



Carbon sequestration and mitigation potential of soil in different land use systems in Indo-Gangetic Alluvial plains of Haryana

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Abstract

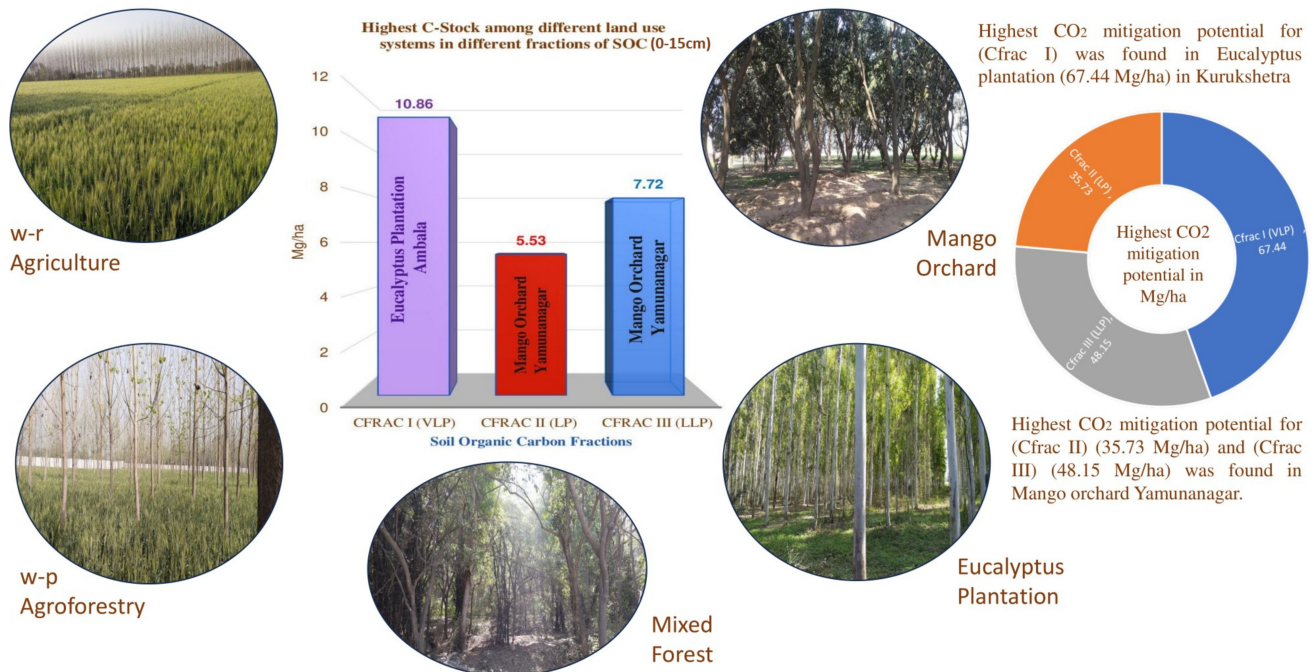
Indo-Gangetic plains in Haryana, India are the area of great agricultural value and environmental significance. Soil under wheat-rice (w-r) agriculture, wheat-poplar agroforestry, mango orchards, *Eucalyptus* plantations, and mixed forestry systems were evaluated to understand the carbon mitigation potential up to 30 cm depth in the Indo-Gangetic region of Northern Haryana. The highest carbon stock values were found in the 0–15 cm soil depth layer. For the very labile pool (Cfrac I), the highest value of carbon stocks (10.86 Mg/ha) was found in *Eucalyptus* plantation at Ambala. For the labile pool (Cfrac II) and less labile pool (Cfrac III), it was 5.53 Mg/ha and 7.72 Mg/ha respectively in the mango orchards at Yamunanagar. The lowest C stock values were found in the 15–30 cm soil depth layer. For the very labile pool (Cfrac I), it was 2.23 Mg/ha in the forest at Ambala. For the labile pool (Cfrac II), it was 0.70 Mg/ha in wheat-poplar agroforestry at Ambala and for the less labile pool (Cfrac III), it was 1.70 Mg/ha in the mango orchard at Ambala. The mitigation potential calculation revealed that the highest mitigation potential summed up for 30 cm soil depth for (Cfrac I) was found in *Eucalyptus* plantation (67.44 Mg/ha) in Kurukshetra, however the mango orchards at Yamunanagar accounted for highest carbon mitigation potential in Cfrac II (35.73 Mg/ha) and in Cfrac III (48.15 Mg/ha). The findings of the present study emphasize the importance of soil depth and land use type in determining carbon sequestration and mitigation potential.

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Graphical abstract

The estimation of the fractions of soil organic carbon under different land use systems at various site of Indo-Gangetic alluvial plain helped in getting insights that most of the SOC are build up in (Cfrac I) and (Cfrac III) in all land uses following the order Cfrac I > Cfrac III > Cfrac II



Keywords Carbon mitigation potential · Soil organic carbon · Labile pool · Carbon fractions · Carbon stocks

Introduction

Soil Organic Carbon (SOC) sequestration and carbon dioxide removal (CDR) methods have drawn a lot of interest from the scientific community and society recently. Almost all techniques depend on removing CO₂ from the atmosphere to keep global warming to 1.5 °C. SOC sequestration is marketed as a “no regret” or “win–win” solution since there are many co-benefits and few drawbacks to its use (Masson-Delmotte et al. 2021). SOC sequestration may be described as a condition of the soil in which an increase in SOC stocks results from an excess of soil carbon inputs over soil carbon release. Consequently, it follows, that increasing soil inputs or lowering losses can both lead to SOC sequestration (Moinet et al. 2022). Anything that takes in more carbon from the atmosphere than it emits is referred to as a carbon sink, and the process of moving atmospheric carbon dioxide into long-living carbon pools allows it to be stored there for a long time. In addition to being a component of soil fertility, soil organic carbon serves as a carbon sink. Therefore, it is frequently assumed that SOC sequestration aids in the mitigation of climate change (Chenu et al. 2019). Gaining knowledge of the dynamics of soil carbon (C) stocks and the potential role that soils may play in the long-term buildup

and sequestration of atmospheric C is becoming increasingly important.

With 1700 Gt C in the top meter, or four times as much as all of the world’s vegetation, twice as much as the atmosphere, and 160 times more than the present yearly rate of anthropogenic CO₂ emissions, soils constitute the biggest store of carbon in the terrestrial biosphere (Friedlingstein et al. 2022). Because of this, soil is not only a great place to store carbon dioxide from the atmosphere but also a significant concern since improper land management techniques and climatic changes can release soil-stored carbon dioxide and worsen global warming (Moinet et al. 2022). The term total organic carbon (TOC) refers to the total amount of organic carbon found in a sample (soil, sediment or water). In specific context of soil, the terms SOC and TOC can thus be used interchangeably as SOC also denotes the organic carbon present in the soil sample. It is very crucial for determination of overall health of soil, its fertility, carbon sequestration potential (Koorneef et al. 2024) and its contribution to climate change mitigation (Petersson et al. 2024).

Additionally, soils have a substantial quantity of inorganic C (Lal. 2021) but the main focus of our study remains on soil organic carbon fractions. The two main categories of SOC fractions are called the labile or active pool and the

passive pool. The passive pool includes the more complex carbonaceous materials that are resistant to decomposition, while the active pool is made up of the microbial biomass C and other fractions that are subject to rapid decomposition and cycling within the soil system. The relative quantity of various soil carbon fractions determines the quality of the soil and the pattern of mineralization (Ghosh et al. 2012), and in any land-use system, having a good understanding of these fractions will aid in determining the sustainability, quality, and the carbon sequestration potential of soil at the fractional level.

The management and alteration of the natural environment or wildness into constructed environments, such as towns, pastures, arable fields, and managed forests, as well as horticulture, agroforestry, plantations, and so forth, is known as land use change. The conversion of forests to other land uses may contribute to the increase in atmospheric CO₂ concentrations, which in turn may cause global climate change (Contosta et al. 2022). Estimates of the top-soil SOC pool are therefore essential for comprehending the dynamics of soil carbon under human land use and the soil's capacity to mitigate the rising atmospheric CO₂ through soil C sequestration (Song et al. 2005). The top 30 cm of the soil contains the majority of SOC. As a result, anthropogenic (human-induced) disturbances like farming and changes in land use quickly deplete it (Post et al. 1982); (Tian et al. 2002). Hence, in the present study, the soil organic carbon stock was measured down to a depth of 30 cm.

Materials and methods

Study sites

The present study was carried out in the year 2022–2023 to gain insights into the carbon sequestration potential of different fractions of SOC for different land use categories such as the wheat–rice (w–r) system in agriculture, the wheat–poplar system in agroforestry, mango orchards, *Eucalyptus* in block plantation and mixed forestry from the Agroecological zone of Indo-Gangetic Alluvial Plains of Haryana, (growing period 150–180 days) covering the districts of Ambala, Kurukshetra and Yamunanagar.

Soil sample collection

The study area from the Indo-Gangetic Alluvial Plains of Haryana was divided into 3 regions covering Ambala, Kurukshetra, and Yamunanagar. The soil was sampled for each of the five land uses mentioned above. The study sites were marked with geographical attributes with the help of a GPS-enabled freeware mobile-based photograph application (Table 1). Composite samples were prepared from a total of

Table 1 Geographical attributes of sampling sites

Sites → Land use ↓	Ambala		Kurukshetra		Yamunanagar	
	Latitude and longitude	Altitude	Latitude and longitude	Altitude	Latitude and longitude	Altitude
Wheat-Rice Agri-culture	30°18'51.32N 76°52'24.48E	N_228m	29°57'33.69N 76°46'18.91E	NW_205m	30°15'56.6N 77°22'36.24E	W_169m
Wheat-Poplar Agro-forestry	30°18'53.94N 76°52'24.36E	W_237m	29°57'40.77N 76°47'0.34E	W_203m	30°15'55.85N 77°22'36.8E	SW_246m
Mango Orchard	30°23'50.36N 76°52'35.72E	W_252m	29°57'55.9"N 76°49'38.7"E	NW_209m	30°15'4.3N 77°22'44.79E	SE_250m
<i>Eucalyptus</i> Plantation	30°18'20.66N 76°53'21.21E	N_237m	29°58'59N 76°53'28.01E	N_244m	30°15'22.95N 77°22'32.01E	SE_252m
Forest	30°22'8.41N 76°52'15.85E	NW_251m	30°5'1.95N 76°46'25.66E	S_214m	30°18'41.99N 77°19'18.68E	SE_265m



5 samples taken randomly from each site from two depths (0–15 cm: surface soil, and 15–30 cm: subsurface soil). The soil samples were put in plastic bags, marked carefully, and brought to the laboratory for physico-chemical analysis.

Soil analysis

Physico-chemical properties: Soil pH, and Electrical Conductivity were measured by pH and EC meter, % Soil moisture by hot air oven method, Bulk density by soil core method. The wet combustion method, or quick titration method, as outlined by Walkley and Black (Walkley and Black, 1934), was used to estimate SOC. Various SOC fractions were calculated Using 5, 10, and 20 ml of concentrated sulfuric acid (H_2SO_4) through the Modified Walkley and Black Method. This equates to three acid aqueous solution ratios of 0.5:1, 1:1, and 2:1, which correspond to 12 N, 18 N, and 24 N H_2SO_4 , respectively (Chan et al. 2001; Ghosh et al. 2010; Mandal et al. 2007). The fractions of SOC and the methods of estimations are listed in Table 2.

To ensure accuracy and reliability in soil parameter analysis, all the instruments were calibrated as required for quality control. pH and EC meters were calibrated before each set of measurements using buffer solutions and standard conductivity solutions respectively. Moisture content was determined using a hot air oven at 105 °C for 24 h (time calculated once the temperature fully reached the max). Bulk density was measured using the soil core sampler in triplicates.

For soil organic carbon (SOC) and its fractions, the Walkley–Black method modified by Chan et al. (2001) was used to differentiate between very labile (CFrac-I), labile (CFrac-II), and less labile carbon (CFrac-III) based on difference in oxidizabilities. Quality control measures included triplicate analyses using analytical grade chemicals, blank sample tests, and recovery percentage calculations to ensure methodological accuracy (Walkley and Black method of wet digestion recovers 73% of soil organic carbon for the soil sample). The observed error for each parameter was determined using standard deviation (SD). Table 3 highlights every quality control and precautionary measure during the sample analysis.

The carbon stock was computed following Datta et al. (2018).

Table 2 Methods used for calculating various C fractions

Carbon Fraction	Method
Fraction 1 (VLP)—Very labile Pool (Cfrac I)	Organic C oxidizable under 12 N H_2SO_4
Fraction 2 (LP)—Labile Pool (Cfrac II)	Difference in oxidizable organic C extracted between 18 and 12 N H_2SO_4 (18–12 N H_2SO_4)
Fraction 3 (LLP)—Less Labile Pool (Cfrac III)	Difference in oxidizable organic C extracted between 24 and 18 N H_2SO_4 (24–18N H_2SO_4)

Table 3 Instrument calibration, quality control measures for soil sample analysis

Parameter	Method Used	Calibration Standard	Quality Control Measures
pH	Digital pH Meter	pH 4.0, 7.0, and 10.0 buffers	3-point calibration, triplicate measurements
Electrical Conductivity (EC)	EC Meter	1413 $\mu\text{S}/\text{cm}$ and 12.88 mS/cm solutions	Pre-analysis calibration, triplicate samples
Moisture Content	Hot Air Oven (105 °C)	Internal thermometer check	Cross-check temperature, triplicate samples
Bulk Density	Soil Core Method	Standard soil volume-weight ratio	Triplicate cores per sample
Total SOC	Walkley–Black (Wet Oxidation Method)		Blank correction, triplicate analysis
Very Labile C (Fract-I)	Walkley–Black (Modified Chan et al. 2001) (Weak Oxidation)		Blank correction, triplicate analysis
Labile C (Fract-II)	Walkley–Black (Modified Chan et al. 2001) (Moderate Oxidation)		Blank correction, triplicate analysis
Less Labile C (Fract-III)	Walkley–Black (Modified Chan et al. 2001) (Strong Oxidation)		Blank correction, triplicate analysis

$$\text{C stock in soil} = \% \text{SOCFrac content} \times \text{Bulk density (Mg/m}^3\text{)} \times \text{Depth (m)} \times 10^4 (\text{m}^2/\text{ha}) \times 100$$

To quantify the amount of CO₂ mitigated by soil, the SOC was converted to CO₂-equivalent using the molecular weight ratio (44/12=3.67) following IPCC, (2006) and Lal, (2004). Hence, the mitigation potential of soil was calculated as

$$\text{CO}_2 \text{ Mitigation (Mg/ha)} = \text{SOC Sequestered} \times 3.67$$

Statistical analysis was done by one way ANOVA, Pearson's Correlation and Linear Regression using MS Excel, Google Sheets and XLMiner.

Results and discussion

Physico-chemical properties

Moisture content: The highest % moisture content in soil was estimated in wheat-poplar agroforestry system in

Yamunanagar 17.31% preceded by agroforestry of Kurukshetra with 17.18% followed by agroforestry Ambala with 14.08% in 0–15 cm layer of soil even the 15–30 cm retains a fair amount of moisture showing that the soil under agroforestry carries more moisture when compared with other land use. The lowest moisture was estimated in agricultural field of Ambala in 15–30 cm soil layer. Overall value of % moisture content in soil is less than the ideal value of 20–40% as required by the crops, as the timing of sampling is after the irrigation period is over (Table 4). The p-value of 0.270 indicates that the % moisture content under different land use types was not significantly different.

pH: Value of soil pH were ideal between 6.5 to 8.5 which is suitable for most of the crops and plantations (Table 5). The pH of soil in all the land use was slightly alkaline with exception of *Eucalyptus* plantation at 0–15 cm soil layer with pH of 6.63 which was quiet near to neutral. The highest pH (9.03) was estimated in wheat-rice agriculture in

Table 4 % Moisture content of soil in different land use systems in Indo-Gangetic plains of Haryana

Study Areas		Ambala	Kurukshetra	Yamunanagar
Land use system	Depth (cm)			
Wheat-Rice Agriculture	0–15	6.30 ± 0.51	13.74 ± 0.98	4.44 ± 0.52
	15–30	2.30 ± 0.46	10.93 ± 0.34	5.11 ± 0.13
Wheat-Poplar Agroforestry	0–15	14.08 ± 0.92	17.18 ± 0.72	17.31 ± 0.21
	15–30	13.27 ± 0.42	12.28 ± 0.46	11.99 ± 0.36
Mango Orchard	0–15	7.10 ± 0.32	4.97 ± 0.17	9.33 ± 0.52
	15–30	10.19 ± 0.67	3.49 ± 0.39	11.04 ± 0.50
<i>Eucalyptus</i> plantation	0–15	4.11 ± 0.61	12.44 ± 0.95	2.61 ± 0.25
	15–30	4.85 ± 0.47	10.16 ± 0.53	3.46 ± 0.27
Forest	0–15	2.45 ± 0.27	7.32 ± 0.45	5.28 ± 0.26
	15–30	2.38 ± 0.26	6.93 ± 0.49	8.21 ± 0.45

Table 5 pH of soil in different land use systems in Indo-Gangetic plains of Haryana

Study Areas		Ambala	Kurukshetra	Yamunanagar
Land use system	Depth (cm)			
Wheat-Rice Agriculture	0–15	9.03 ± 0.06	8.43 ± 0.06	8.10 ± 0.17
	15–30	8.63 ± 0.06	8.43 ± 0.06	8.20 ± 0.17
Wheat-Poplar Agroforestry	0–15	8.47 ± 0.12	8.20 ± 0.10	7.57 ± 0.06
	15–30	8.43 ± 0.12	8.27 ± 0.15	7.93 ± 0.06
Mango Orchard	0–15	7.17 ± 0.06	7.87 ± 0.00	7.47 ± 0.06
	15–30	7.87 ± 0.06	8.17 ± 0.12	7.60 ± 0.12
<i>Eucalyptus</i> plantation	0–15	8.47 ± 0.06	8.17 ± 0.06	6.63 ± 0.06
	15–30	8.53 ± 0.00	8.37 ± 0.06	7.17 ± 0.12
Forest	0–15	7.73 ± 0.12	7.57 ± 0.06	8.03 ± 0.06
	15–30	8.67 ± 0.00	7.80 ± 0.17	8.80 ± 0.12



0–15 cm soil layer followed by forest with pH (8.67) at 15–30 cm soil layer and least (7.17) was estimated in *Eucalyptus* plantation at 15–30 cm in Yamunanagar. P value of 0.057, indicating that pH under different land use types was significantly different.

Electrical Conductivity: The highest Electrical Conductivity (EC) was estimated to be 956 $\mu\text{S}/\text{cm}$ in 15–30 cm soil layer of Forest in Kurukshetra followed by 0–15 cm soil layer of wheat-poplar agroforestry in Kurukshetra (Table 6). The lowest EC was estimated in 15–30 cm layer of *Eucalyptus* plantation of Kurukshetra. The value of EC less than 2000 $\mu\text{S}/\text{cm}$ indicates very less salinity and all the values obtained from the studied soil samples were below this value indicating the soils in these areas to be free from the menace of salinization. The p-value of 0.046 indicates that the EC under different land use types was significantly different.

Bulk Density: Table 7 represents the values of bulk density of soil in all the sampling sites. The highest bulk density was estimated in 15–30 cm soil layer (1.39 Mg/m^3) in *Eucalyptus* plantation of Kurukshetra followed by Yamunanagar with (1.34 Mg/m^3). The lowest bulk density was estimated in 15–30 cm soil layer (1.10 Mg/m^3) in forest of Kurukshetra. P value = 0.020, indicating that bulk density under different land use types was significantly different.

Soil organic carbon (%) and carbon stock: Value of % Soil Organic Carbon (SOC) estimated in the study was found to be moderate to high in 0–15 cm of soil layer (0.500%–1.500%) particularly in mixed forest and orchard system (Table 8). The highest % SOC was estimated in forest site at Kurukshetra in 0–15 cm soil layer (1.555%) followed by mango orchard Yamunanagar (1.210%), followed by wheat-poplar agroforestry (1.155%) and wheat-rice agriculture (0.945%) in 0–15 cm soil layer of Kurukshetra. The least % SOC was estimated in forest site of Ambala (0.300%) in 15–30 cm soil layer. The p-value = 0.101, indicating that the % SOC under different land use types was not significantly different. The Soil organic carbon stock

also followed the similar trend. C-stocks were found to be highest in mango orchard in Yamunanagar followed by agroforestry in Kurukshetra as no tillage was being practiced at both study sites. The highest Soil Organic Carbon stock was estimated (21.59 Mg/ha) in the soil layer of 0–15 cm for mango orchard in Yamunanagar, followed by wheat-poplar agroforestry Kurukshetra (20.44 Mg/ha) in 0–15 cm soil layer, least been estimated in forest Ambala (5.44 Mg/ha) in 15–30 cm soil layer. The forest in Ambala was dominated by kikar species which usually has little litterfall. Also, the soil samples of this site had least values of bulk density and predominantly were sandy in texture with least moisture content resulting in comparatively low microbial activity. These factors justified the low SOC stocks of the sampling site of Ambala. The p-value of 0.196 indicates that carbon stocks in different land use types were not significantly different.

Total Soil Organic Carbon Stock: Soil Organic Carbon (SOC) stocks represent a critical component of soil health and ecosystem function. In the present study the total soil organic carbon stock of the study sites was calculated up to a depth of 30 cm as this layer is crucial for plant growth, microbial activity, and carbon sequestration. The upper 30 cm of soil often contains the highest concentrations of organic carbon due to the accumulation of plant residues, root biomass, and organic matter inputs from surface litter. the highest SOC-stocks were found to be highest in Mango orchard (37.21 Mg/ha) Yamunanagar followed by agroforestry in Kurukshetra (34.05 Mg/ha), least being in mixed forestry Ambala (18.77 Mg/ha) (Fig. 1).

Soil organic carbon fractions and their mitigation potential

Soil organic carbon can be fractionated into three major types depending on how much easily it gets decomposed or metabolized by microorganisms present in soil-very labile pool (VLP), labile pool (LP) and less labile pool (LLP).

Table 6 EC ($\mu\text{S}/\text{cm}$) of soil in different land use systems in Indo-Gangetic plains of Haryana

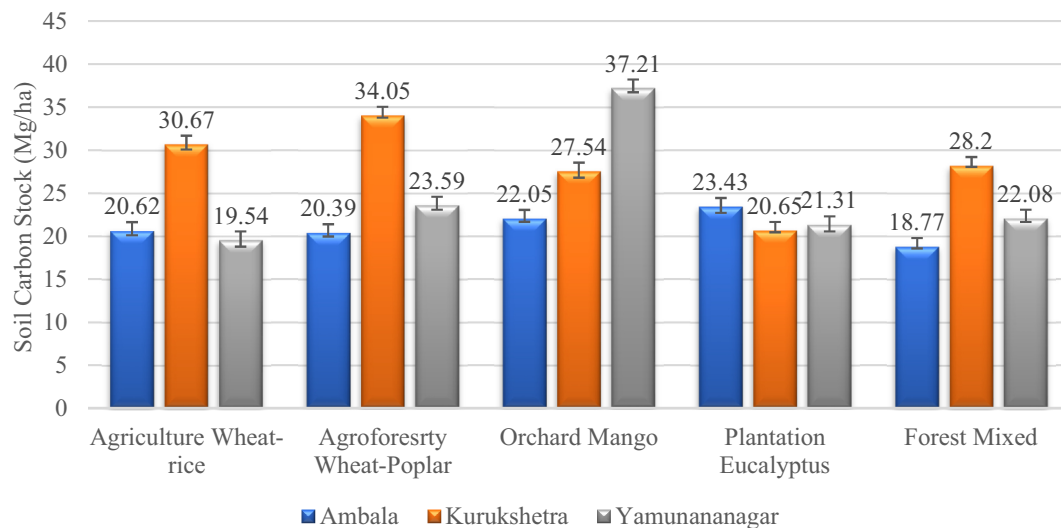
Study Areas		Ambala	Kurukshetra	Yamunanagar
Land use system	Depth (cm)			
Wheat-Rice Agriculture	0–15	253.33 $\pm$ 2.52	370.33 $\pm$ 2.31	114.00 $\pm$ 5.29
	15–30	371.00 $\pm$ 2.00	88.33 $\pm$ 3.21	92.67 $\pm$ 2.08
Wheat-Poplar Agroforestry	0–15	174.67 $\pm$ 1.53	409.67 $\pm$ 2.89	206.00 $\pm$ 2.65
	15–30	147.00 $\pm$ 2.65	159.67 $\pm$ 1.15	85.00 $\pm$ 1.73
Mango Orchard	0–15	67.33 $\pm$ 1.53	230.00 $\pm$ 2.00	146.33 $\pm$ 4.04
	15–30	85.33 $\pm$ 3.51	194.67 $\pm$ 2.08	147.33 $\pm$ 1.15
<i>Eucalyptus</i> plantation	0–15	165.33 $\pm$ 0.58	344.33 $\pm$ 4.93	95.67 $\pm$ 4.16
	15–30	232.67 $\pm$ 1.15	57.67 $\pm$ 1.53	65.00 $\pm$ 1.73
Forest	0–15	61.00 $\pm$ 1.00	366 $\pm$ 1.00	197 $\pm$ 3.46
	15–30	116.66 $\pm$ 2.52	956 $\pm$ 2.65	265 $\pm$ 2.45

Study Areas		Ambala	Kurukshetra	Yamunanagar
Land use system		Depth (cm)		
Wheat-Rice Agriculture	0-15	1.31 ± 0.03	1.18 ± 0.01	1.17 ± 0.01
	15-30	1.23 ± 0.02	1.24 ± 0.02	1.29 ± 0.02
Wheat-Poplar Agroforestry	0-15	1.27 ± 0.02	1.18 ± 0.01	1.17 ± 0.01
	15-30	1.31 ± 0.03	1.21 ± 0.01	1.29 ± 0.02
Mango Orchard	0-15	1.24 ± 0.02	1.19 ± 0.01	1.19 ± 0.01
	15-30	1.31 ± 0.03	1.24 ± 0.03	1.31 ± 0.04
Eucalyptus plantation	0-15	1.27 ± 0.02	1.20 ± 0.02	1.25 ± 0.02
	15-30	1.39 ± 0.03	1.29 ± 0.02	1.34 ± 0.03
Forest	0-15	1.17 ± 0.01	1.10 ± 0.01	1.27 ± 0.01
	15-30	1.21 ± 0.02	1.13 ± 0.01	1.34 ± 0.03

Labile SOC pool: SOC in layer of soil 0–15 cm the C stock was found highest in mango orchard (5.53 Mg/ha) in Yamunanagar followed by forest (4.48 Mg/ha) in Kurukshetra and the least SOC was found in agriculture in Ambala (1.88 Mg/ha). The statistical analysis showed that soil organic carbon (SOC) stocks under different land uses were not significantly different, with a P value of 0.643 for the depth of 0–15 cm. For 15–30 cm soil depth, the C stock was found highest in mango orchard in Yamunanagar (4.70 Mg/ha) followed by wheat-rice agriculture in Kurukshetra (2.39 Mg/ha), and the least SOC was found in wheat-poplar agroforestry in Ambala (0.70 Mg/ha). The statistical analysis showed that soil organic carbon (SOC) stocks under different land uses were not significantly different at the 15–30 cm depth, with a P value of 0.199. Mitigation potential of forest was observed to be highest (16.44 Mg/ha) at 0–15 cm depth and 3.15 times more when compared with least mitigation potential observed in agroforestry land use at 15–30 cm layer of soil in Kurukshetra (5.21 Mg/ha). In Yamunanagar, the highest potential was inferred in orchards at surface soil layer. It is 3.5 times more than the least potential observed forest (5.68 Mg/ha) at 15–30 cm depth. In Ambala, the LP of wheat-poplar agroforestry reported for both highest (14.16 Mg/ha) and lowest (2.56 Mg/ha) mitigation potential

Table 8 % Soil Organic Carbon and Soil Organic Carbon Stock (Mg/ha) for different land use systems in Indo-Gangetic plains of Haryana

Study areas		Ambala	Kurukshetra	Yamunanagar
Land use system	Depth (cm)			
Wheat-Rice Agriculture	0–15	0.585 ± 0.08	0.945 ± 0.05	0.750 ± 0.04
		11.49 ± 1.57	16.72 ± 0.89	13.16 ± 0.70
	15–30	0.495 ± 0.01	0.750 ± 0.03	0.330 ± 0.03
Wheat-Poplar Agroforestry	0–15	0.665 ± 0.02	1.155 ± 0.05	0.865 ± 0.03
		13.06 ± 0.39	20.44 ± 0.88	15.18 ± 0.53
	15–30	0.385 ± 0.02	0.750 ± 0.03	0.435 ± 0.02
Mango Orchard	0–15	7.33 ± 0.38	13.61 ± 0.54	8.41 ± 0.38
		0.790 ± 0.03	0.965 ± 0.05	1.210 ± 0.04
	15–30	14.69 ± 0.56	17.22 ± 0.89	21.59 ± 0.71
<i>Eucalyptus</i> plantation	0–15	0.375 ± 0.03	0.555 ± 0.03	0.795 ± 0.01
		7.36 ± 0.59	10.32 ± 0.56	15.62 ± 0.19
	15–30	0.875 ± 0.03	0.750 ± 0.03	0.660 ± 0.01
Forest	0–15	16.66 ± 0.57	13.50 ± 0.54	12.37 ± 0.19
		0.325 ± 0.01	0.370 ± 0.01	0.445 ± 0.03
	15–30	6.77 ± 0.21	7.15 ± 0.19	8.94 ± 0.60
Forest	0–15	0.760 ± 0.04	1.555 ± 0.02	0.780 ± 0.03
		13.33 ± 0.70	19.05 ± 0.33	14.85 ± 0.57
	15–30	0.300 ± 0.03	0.540 ± 0.05	0.360 ± 0.06
		5.44 ± 0.54	9.15 ± 0.84	7.23 ± 1.21

**Fig. 1** The total SOC stocks (Mg/ha) in different land use systems in Indo-Gangetic plains of Haryana

at surface (0–15 cm) and subsurface (15–30 cm) depth of soil (Table 10).

Less labile SOC pool: In this fraction, the highest C stock was found in orchard (7.72 Mg/ha) at 0–15 cm soil depth in Yamunanagar followed by wheat-poplar agroforestry in Kurukshetra (6.58 Mg/ha) and the least SOC was found in *Eucalyptus* plantation in Ambala (3.23 Mg/ha). Statistically, SOC stocks under different land use at 0–15 cm soil layer were not significantly different, P value 0.321.

At depth of 15–30 cm, the C stock was highest in mango orchard in Yamunanagar (5.40 Mg/ha) followed by wheat-rice agriculture in Kurukshetra (4.46 Mg/ha), and the least SOC was also found in mango orchard in Ambala (1.70 Mg/ha). Again, the differences were not significant ($P=0.230$). Further, mitigation potential of orchard (28.33 Mg/ha at 0–15cm) was 4.5 times more than agroforestry (6.35 Mg/ha at 15–30 cm) in Yamunanagar. In Kurukshetra it was 3 times more in agroforestry (24.15 Mg/ha at 0–15cm) when

Table 9 SOC Fraction I (Very labile) and its mitigation potential

Study areas	Land Use system	Depth (cm)	Ambala		Kurukshetra		Yamunanagar	
			C Stock (Mg/ha)	Mitigation potential (Mg/ha)	C stock (Mg/ha)	Mitigation potential (Mg/ha)	C Stock (Mg/ha)	Mitigation potential (Mg/ha)
Wheat–Rice agriculture		0–15	5.32±0.29	19.52±1.06	7.71±0.65	28.29±2.38	5.60±0.60	20.55±2.20
		15–30	4.76±0.40	17.46±1.46	6.69±0.39	24.55±1.43	2.35±0.42	8.62±1.54
Wheat–Poplar Agroforestry		0–15	4.72±0.29	17.32±1.06	9.65±0.49	35.41±1.32	8.76±±0.09	32.14±0.33
		15–30	4.70±0.27	17.24±0.99	8.73±0.68	32.03±2.49	4.89±0.23	17.94±0.84
Mango Orchard		0–15	6.21±0.49	22.79±1.79	8.77±0.55	32.18±2.02	8.33±0.27	30.57±0.99
		15–30	4.31±0.30	15.81±1.10	4.62±0.16	16.95±1.57	5.52±0.14	20.25±0.51
<i>Eucalyptus</i> plantation		0–15	10.86±0.43	39.85±1.57	7.90±0.42	28.99±1.54	5.33±0.23	19.56±0.84
		15–30	3.50±0.41	12.84±1.50	3.66±0.16	13.43±0.59	4.30±0.27	15.78±0.99
Forest		0–15	6.25±0.50	22.93±1.83	9.95±0.57	36.51±2.10	6.38±0.71	23.41±2.60
		15–30	2.23±0.09	8.18±0.33	4.43±0.50	16.25±1.83	3.28±0.21	12.03±0.77

compared with *Eucalyptus* plantation (6.83 Mg/ha at 15–30 cm). In Ambala, the potential was found to be 2.76 times in 0–15 cm soil layer (17.21 Mg/ha) than (6.23 Mg/ha) in 15–30 cm soil layer in mango orchard (Table 11).

SOC is a large carbon pool within the biosphere (Grace et al. 2006) and irrespective of the studies of different land use systems, the content of SOC and its fraction gradually decreased from top to bottom. For the soil layer of 0–15 cm, SOC content was relatively more and then decreased significantly for 15–30 cm soil layer (Wu et al. 2016). The values of SOC in Carbon fraction I (VLP) was comparatively higher than labile and less labile pools due to active microbial processes that prevail in the topmost layer, where the values of SOC in Cfrac I generally ranged from on an average 4.5 Mg/ha to 8.5 Mg/ha, the Cfrac II (LP) and Cfrac III (LLP) ranged on an average 1.5 Mg/ha to 4.5 Mg/ha. Mostly the trend followed by carbon fractions were Cfrac I > Cfrac III > Cfrac II which often allied with Sheron et al. (2018) who reported similar kinds of results in the conventional farming section of the light fraction organic carbon at different locations of Haryana in the Indo-Gangetic region Sheoran et al. (2019). This may also be attributed to the stand age of approx. 5 years and undisturbed soil (no till). Study conducted on soil organic carbon stocks and carbon fractions of different trees species in the orchards of eastern plateau and hill region of India showed the similar kind of trend in carbon fractions of mango Naik et al. (2017). Mishra et al. (2020) studied the relationship between total organic carbon and soil carbon pools under different land management systems of Garo hills, Meghalaya and found similar behavior of soil organic carbon fractions. Benbi et al. (2015) studied the total and labile pools of soil organic carbon in cultivated and undisturbed soils in areas of western Punjab in northern India and reported that the land which is not under cultivation gradually starts losing the labile C. for Cfrac I, the location wise trend followed was as Ambala > Kurukshetra > Yamunanagar in *Eucalyptus* plantation while it got reversed as Yamunanagar > Kurukshetra > Ambala in orchard presenting how both the land use holds equal potential of C storage of (VLP) but it was just the matter of how well these systems were managed.

The data obtained after soil analysis were subjected to correlation and regression analysis. The correlation matrix analysis of soil properties at surface layer revealed intricate interdependencies that shed light on soil health dynamics (Table 12). The significant correlations in the matrix indicate that % Moisture Content (% MC) and Electrical Conductivity (EC) were positively correlated ($r=0.596$, $p<0.05$), suggesting that as % MC increases, EC also tends to increase. Soil Organic Carbon (SOC) showed strong positive correlations with Very Labile Pool (VLP) ($r=0.753$, $p<0.01$), Labile Pool (LP) ($r=0.623$, $p<0.05$), and Less Labile Pool



Table 10 SOCFraction 2 (labile) and its mitigation potential

Study areas		Ambala		Kurukshetra		Yamunanagar	
Land Use system	Depth (cm)	C Stock (Mg/ha)	Mitigation potential (Mg/ha)	C Stock (Mg/ha)	Mitigation potential (Mg/ha)	C stock (Mg/ha)	Mitigation potential (Mg/ha)
Wheat-Rice Agri-culture	0–15	1.88 ± 0.13	6.89 ± 0.47	3.10 ± 0.32	11.37 ± 1.18	3.56 ± 0.40	13.06 ± 1.46
	15–30	1.70 ± 0.15	6.23 ± 0.55	2.39 ± 0.26	8.77 ± 0.95	1.67 ± 0.29	6.12 ± 1.06
Wheat-Poplar Agroforestry	0–15	3.86 ± 0.45	14.16 ± 1.65	3.21 ± 0.23	11.87 ± 0.84	2.72 ± 0.17	9.98 ± 0.62
	15–30	0.70 ± 0.12	2.56 ± 0.44	1.42 ± 0.14	5.21 ± 0.51	1.65 ± 0.18	6.05 ± 0.66
Mango Orchard	0–15	3.78 ± 0.41	13.87 ± 1.52	2.81 ± 0.47	10.39 ± 1.72	5.53 ± 0.35	20.29 ± 1.28
	15–30	1.35 ± 0.18	4.95 ± 0.66	2.15 ± 0.11	7.89 ± 0.40	4.70 ± 0.40	17.24 ± 1.46
<i>Eucalyptus</i> plantation	0–15	2.57 ± 0.14	9.43 ± 0.51	2.13 ± 0.26	7.81 ± 0.95	2.46 ± 0.22	9.02 ± 0.80
	15–30	1.29 ± 0.27	4.73 ± 0.99	1.63 ± 0.13	5.98 ± 0.48	2.02 ± 0.16	7.41 ± 0.58
Forest	0–15	2.85 ± 0.12	10.45 ± 0.44	4.48 ± 0.40	16.44 ± 1.46	3.54 ± 0.27	12.99 ± 0.99
	15–30	1.50 ± 0.15	5.50 ± 0.55	2.01 ± 0.25	7.37 ± 0.92	1.55 ± 0.13	5.68 ± 0.47

Table 11 SOCFraction 3 (less labile) and its mitigation potential

Study areas		Ambala		Kurukshetra		Yamunanagar	
Land use system	Depth (cm)	C Stock (Mg/ha)	Mitigation potential (Mg/ha)	C Stock (Mg/ha)	Mitigation potential (Mg/ha)	C stock (Mg/ha)	Mitigation potential (Mg/ha)
Wheat-Rice Agriculture	0–15	3.70 ± 0.52	13.57 ± 1.90	5.19 ± 0.29	19.05 ± 1.06	4.00 ± 0.19	14.68 ± 0.69
	15–30	3.10 ± 0.18	11.37 ± 0.66	4.86 ± 0.40	17.84 ± 1.46	1.73 ± 0.30	6.35 ± 1.10
Wheat-Poplar Agroforestry	0–15	4.65 ± 0.27	17.06 ± 0.99	6.58 ± 0.51	24.15 ± 1.87	4.32 ± 0.22	15.85 ± 0.81
	15–30	2.17 ± 0.15	7.96 ± 0.55	4.46 ± 0.26	16.37 ± 0.95	1.88 ± 0.27	6.9 ± 0.99
Mango Orchard	0–15	4.69 ± 0.38	17.21 ± 1.39	5.54 ± 0.35	20.33 ± 1.28	7.72 ± 0.36	28.33 ± 1.32
	15–30	1.70 ± 0.26	6.23 ± 0.95	3.51 ± 0.24	12.88 ± 0.88	5.40 ± 0.11	19.82 ± 0.40
<i>Eucalyptus</i> plantation	0–15	3.23 ± 0.29	11.85 ± 1.06	3.49 ± 0.19	12.81 ± 0.69	4.57 ± 0.31	16.77 ± 1.13
	15–30	1.99 ± 0.26	7.30 ± 0.95	1.86 ± 0.25	6.83 ± 0.92	2.63 ± 0.29	9.65 ± 1.06
Forest	0–15	4.25 ± 0.29	15.59 ± 1.07	4.61 ± 0.32	16.92 ± 1.18	4.95 ± 0.50	18.17 ± 1.83
	15–30	1.71 ± 0.24	6.27 ± 0.88	2.71 ± 0.17	9.95 ± 0.62	2.40 ± 0.17	8.81 ± 0.62

Table 12 Correlation matrix of physico-chemical properties, SOC and SOC fractions under different land use categories for depth of 0–15 cm soil layer

	% MC	pH	EC	BD	SOC	VLP	LP	LLP
% MC	1.000							
pH	0.237 ^{NS}	1.000						
EC	0.596 [*]	0.433	1.000					
BD	− 0.212 ^{NS}	0.316 ^{NS}	− 0.323 ^{NS}	1.000				
SOC	0.314 ^{NS}	− 0.121 ^{NS}	0.416 ^{NS}	− 0.508 ^{NS}	1.000			
VLP	0.247 ^{NS}	0.032 ^{NS}	0.503 ^{NS}	− 0.463 ^{NS}	0.753 ^{**}	1.000		
LP	0.079 ^{NS}	− 0.303 ^{NS}	− 0.101 ^{NS}	− 0.370 ^{NS}	0.623 [*]	0.108 ^{NS}	1.000	
LLP	0.290 ^{NS}	− 0.262 ^{NS}	0.145 ^{NS}	− 0.273 ^{NS}	0.755 ^{**}	0.188 ^{NS}	0.669 ^{**}	1.000

“*” are statistically significant at the 0.05 level ($p < 0.05$); “**” are statistically significant at the 0.05 level ($p < 0.01$); NS Not statistically significant

(LLP) ($r=0.755$, $p<0.01$), indicating that higher levels of SOC are associated with higher levels of these pools. Additionally, LLP was positively correlated with LP ($r=0.669$, $p<0.01$), suggesting that these two pools increase together. It further emphasized the interconnectedness of different carbon fractions, reinforcing the holistic nature of soil carbon dynamics. These findings provide valuable insights for soil management and conservation strategies.

The correlation matrix for 15–30 cm soil depth indicated that the % moisture Content (% MC) was positively correlated with Very Labile Pool (VLP) ($r=0.551$, $p<0.05$), indicating that as % MC increases, VLP also tends to increase. Bulk Density (BD) showed a negative correlation with Electrical Conductivity (EC) ($r=-0.578$, $p<0.05$), suggesting that higher BD is associated with lower EC. Soil Organic Carbon (SOC) had strong positive correlations with VLP ($r=0.699$, $p<0.01$), Labile Pool (LP) ($r=0.593$, $p<0.05$), and Less Labile Pool (LLP) ($r=0.840$, $p<0.01$). Additionally, LLP was strongly correlated with both VLP ($r=0.754$, $p<0.01$) and LP ($r=0.710$, $p<0.01$), suggesting that these pools tend to increase together (Table 13).

The regression analysis revealed that SOC and its fractions (VLP, LP, LLP) had a significant influence at both soil depths. In the 0–15 cm depth, SOC variability was best explained by LLP ($R^2=0.5702$), with VLP also providing a strong explanation ($R^2=0.5677$). At 15–30 cm depth, LLP showed the strongest relationship with SOC ($R^2=0.7059$), indicating that less labile carbon pools are particularly important for SOC content at deeper soil layers (Table 14).

CO₂ Mitigation potential

The CO₂ mitigation potential of soil is a natural, cost-effective and win–win strategy in the global effort to mitigate climate change, while simultaneously addressing food security and land degradation challenges. In the present study, the mitigation potential calculated on the basis of soil organic carbon stocks revealed that the mitigation potential was highest in Mango orchard (136.56 Mg/ha) of Yamunanagar followed by agroforestry in Kurukshetra (124.96 Mg/ha), least being in forest Ambala (68.88 Mg/ha) (Fig. 2). CO₂ mitigation potential is higher in orchards as compared to agroforestry systems due to the differences in soil organic matter stability and, accumulation and conservation of carbon stock over time without disturbance. The orchard was well surrounded by agricultural fields getting plenty of irrigation water and run off nutrients. On the other hand, agroforestry has a fair amount of mitigation potential as the poplar litter adds more SOC in soil along with the crop mulch and only a little tilling is done. Lorenz and Lal, (2014) discussed the potential of agroforestry systems to sequester carbon, aligning with our observation of high SOC stocks in agroforestry in Kurukshetra. Forestry in Ambala was dominated by kikar plantation and sandy soil with less moisture and less microbial activity resulting in least mitigation potential. Smith et al. (2008) in their study on soil carbon mitigation potential highlighted that appropriate land management can enhance SOC stocks which correlates with our findings that proper land management and right cultivation practices can

Table 13 Correlation matrix of physico-chemical properties, SOC and SOC fractions under different land use categories for depth of 15–30 cm soil layer

	% MC	pH	EC	BD	SOC	VLP	LP	LLP
% MC	1.000							
pH	− 0.077 ^{NS}	1.000						
EC	− 0.195 ^{NS}	− 0.031 ^{NS}	1.000					
BD	0.092 ^{NS}	− 0.048 ^{NS}	− 0.578 [*]	1.000				
SOC	0.260 ^{NS}	− 0.191 ^{NS}	0.023 ^{NS}	0.035 ^{NS}	1.000			
VLP	0.551 [*]	− 0.171 ^{NS}	− 0.012 ^{NS}	− 0.282 ^{NS}	0.699 ^{**}	1.000		
LP	0.056 ^{NS}	− 0.460 ^{NS}	0.022 ^{NS}	− 0.043 ^{NS}	0.593 [*]	0.213 ^{NS}	1.000	
LLP	0.259 ^{NS}	− 0.179 ^{NS}	0.031 ^{NS}	− 0.249 ^{NS}	0.840 ^{**}	0.754 ^{**}	0.710 ^{**}	1.000

“*” are statistically significant at the 0.05 level ($p<0.05$); “**” are statistically significant at the 0.05 level ($p<0.01$); NS Not statistically significant

Table 14 Linear Regression Analysis for SOC and SOC fractions

Carbon fractions →	VLP	LP	LLP
0–15 cm	$y=0.4786x+0.0056$ $R^2=0.5677$	$y=0.1948x+0.2014$ $R^2=0.3884$	$y=0.2927x+0.2134$ $R^2=0.5702$
15–30 cm	$y=0.363x+1.0623$ $R^2=0.4887$	$y=0.1678x+0.2454$ $R^2=0.352$	$y=0.3275x-0.3226$ $R^2=0.7059$



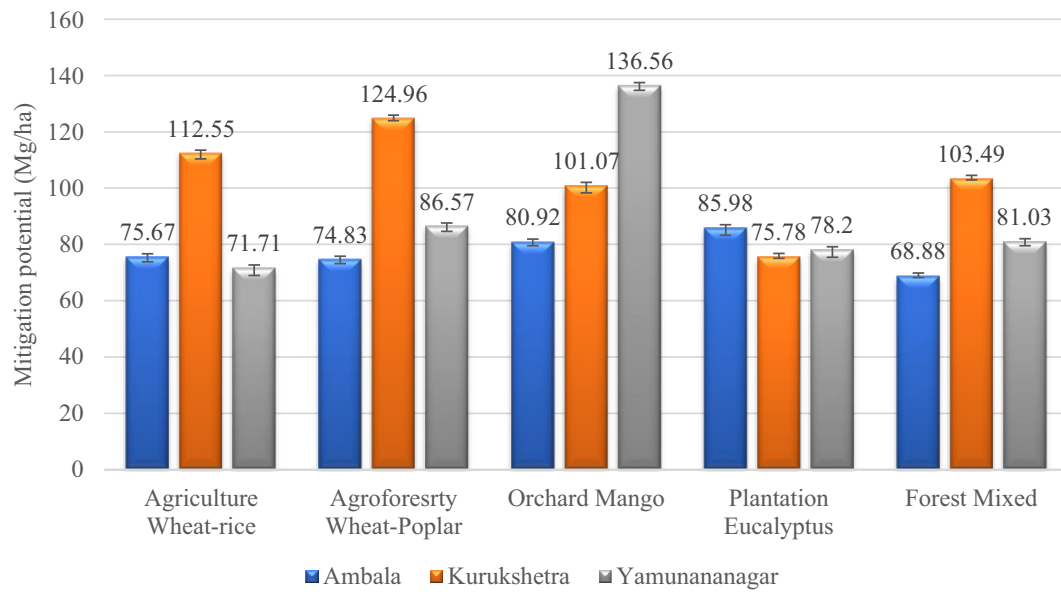


Fig. 2 Mitigation potential of soil carbon stocks in different land use systems in Indo-Gangetic Plains of Haryana

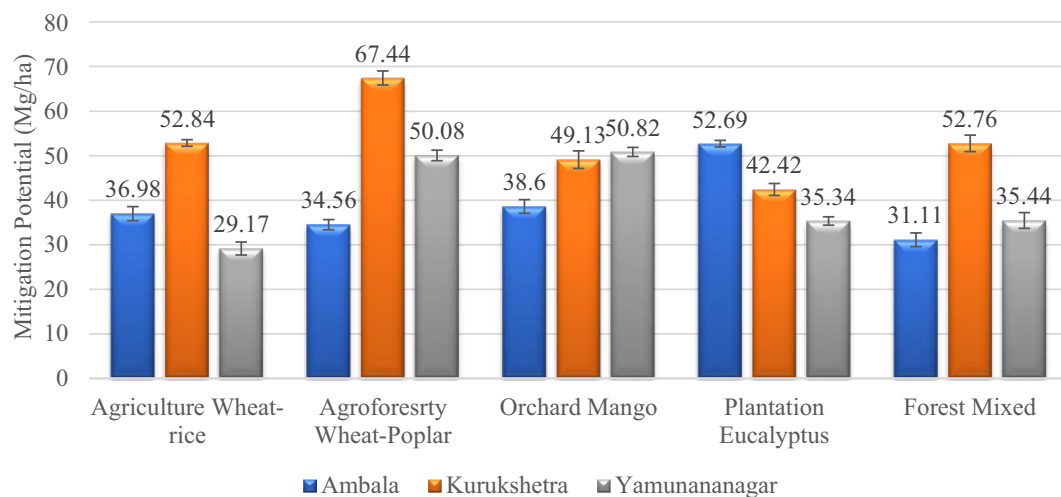


Fig. 3 Mitigation potential of (C-fraction I) Very Labile Pool (VLP) in different land use systems up to 30 cm soil depth

substantially increase the CO₂ mitigation potential across different land uses.

The highest mitigation potential for (C-fraction I) Very Labile Pool (VLP) in different land use systems up to 30 cm soil depth was found in wheat-poplar agroforestry in Kurukshetra (67.44 Mg/ha) followed by wheat-rice agriculture in Kurukshetra (52.84 Mg/ha) and the least being in wheat-rice agriculture in Yamunanagar (29.17 Mg/ha) (Fig. 3). For (C-fraction II) Labile Pool (LP) mango orchard in Yamunanagar reported highest potential (37.53 Mg/ha) followed by mixed forest in Kurukshetra (23.81 Mg/ha) and the least being in wheat-rice agriculture in Ambala (13.12 Mg/ha) (Fig. 4).

For (C-fraction III) Less Labile Pool (LLP) again the mango orchard in Yamunanagar (48.15 Mg/ha) had maximum mitigation potential (40.52 Mg/ha) while it was minimum in *Eucalyptus* plantation in Ambala (19.15 Mg/ha) (Fig. 5).

In the comparative analysis done for soil CO₂ sequestration potential across various land use systems focused on different carbon fractions up to 30 cm soil depth, there was a significant variability in the mitigation potential of the Very Labile Pool (VLP), Labile Pool (LP), and Less Labile Pool (LLP) among different land use practices in Kurukshetra, Yamunanagar, and Ambala. C-fraction I showed a good amount of CO₂ mitigation potential in agroforestry and orchards in

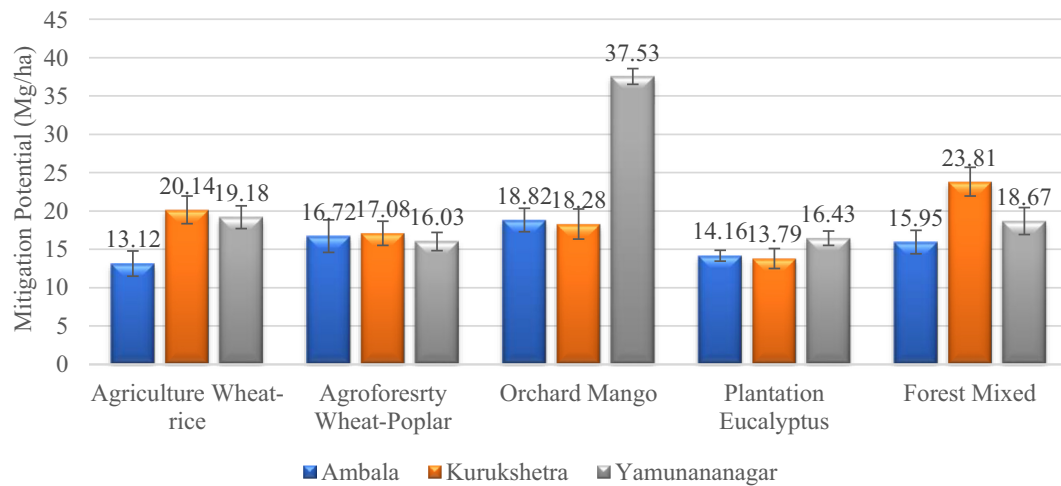


Fig. 4 Mitigation potential of (C-fraction II) Labile Pool (LP) in different land use systems in Indo-Gangetic plains of Haryana 30 cm depth

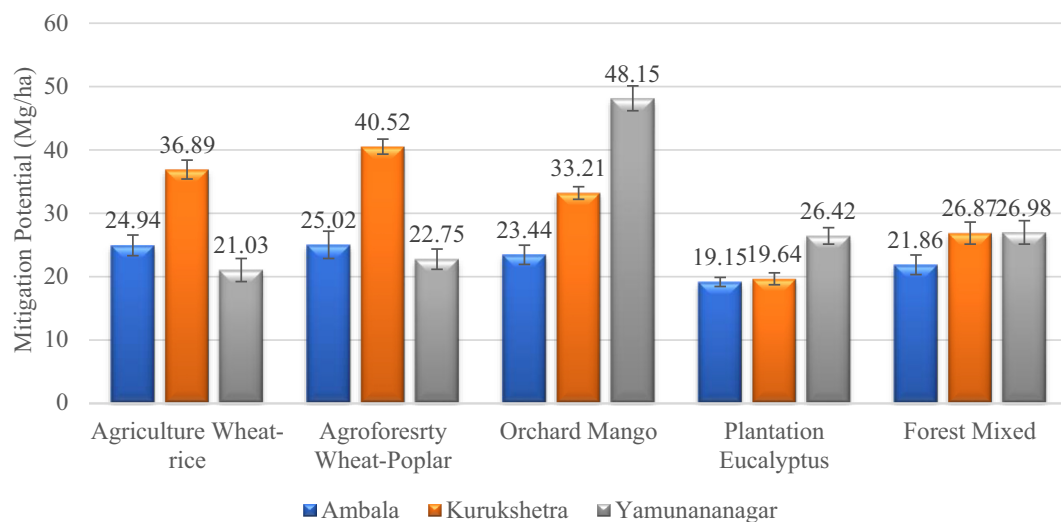


Fig. 5 Mitigation potential of (C-fraction III) Less Labile Pool (LLP) in different land use systems in Indo-Gangetic plains of Haryana 30 cm soil depth

two locations when compared with agriculture showed that a well-managed tree system such as agroforestry is potentially viable as compared to agriculture. This could be attributed to extensive root systems and the organic matter input from leaf litter and root exudates and it is also important to mention, as soil covers a very big portion of land and the slight increase or decrease in carbon from top layer plays a big role in the amount of CO₂ in atmosphere. Forest with mostly kikar plantation along with shrubs showed a stability and evenness in all carbon fraction especially in the less labile pool at all three locations. For Cfrac I both orchard and *Eucalyptus* plantation showed complementary trend but in Cfrac II and Cfrac III orchard took the lead.

The study conducted demonstrated that tree-based systems such as orchards and wheat-poplar system significantly

enhanced soil C-sequestration particularly in very labile and less labile pools, compared to agricultural land use. This highlights the critical role of diverse land use practices, including agroforestry, cover cropping, orchards, in sequestering substantial amounts of carbon within the soil. Particularly, the carbon stabilization in less labile pools contributes to long term carbon storage, thereby enhancing the potential for CO₂ mitigation. These findings are in alignment with previous research Bossio et al. (2020); Poeplau and Don (2013), reinforcing the effectiveness and efficiency of tree-based systems in carbon sequestration. Large-scale land-based carbon sequestration in such systems can also be attributed to intricate interaction or association of microbial activity and root exudates, which are of utmost importance in the process of carbon stabilization. The improvements



in these associations through sustainable land-use practices are increasingly recognized as a significant mitigation option following the Paris agreement-2015 Rumpel et al. (2020); Koushika et al. (2024). The results of the present study also inferred that even small difference in SOC stocks among various land uses can have significant implications for atmospheric CO₂ levels. This underscores the need and importance of proactive soil carbon management in achieving the climate goals at both local and global level. Amelung et al. (2020) also emphasized that even small increases in SOC stocks can impact global climate change mitigation. Jha et al. (2012) studied soil carbon pools, mineralization and fluxes associated with land use change in vertisols of Central India and found that the forest land-use system had the highest mitigation potential followed by horticulture and agriculture. The present study along with the reported studies, collectively affirm that agroforestry, orchards and other tree-based systems are highly effective in enhancing soil carbon sequestration. Their extensive root systems, high organic matter inputs and superiority to stabilize carbon pools make them viable and sustainable strategies for mitigating climate change.

Conclusion

The study concluded that agroforestry and orchard systems showed over all substantial carbon sequestration potential as compared to other land uses. The estimation of the fractions of soil organic carbon helped in getting insights that most of the SOC are build up in (Cfrac I) and (Cfrac II) in all land uses following the order Cfrac I > Cfrac III > Cfrac II. The mitigation potential helped in shedding light on comparing land uses sequestering carbon both region wise and depth wise. The findings of the study revealed that forest and agroforestry systems are comparatively more consistent in sequestering more carbon than conventional agricultural lands. This emphasizes the potential of tree-based systems in enhancing soil carbon storage while providing additional environmental and economic benefits. Even if any system e.g. agriculture and plantation showed less carbon socks it cannot be replaced by the other systems as the area of Indo-Gangetic alluvial plains, Haryana is a region of great importance for food, fuel, fodder etc., and by following healthy farming practices and increasing soil C, not only the productivity will increase but it will also act as carbon sink that will help in mitigating climate change.

Overall, SOC level, whether occurring naturally or managed through land-use practices, exhibit significant variability across different SOC fractions. The study revealed each SOC fraction responded differently to land-use changes, with variations observed across different study sites. These variations are supposed to be influenced by multiple factors

such as the type of plantation, degree of soil disturbance, water supply and availability, fertilizer application, age of stand and overall management practices. Diverse cropping systems generally contributed towards enhanced SOC stocks, offering substantial mitigation potential. This was particularly evident in agroforestry systems with deep rooted species facilitating carbon sequestration; in mango orchards, where large canopy aids in reducing soil erosion and enhancing organic matter accumulation; and in mixed forest where high species diversity and stand density play a crucial role in improving both the above ground and below ground carbon inputs. These systems, no doubt present wide scale opportunities for increasing the SOC stocks, but practical challenges are faces in field implementation. One of the key concerns is to maintain a balance between biomass removal for economic consideration while minimizing the soil disturbance. Further, to increase the potential of agricultural land-use, stubble burning needs to be avoided for preserving microbial communities which are essential for maintaining nutrient cycling and soil health. To ensure that sustainable land-use practices contribute to long term carbon sequestration and climate change mitigation, ecological processes are required to be maintained effectively. This will help in addressing the challenges through integrated soil management strategies to optimize SOC retention, supporting the agricultural productivity and ecosystem resilience simultaneously.

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Data availability All data supporting the findings of this study are available within the paper.

Declarations

Conflict of interest All the authors declare that there is not any type of conflict of interest for the said research work and manuscript.

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