOC fractions with varied stabilities and turnover rates [18]. Improving and sustaining agronomic production requires restoring soil quality and increasing SOC stores [19–21].

Adopting recommended management practices (RMPs), particularly those that provide a positive soil C budget, in different agro ecosystems, is a key strategy for SOC sequestration. While land and soil mismanagement has resulted in SOC depletion and subsequent emissions of CO_2 and other greenhouse gases (GHGs) into the atmosphere. However, increasing the SOC pool could significantly offset fossil fuel emissions [22], improve soil quality, and also generate ecosystem services. The capacity of the SOC sink, on the other hand, is determined by the antecedent level of SOC, climate, profile characteristics, and management. When degraded soils are restored, and marginal agricultural soils are converted to a restorative land use, the SOC sink capacity for atmospheric CO_2 can be considerably increased. Although the specific empirical relationship varies on soil moisture and temperature regimes, nutrient availability, texture, and climate, the SOC content in the surface layer normally increases with increasing bio solids inputs [23].

Adoption of appropriate management methods may sequester carbon in soils, improving soil quality significantly [24,25]. SOC levels were linearly increased when organic manure was applied alone or in conjunction with inorganic fertilizer [26–29]. Furthermore, combining organic and inorganic nutrient sources in soils improves the efficiency of production inputs while also increasing crop yields [30,31]. Most of current research on SOC sequestration has been conducted in temperate regions. In temperate zone of northwest Himalayas, continuous application of synthetic fertilizers reduced the carbon management index (CMI) and sustainability [32]. Similarly, a study by Ding et al. [33] reported that applying organic manure was the most effective way to improve soil productivity and C sequestration in the agroecosystem of northeastern China.

In India, we lack research data on this topic especially in the tropical and sub-tropical rainfed regions [34–38]. Concerns about the environmental and economic consequences of conventional crop cultivation have increased. This has ignited interest in alternative approaches, such as organic farming. However, there are limited long-term studies on the consequences of different crops (sunflower, pigeonpea and greengram) and production systems (organic and integrated) on soil C fractions and C sequestration, particularly in India's rainfed semiarid areas. The selection of the crops was based on the suitability of these crops in the study region. These crops are well suited for the rainfed regions of semi-arid tropics and are widely grown in this region. With this in view, the current research was carried out to determine the impact of various crops and production strategies on soil carbon fractions, carbon sequestration and crop yield We anticipated that since root architecture and production systems differ, C storage and the buildup of diverse SOC pools might be affected. We focused on the variations in SOC and its fractions in this study. The data would aid our understanding of the processes involved in soil C sequestration, as

well as the patterns of accumulation of various C fractions in relation to diverse crops and production systems in the semi-arid tropics.

2. Materials and Methods

2.1. Study Area

The field experiment was conducted during 2012–2019 at Gungal Research Farm of ICAR-CRIDA (17°40′40.4″ N latitude and 78°39′55.7″ E longitude and at a mean sea level of 626 m), Hyderabad, Telangana, India. The average length of growing period is 120–150 days. The farm represents a semi-arid tropical region with a mean annual temperature of 25.7 °C and rainfall of 746 mm. The climate of the region is semi-arid (dry) with distinguished summer (March to May), rainy season (*kharif*) (June to September) and winter (*rabi*) (October to February). The weekly rainfall during the crop season (July–December) during the study period (2012–2018) and the monthly maximum and minimum temperature prevailed during the period are given in Figures 1 and 2. Soil of the experimental site was sandy clay loam (sand, 62.5%; silt, 15.65% and clay, 22%); slightly acidic in reaction (pH 6.51), EC was in normal range (0.05–0.07 dS m^{-1}), low in organic carbon (0.43%), available N (229.1 kg ha^{-1}), high in available P (24.7 kg ha^{-1}) and medium in available K (218.1 kg ha^{-1}).

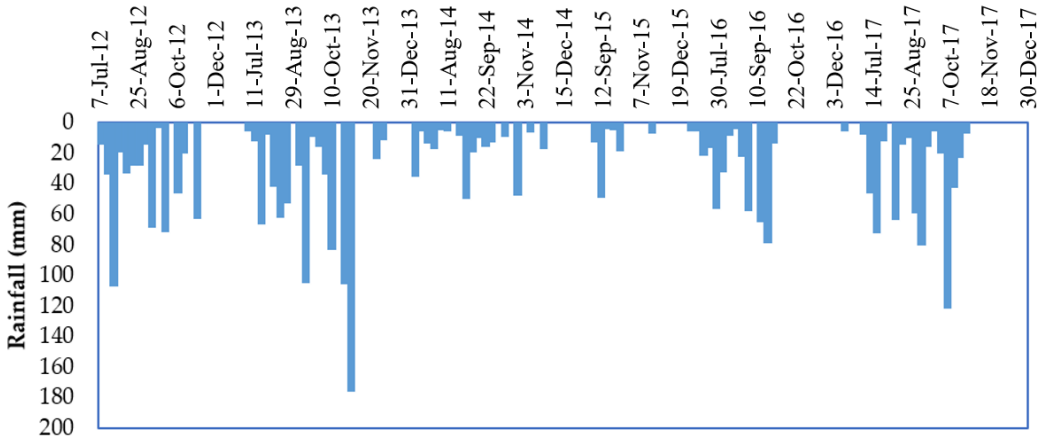

Figure 1. Weekly total rainfall (mm) during the cropping period (July–December) during 2012–2018.

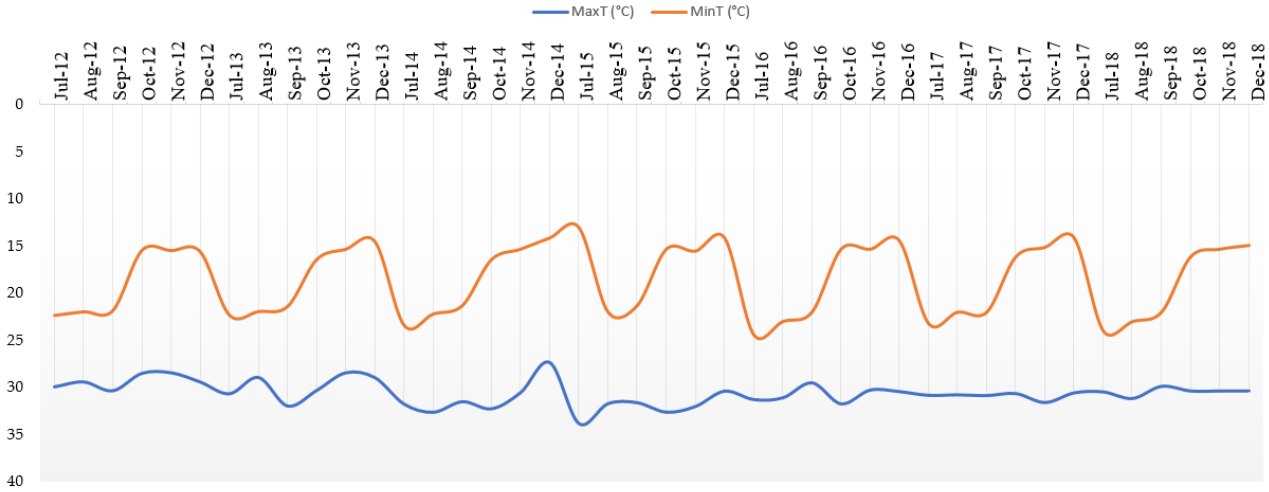

Figure 2. Mean monthly maximum and minimum temperature during the crop period (July–December) during 2012–2018.

2.2. Experimental Design

The experiment was arranged in a strip plot design with three replications. The treatments selected for the present study were three production systems viz. organic, inte-

grated and control) and three field crops viz. sunflower (*Helianthus annuus* L.), pigeonpea (*Cajanus cajan* L.) and greengram [*Vigna radiata* (L) Wilczek]. Each plot was 12 m × 4 m. The varieties of each crop, seed rate and planting geometry are given in Table 1. There was a buffer zone of 1 m between each plot. The farmyard manure (FYM) was collected from the same source every year and was analyzed for N, P, K and micronutrient contents before application. The FYM had an average composition of 0.5% N, 0.27% P, 0.4% K, 27.9 ppm Cu, 228.7 ppm Mn, 452 ppm Fe and 143.1 ppm Zn.

Table 1. Variety, seed rate, and planting geometry used for each crop.

Crop	Variety	Seed Rate (kg ha^{-1})	Planting Geometry (cm)
Sunflower	DRSH-1	6	60 × 30
Greengram	WGG-37	15	30 × 15
Pigeonpea	PRG-158	15	90 × 20

The experimental plots were tilled to a depth of 15–20 cm with tractor-drawn cultivator twice before sowing of the crops in all years. The FYM was treated with *Trichoderma viridae* at 2.5 kg ha^{-1}, as a prophylactic measure against soil borne diseases, then incubated for about 20 days [39] and was thoroughly incorporated into 15 cm surface soil two-weeks before sowing of crops. In the plots under organic management, FYM was applied on the recommended N equivalent basis to all of the three crops and the additional P requirement was supplemented through rock phosphate (7.2% P). In the plots under integrated management, 25% of equivalent recommended N was applied through FYM. The remaining 75% N and 100% P and K was applied through mineral fertilizers. The plots under control received recommended dose of mineral fertilizers (Table 2). In the plots under pigeonpea and greengram, all of the mineral fertilizers and rock phosphate were applied at the time of sowing. In sunflower, 50% N and 100% P and K were applied at the time of sowing. Remaining N was top-dressed in two equal splits, 30 and 60 days after sowing.

The crops were sown during first fortnight of July in all of the years, after receipt of monsoon rainfall. In the plots under organic management, no chemical herbicides, insecticides or fungicides were used, in keeping with organic standards. Weeds were controlled by manual weeding once, followed by two hoeings using a manually operated wheel-hoe. Azadirachtin (*Azadirachta indica* based formulation) was sprayed at 20–25 days interval during crop growth as a prophylactic measure against insect-pests. In the plots under control, crop-specific recommended herbicides and pesticides were sprayed for control of weeds, insect-pests and diseases. In the plots under integrated management, recommended integrated pest management (IPM) modules were implemented. Greengram and sunflower were harvested by hand during first fortnight of October whereas pigeonpea was harvested during second fortnight of December in all of the years. Seed yield were adjusted to 15% moisture contents. Seed yield of sunflower and greengram were converted to pigeonpea equivalent yield (PEY) based on market price of the produce.

2.3. Soil Sampling and Analysis

Initial soil samples as well as after the harvest of crops in 2018–2019 were taken from different layers (0–20 cm, 20–40 cm, and 40–60 cm soil depth) of each plot using a 5 cm diameter and 20 cm depth core sampler. Composite soil samples from each plot (more than five random subsamples) were well mixed, packed in polyethylene bags, and brought to the laboratory. Visible roots and plant fragments were removed in the laboratory. A 2-mm sieve was used to filter the composite samples. For the examination of various C fractions, one part of the treated sample was air-dried. For total C analysis, the leftover soil was oven dried at 50 °C and ground to pass a 0.25-mm filter.

Table 2. Application rates of organic manure and mineral fertilizers in different treatments.

Treatment	Sunflower					Pigeonpea					Greengram				
	Manure (Mg ha^{-1})	Mineral Fertilizers (kg ha^{-1})			Rock Phosphate (kg ha^{-1})	Manure (Mg ha^{-1})	Mineral Fertilizers (kg ha^{-1})			Rock Phosphate (kg ha^{-1})	Manure (Mg ha^{-1})	Mineral Fertilizers (kg ha^{-1})			Rock Phosphate (kg ha^{-1})
		N	P	K			N	P	K			N	P	K	
Organic	13.3	0	0	0	0	4.4	0	0	0	167	4.4	0	0	0	167
Integrated	10.0	45	60	30	0	3.3	15	50	0	0	3.3	15	50	0	0
Control	0	60	60	30	0	0	20	50	0	0	0	20	50	0	0

The rapid titration method using 1 N $K_2Cr_2O_7$ solution as described by Walkley and Black [40] was followed for the determination of SOC. Total carbon, total inorganic carbon (SIC) and total organic carbon was estimated using method of Nelson and Sommers [41].

2.3.1. Soil Carbon Stock

Soil carbon stock was estimated by multiplying SOC content with soil bulk density and soil layer depth as described by Batjes [42].

2.3.2. Water Holding Capacity and Total Porosity

Water holding capacity and total porosity of soil were determined by using the Hilgard or Keen Rackzowski box method [43].

2.3.3. Soil Carbon Fractions

Using a sulphuric acid (H_2SO_4)-aqueous dichromate solution at a ratio of 0.5:1, 1:1, or 2:1, which corresponds to 6, 9, or 12 mol L^{-1} H_2SO_4, different fractions of soil organic C were determined under a gradient of oxidizing conditions. According to Chan et al. [44], organic carbon fractions were calculated. Soil organic C oxidized by 6.0 mol L^{-1} H_2SO_4 was termed as easily oxidizable C (fraction 1), the difference in soil organic C between 9 and 6.0 mol L^{-1} H_2SO_4 was oxidizable C (fraction 2), the difference between SOC oxidizable by 9.0 mol L^{-1} H_2SO_4 (18 N) and that of 12.0 mol L^{-1} H_2SO_4 (24 N) was weakly oxidizable C (fraction 3), and the difference between total SOC and SOC oxidizable by 12.0 mol L^{-1} was termed as non-oxidizable C (fraction 4).

2.3.4. Soil Bulk Density

The bulk density of the soil was calculated by collecting undisturbed soil samples of known weight in metallic cores of known volume (internal diameter of 7.0 cm and length of 4.5 cm). Soil samples were oven dried for 24 h at 105 °C to determine the soil dry weight [45]. The following equation was used to compute the bulk density of undisturbed soil samples:

$$D_b = \frac{W_s}{V_t}$$

where 'D_b' is bulk density of soil (Mg m^{-3}), 'W_s' is weight of soil (Mg) and 'V_t' is the volume of soil sample (m^3).

SOC pools were calculated as: SOC pool (Mg ha^{-1}) = SOC concentration (%) × soil depth (m)×bulk density (Mg m^{-3}) × 104 m^2 ha^{-1} × 10^{-2}. The carbon sequestration was determined by subtracting the value of C pools at start of the experiment (2012) from the value of C pools in the year 2018–2019.

2.4. Statistical Analysis

Results of soil analysis were expressed as means of four replicates (n) ± standard deviation. Data were statistically analyzed using International Rice Research Institute (IRRI) Star with ANOVA. To elucidate significant differences between means ($p < 0.05$), post hoc comparisons were made using Tukey's HSD. The crop yield data were expressed as means of three replicates (n) ± standard deviation. The correlation matrix was created using R studio version 1.4.1717 utilizing the 'ggcorrplot' package.

3. Results

3.1. Soil Bulk Density, Porosity and Water Holding Capacity

The soil bulk density showed an increasing trend with increase in soil depth (0–60 cm) in respective treatments. Among the crops, considerably lower bulk density was recorded with pigeonpea at all of the soil profile depths except 40–60 cm. Among the three production systems, plots under organic management had significantly lower bulk density of soil across all depths (Table 3). Pigeonpea crop resulted in considerably higher soil porosity at all of the soil profile depths, 0–20 cm (54.21%), 20–40 m (49.54%) and 40–60 m (47.59%). Amongst the three

production systems, plots under organic management had significantly higher porosity at all of the profile depths, i.e., 0–20 cm (53.56%), 20–40 m (46.60%) and 40–60 m (49.39%) compared to control. Similarly, water holding capacity of soils was significantly higher in the plots under pigeonpea across all soil depths except for greengram at 20–40 cm depth. Among the production systems, soils under organic management being on par with integrated production system had significantly higher water holding capacity across all soil depths (Table 3).

Table 3. Effect of crops and production systems on soil physical parameters at different soil profile depths.

Treatment	Bulk Density (Mg m^{-3})			Porosity (%)			Water Holding Capacity (%)		
	0–20 cm	20–40 cm	40–60 cm	0–20 cm	20–40 cm	40–60 cm	0–20 cm	20–40 cm	40–60 cm
					Crop				
Sunflower	1.24 ± 0.1 a	1.26 ± 0.1 a	1.26 ± 0.2 a	51.21 ± 0.2 b	44.54 ± 0.4 b	44.59 ± 0.1 b	37.03 ± 0.2 b	42.76 ± 0.2 b	42.99 ± 0.3 b
Pigeonpea	1.19 ± 0.2 b	1.21 ± 0.3 b	1.20 ± 0.2 b	54.42 ± 0.1 a	49.52 ± 0.2 a	47.39 ± 0.1 b	38.90 ± 0.2 a	43.90 ± 0.1 a	45.99 ± 0.4 a
Greengram	1.21 ± 0.1 ab	1.25 ± 0.1 a	1.22 ± 0.1 ab	51.02 ± 0.3 b	45.93 ± 0.2 b	47.95 ± 0.3 b	37.41 ± 0.2 b	43.04 ± 0.2 ab	42.74 ± 0.2 b
					Production system				
Control	1.25 ± 0.0 a	1.27 ± 0.1 a	1.24 ± 0.1 a	50.97 ± 0.1 b	45.40 ± 0.2 b	44.45 ± 0.2 b	37.24 ± 0.1 b	41.52 ± 0.1 b	41.98 ± 0.1 b
Organic	1.18 ± 0.2 b	1.22 ± 0.2 b	1.20 ± 0.2 b	53.56 ± 0.2 a	46.60 ± 0.2 a	49.39 ± 0.1 a	38.65 ± 0.2 a	44.50 ± 0.2 a	45.36 ± 0.2 a
Integrated	1.21 ± 0.2 b	1.24 ± 0.1 b	1.23 ± 0.1 a	52.11 ± 0.1 a	45.99 ± 0.3 ab	48.08 ± 0.1 a	37.45 ± 0.1 b	43.68 ± 0.1 ab	44.36 ± 0.1 a

Initial bulk density values were 1.21 Mg m^{-3} (0–20 cm), 1.25 Mg m^{-3} (20–40 cm) and 1.23 Mg m^{-3} (40–60 cm); means in the same columns with different letters are significantly ($p < 0.05$) different.

3.2. Total Carbon (TC), total Inorganic Carbon (TIC) and Total Organic Carbon (TOC)

The total carbon stocks at different soil profile depths differed significantly ($p < 0.05$) among various crops and production systems (Table 4). In general, the TOC content was greater than TIC content. Among different crops, plots under legumes (pigeonpea and greengram) had similar but significantly higher TOC content than that under sunflower across all of the soil depths. Plots under pigeonpea had greater TIC content in surface layer (0–20 cm) whereas at 20–40 cm, greengram had higher TIC content. Similarly, the TC content was higher in 0–20 cm soil depth with pigeonpea. However, the TC content in 20–40 cm and 40–60 cm was similar in the plots under pigeonpea and greengram but significantly greater than that under sunflower.

Table 4. Effect of crops and production systems on soil inorganic carbon, organic carbon, and total carbon.

Treatment	Total Carbon (Mg C ha^{-1})			Total Inorganic Carbon (Mg C ha^{-1})			Total Organic Carbon (Mg C ha^{-1})		
	0–20 cm	20–40 cm	40–60 cm	0–20 cm	20–40 cm	40–60 cm	0–20 cm	20–40 cm	40–60 cm
					Crop				
Sunflower	36.09 ± 0.1 c	32.58 ± 0.1 b	29.56 ± 0.2 b	9.81 ± 0.1 b	9.21 ± 0.2 b	8.63 ± 0.1 b	26.28 ± 0.2 b	23.37 ± 0.1 b	20.93 ± 0.1 b
Pigeonpea	38.88 ± 0.1 a	38.18 ± 0.1 a	36.46 ± 0.1 a	12.13 ± 0.1 a	10.52 ± 0.2 b	11.50 ± 0.1 a	26.75 ± 0.2 b	27.66 ± 0.1 a	24.96 ± 0.2 a
Greengram	37.11 ± 0.2 b	39.20 ± 0.1 a	34.83 ± 0.1 a	10.05 ± 0.1 b	13.77 ± 0.1 a	10.72 ± 0.3 a	27.06 ± 0.2 a	25.43 ± 0.1 ab	24.11 ± 0.1 a
					Production system				
Control	36.53 ± 0.1 b	35.67 ± 0.1 a	31.13 ± 0.1 a	12.15 ± 0.1 a	12.33 ± 0.2 a	10.52 ± 0.1 b	24.38 ± 0.1 b	23.34 ± 0.1 b	20.61 ± 0.2 a
Organic	40.05 ± 0.2 a	36.27 ± 0.2 a	33.82 ± 0.2 a	11.43 ± 0.1 a	10.46 ± 0.2 b	11.75 ± 0.2 a	28.62 ± 0.1 a	25.81 ± 0.2 a	22.07 ± 0.1 a
Integrated	38.67 ± 0.1 a	35.77 ± 0.1 a	32.87 ± 0.1 a	12.59 ± 0.2 a	11.45 ± 0.1 ab	11.54 ± 0.1 a	26.08 ± 0.2 a	24.32 ± 0.1 b	21.33 ± 0.1 a

Means in the same columns with different letters are significantly ($p < 0.05$) different.

Among the three production systems, organically managed plots had significantly higher TOC content in 0–20 cm whereas both organic and integrated production systems had similar TOC content in 20–40 cm depth (Table 4). However, the TIC content did not vary much across three production systems. The plots under organic production systems being on par with integrated production system had greater TC content in 0–20 cm and 20–40 cm depths compared to that under control. At 40–60 cm depth, the production systems had no significant effect on TC content.

3.3. Soil Organic C Pools

To assess the effect of crops and production systems on different C pools, the organic C was further sorted into easily oxidizable, oxidizable, weakly oxidizable and non-oxidizable fractions. Different crops and production systems had significant effect on soil organic C fractions of different oxidizability in different soil layers (Table 5). Irrespective of the

treatment, the easily oxidizable organic C fraction comprised a larger pool of soil organic C than the other three fractions. Among the crops, plots under pigeonpea had higher oxidizable organic C fraction in 0–20 and 20–40 cm depths whereas no significant differences were observed at 40–60 cm depth. However, the oxidizable organic C fraction was higher at 0–20 cm in the plots under greengram compared to other crops. The weakly oxidizable organic C fraction was higher in the plots under pigeonpea compared with other crops. On contrary, non-oxidizable organic C fraction was greater at 0–20 cm and 20–40 cm depths in the plots under sunflower whereas no significant differences were observed at 40–60 cm depth (Table 5).

Among the production systems, plots under organic management had significantly higher amount of easily oxidizable and oxidizable organic C fractions in all depths compared to control. However, easily oxidizable organic C fraction at 40–60 cm depth did not differ significantly among different production systems. Similarly, organic production system being on par integrated production system had greater weakly oxidizable organic C fraction than control (Table 5). However, different production systems had similar amount of weakly oxidizable organic C fractions at 40–60 cm depth. Similarly, the non-oxidizable organic C fraction was similar but significantly higher under organic and integrated production systems than that under control.

3.4. Carbon Sequestration

The data on depth-wise soil organic carbon and carbon sequestration over seven years of the experimental soil as influenced by various crops and production systems are presented in Table 6. Among the crops, plots under greengram had significantly higher organic C (0.62%) in surface layer (0–20 cm) compared with that under sunflower and pigeonpea (Table 6). However, pigeonpea cultivation resulted in significantly higher organic C in 20–40 and 40–60 cm depths compared to greengram and sunflower. Cultivation of both the legumes (greengram and pigeonpea) resulted in similar but significantly higher carbon sequestration rate than that of sunflower. Among the production systems, plots under organic production system had significantly higher organic C and carbon sequestration rate across all depths compared to other production systems (Table 6). The carbon sequestration rate was negligible (0.01–0.04 Mg ha^{-1} yr^{-1}) in the plots under control which had no organic input additions.

3.5. Crops Yield

There were significant differences among crops and production systems with respect to pigeonpea equivalent yield (PEY) in all of the years (Figure 3). In general, the PEY was higher during first two years (2012–2013 and 2013–2014) across all of the treatments due to better rainfall in terms of both amount and distribution (Figure 3), leading to less moisture stress in the crops. However, the PEY was less than 1000 kg ha^{-1} in all of the treatments during 2014–2019 due to intermittent dry spells and poor rainfall (Figures 1 and 3). Among the crops, the PEY was similar for all of the crops in 2012–2013. However, pigeonpea recorded significantly higher PEY in 2013–2014 whereas, sunflower produced higher PEY in other years except that greengram performed better during 2015 compared to other crops. Averaged across the years, sunflower gave significantly higher PEY than other crops.

Among the production systems, in the first year (2012–2013), integrated production system produced significantly higher PEY than did the organic and control plots. In 2013–2014, both integrated organic production systems yielded similar results and produced significantly higher PEY than control. However, during the next three years (2014–2017), different production systems had no significant effect on PEY possibly due to very poor yields across the treatments. During 2017–2018 and 2018–2019, integrated production system being on par with organic production system produced higher PEY compared to control (Figure 4). On average, integrated production system being on par with organic management recorded significantly higher PEY (886 kg ha^{-1}) compared to the control (792 kg ha^{-1}).

Table 5. Effect of crops and production systems on soil organic C fractions at different soil depths.

Treatment	Easily Oxidizable C (Mg C ha^{-1})			Oxidizable C (Mg C ha^{-1})			Weakly Oxidizable C (Mg C ha^{-1})			Non-Oxidizable C (Mg ha^{-1})		
	0–20 cm	20–40 cm	40–60 cm	0–20 cm	20–40 cm	40–60 cm	0–20 cm	20–40 cm	40–60 cm	0–20 cm	20–40 cm	40–60 cm
Crop												
Sunflower	5.87 ± 0.1 a	5.01 ± 0.2 b	4.67 ± 0.1 a	1.68 ± 0.3 b	1.48 ± 0.1 b	1.44 ± 0.1 b	2.75 ± 0.3 a	2.22 ± 0.1 b	2.03 ± 0.1 a	1.87 ± 0.1 a	2.92 ± 0.1 a	3.14 ± 0.1 a
Pigeonpea	5.67 ± 0.2 a	6.28 ± 0.1 a	5.35 ± 0.1 a	1.74 ± 0.1 b	2.17 ± 0.2 a	1.70 ± 0.1 a	3.39 ± 0.2 a	2.92 ± 0.1 a	2.31 ± 0.2 a	1.79 ± 0.2 a	2.29 ± 0.2 b	3.13 ± 0.2 a
Greengram	6.34 ± 0.2 a	5.58 ± 0.2 ab	4.72 ± 0.2 a	1.97 ± 0.2 a	2.09 ± 0.1 a	1.56 ± 0.1 b	1.95 ± 0.2 b	2.43 ± 0.1 ab	2.10 ± 0.1 a	1.19 ± 0.2 b	2.69 ± 0.1 ab	3.64 ± 0.1 a
Production system												
Control	5.89 ± 0.1 b	4.46 ± 0.1 b	4.65 ± 0.2 a	1.69 ± 0.1 b	1.65 ± 0.1 b	1.10 ± 0.1 b	2.66 ± 0.2 b	1.68 ± 0.2 b	1.76 ± 0.1 b	1.80 ± 0.1 a	2.49 ± 0.2 b	2.74 ± 0.1 ab
Organic	6.95 ± 0.1 a	5.94 ± 0.1 a	5.14 ± 0.2 a	1.97 ± 0.1 a	1.99 ± 0.2 a	1.74 ± 0.1 a	3.43 ± 0.2 a	3.26 ± 0.1 a	2.17 ± 0.1 a	1.59 ± 0.2 a	3.44 ± 0.1 a	2.97 ± 0.2 a
Integrated	6.00 ± 0.1 ab	5.58 ± 0.1 a	4.94 ± 0.1 a	1.83 ± 0.1 ab	1.89 ± 0.1 ab	1.66 ± 0.2 a	3.00 ± 0.2 ab	2.63 ± 0.2 a	2.51 ± 0.1 a	1.45 ± 0.1 a	2.98 ± 0.3 ab	2.20 ± 0.1 b

Means in the same columns with different letters are significantly ($p < 0.05$) different.

Table 6. Effect of crops and production systems on soil organic carbon and carbon sequestration rate at different soil depths.

Treatment	Soil Organic Carbon (%)			Soil Organic Carbon (Mg C ha^{-1})			C Sequestration Rate (Mg ha^{-1} yr^{-1})		
	0–20 cm	20–40 cm	40–60 cm	0–20 cm	20–40 cm	40–60 cm	0–20 cm	20–40 cm	40–60 cm
Crop									
Sunflower	0.51 ± 0.1 c	0.47 ± 0.2 b	0.41 ± 0.1 b	12.55 ± 0.2 b	11.90 ± 0.2 b	10.41 ± 0.1 a	0.30 ± 0.1 b	0.19 ± 0.2 b	0.07 ± 0.2 b
Pigeonpea	0.56 ± 0.2 b	0.59 ± 0.1 a	0.51 ± 0.2 a	13.38 ± 0.2 b	14.30 ± 0.1 a	11.93 ± 10.2 a	0.57 ± 0.2 a	0.40 ± 0.1 a	0.25 ± 0.1 a
Greengram	0.62 ± 0.1 a	0.50 ± 0.1 b	0.44 ± 0.1 b	14.63 ± 0.1 a	12.55 ± 0.2 b	10.74 ± 0.1 a	0.48 ± 0.1 a	0.23 ± 0.1 b	0.20 ± 0.2 a
Production system									
Control	0.54 ± 0.2 b	0.49 ± 0.1 b	0.42 ± 0.1 b	12.96 ± 0.2 b	12.34 ± 0.1 b	10.33 ± 0.2 b	0.02 ± 0.1 c	0.01 ± 0.2 c	0.04 ± 0.2 c
Organic	0.60 ± 0.2 a	0.57 ± 0.1 a	0.50 ± 10.2 a	13.98 ± 0.2 a	13.79 ± 0.2 a	11.80 ± 0.2 a	0.85 ± 0.1 a	0.55 ± 0.2 a	0.21 ± 0.2 a
Integrated	0.55 ± 0.2 b	0.51 ± 0.2 b	0.44 ± 0.1 b	13.56 ± 0.2 a	12.65 ± 0.2 b	10.95 ± 0.2 b	0.49 ± 0.2 b	0.25 ± 0.1 b	0.12 ± 0.2 b

Means in the same columns with different letters are significantly ($p < 0.05$) different.

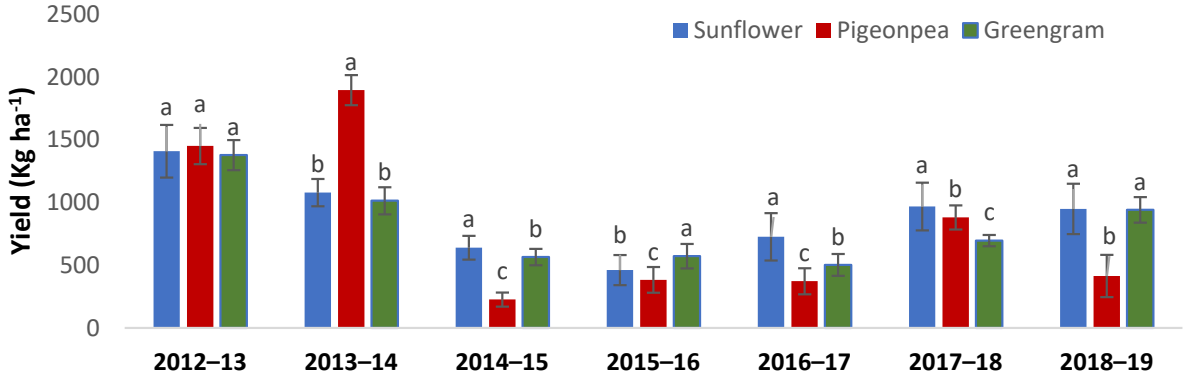

Figure 3. Pigeonpea equivalent yield of crops during 2012–2019 (averaged across three production systems). Bars with different letters within each year are significantly ($p < 0.05$) different.

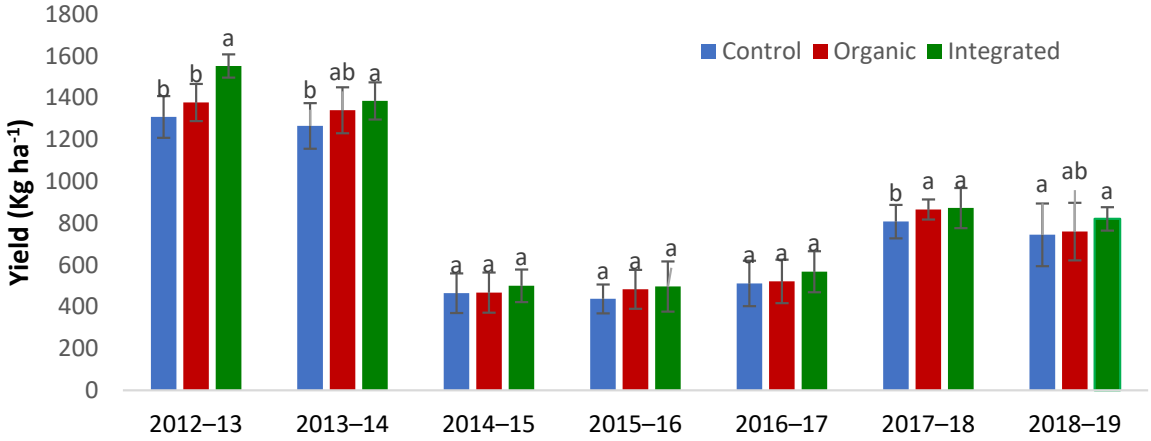

Figure 4. Effect of different production systems on pigeonpea equivalent yield of crops during 2012–2019 (averaged across three crops). Bars with different letters within each year are significantly ($p < 0.05$) different.

4. Discussion

A better understanding of various production systems to achieve higher carbon sequestration in agricultural fields, improve soil properties and for sustainable crop production. Organic farming practices have been linked to a number of beneficial soil characteristics, including a reduction in bulk density [46–48]. In this study, the soil bulk density was significantly lower in the plots under organic management compared with other production systems. Several researchers [49–51] reported the lowering of soil bulk density with the application of different organic amendments in soils due to greater SOC concentration and root biomass [52], resulting in improved soil aeration and aggregation [53]. Mosavi et al. [54] and Ge et al. [55] found that continuous application of organic amendments reduced soil BD considerably. Organic amendments were applied regularly for seven years in our experiment. Despite the small decrease in soil bulk density, it was a favourable indication of organic materials' influence on soil bulk density. Increased pore space, soil porosity, and enhanced soil tilth are all indicators of low bulk density.

Improved tilth also benefits root penetration, water infiltration, and soil aeration. Organic amendments improve soil bulk density by aggregating soil mineral particles. Furthermore, the organic component of soils is much lighter than the mineral fraction. The total weight and bulk density of the soil decrease as the organic C fraction increases [56]. Higher organic C (Table 6) resulted in increased overall porosity and improved soil structure, which helped to lower soil BD [57,58]. This further lead to improved porosity and water

holding capacity of soils, which help the rainfed crops to cope with recurring dry spells during crop season.

The correlation coefficients for different production systems are given in Figure 5. The correlation matrix heatmap shows the Pearson's correlation coefficient values for major studied parameters, with positive values in orange and negative values in blue. The correlation matrix (Figure 5) showed some significant relationships among different parameters. The crop yields were positively correlated with water holding capacity of soils, porosity and C fractions. This further strengthens the fact that soil properties play a major role in improving crop yields particularly in semiarid rainfed areas. Similarly, there was a significant positive correlation between soil porosity and water holding capacity with total soil C and organic C fractions.

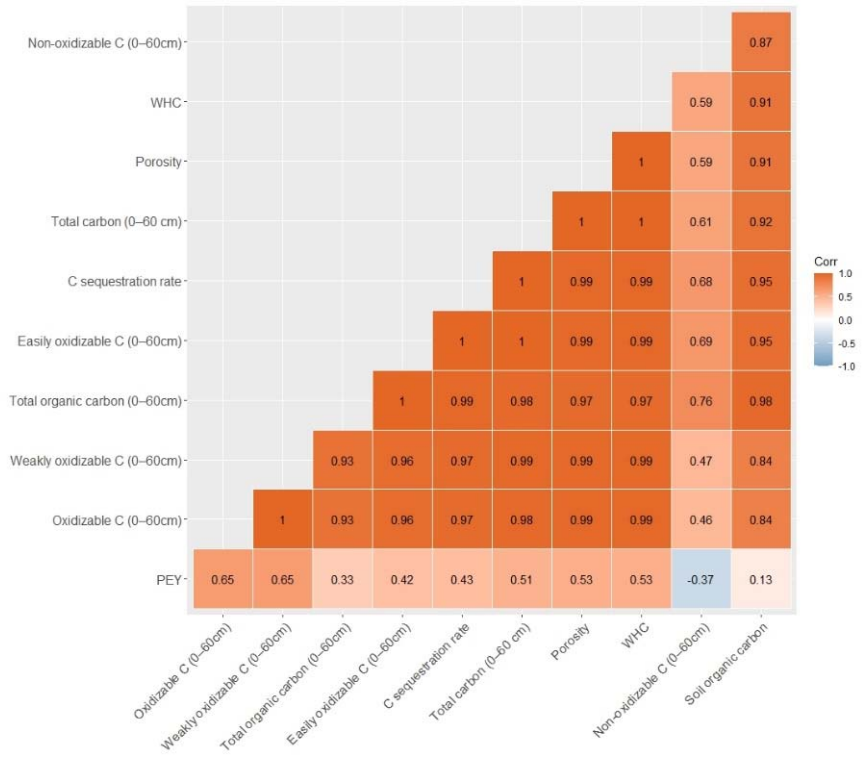

Figure 5. Correlation matrix (heatmap) for different soil parameters and crop yields.

The increase in soil C content is a significant environmental advantage of changing agricultural production techniques [59]. Climate, soil type, management, and the potential of a soil to retain organic matter all influence soil C content [60,61]. Higher agricultural SOC is generated from crop residues left in the field after harvest, as well as higher C inputs from organic manure and root biomass [62]. We examined the long-term effects of application of mineral fertilizers, organic amendments, and combination of mineral fertilizer and organic amendments on soil C. Soil type, climate, and production systems influence the soil organic, inorganic, and total C stocks [38]. In general, concentrations of soil organic C stocks were more than that of soil inorganic C. Organic C stocks were highest in organic plots be due to higher organic matter added to the soil resulting in relatively lower oxidation and slower crop residue decomposition [63].

Across different soil depths, the SOC in different treatments followed comparable trends (Table 6). Explanation for this finding could be the opposing impact of continuous tillage, in which increased manure loads are compensated by the benefits of annual tillage, accelerating SOC mineralization [64]. Among the crops studied, higher C sequestration values were observed with pulse crops. Since this research work needed the crops to remain same over the years to study the impact of crops on various soil properties, soil carbon fractions and carbon sequestration, we have not rotated the crops. Deeper roots might

have contributed to higher C sequestration. Root turnover also constitutes an important addition of humus into the soil, and consequently it is important for carbon sequestration. According to a study conducted by Brar et al. [65], long-term use of organic manure improves SOC. The Organic C, C stock, and C sequestration rates in soils were significantly influenced by different treatments (Table 6). The SOC increased significantly in the plots under organic management.

SOC fractions with varying stabilities and turnover rates can be used to determine the impact of agricultural management on organic matter quality [18]. The use of manure had a positive impact on SOC pools (Table 5). Earlier research has also found that labile SOC pools respond better to management changes than TOC [7,66,67]. The observed increase in the labile C pool size in organic production systems could be explained by differences in external organic matter inputs (Table 5). Our findings are consistent with those of Cambardella and Elliott [68] and Janzen et al. [69], who reported higher labile C levels in high substrate input systems. Since labile C is an important energy source for the soil food web and thus influences nutrient cycling for maintaining soil health and productivity, an increase in labile C fractions with the application of organic amendments indicates that organic production systems help maintain or improve different soil functions [44].

Crop yields and biomass output could be increased by combining organic and synthetic fertilizer application [2,7,70]. We found a similar result in our research (Figure 4). Organic and integrated production systems yielded much higher crop yields than the control plot. This can be explained by the fact that adding organic matter to the soil provides a physically and biologically beneficial environment [71]. Soil organic matter is one of the most important factors in determining crop yields (according to many experts) [72]. Discrepancies in crop yields over time, on the other hand, may be caused by climatic factors, particularly rainfall, under rainfed situations. As a result, there was no noticeable trend in PEY in our research.

5. Conclusions

In semiarid rainfed areas, research-based recommendations for optimal production systems that increase soil qualities, particularly soil carbon sequestration, and bring outstanding yields must be developed. In general, both legumes (pigeonpea and greengram) outperformed sunflower in terms of soil parameters such as bulk density, porosity, water holding capacity, soil organic C fractions, and carbon sequestration potential. Application of organic amendments in organic production system improved soil bulk density, porosity, water holding capacity, and labile pools of soil organic C including easily oxidizable, oxidizable, and weakly oxidizable C compared to other production systems. Long-term application of organic amendments increased both the labile and non-oxidizable pools of soil organic C, as well as the potential for carbon sequestration. Furthermore, crop yields in both organic and integrated production methods were comparable. We conclude our study by stating that organic production systems in semiarid rainfed locations have the potential to improve soil physical characteristics, labile C fractions, C sequestration, and crop yields in the long-run.

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