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ORIGINAL ARTICLE

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Soil Carbon Fractions and Management Indexes in Dragon Fruit (*Hylocereus spp.*) Cultivation in the Western Himalaya

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ABSTRACT

Soil organic carbon (SOC) fractions give key insights into soil quality, nutrient cycling, and carbon storage in agriculture and horticulture. However, little research has explored SOC fractionation and carbon dynamics in dragon fruit systems, especially regarding accession differences. This study assesses SOC fractions and carbon management indices among dragon fruit accessions in the northwestern Himalaya to establish a baseline for this emerging crop. Seven accessions—Pink Gujarat (PG), White Gujarat (WG), Yellow Gujarat (YG), Pink Bangalore (PB), White Bangalore (WB), Local Pink Pulp (LPP), and Local White Pulp (LWP)—along with open field conditions (OC) as reference, were evaluated three years after planting. SOC fractions were measured using standard protocols with the modified Walkley-Black method and different acid concentrations. Results showed significant accession-specific variation in SOC fractions ($p<0.05$). Accessions YG, WB, and PB had the highest very labile (3.65-3.84 mg g^{-1}), labile (2.68-2.83 mg g^{-1}), and active carbon pools (6.33-6.67 mg g^{-1}), with 46-86% higher active pools than open field (3.58 mg g^{-1}). PG had the highest non-labile (6.08 ± 0.36 mg g^{-1}) and passive pools (8.66 ± 0.38 mg g^{-1}). CMI ranged from 134.93 to 212.34, with YG highest. Strong correlations between labile fractions and CMI ($r=0.99$) show labile pools drive management index variation. This is the first baseline of SOC fractions in northwestern Himalayan dragon fruit accessions, revealing profiles: YG, WB, PB with higher active carbon, and PG, LWP with more stable carbon. These reflect SOC status three years after planting and serve as references for future monitoring. Long-term studies are needed to see if differences impact sequestration rates and distinguish plant from soil effects. YG, WB, and PB are promising for carbon research.

1 | INTRODUCTION

Globally, soil organic carbon (SOC) is the largest terrestrial carbon pool, vital for soil health and climate regulation by balancing carbon sequestration and greenhouse gases (Kumar *et al.,* 2020; Kaushal *et al.*, 2022). One meter of topsoil stores about 1500 to 2400 Gt of carbon, surpassing vegetation and atmospheric stores (Sanderman *et al.,* 2017). The total carbon pools are approximately 721 Pg for the world (Chen *et al*., 2025), 36 Pg for India (Sreenivas *et al.*, 2016), and 5.4 Pg for the Himalayan region (Tolangay and Moktan, 2020). SOC fractions offer insights into soil resilience, nutrient cycling, and sequestration potential (Pandher *et al.*, 2020; Kumar *et al.*, 2021). Plant species, genotypes, and accessions influence organic matter inputs, affecting carbon pools (Rakesh *et al*., 2021). Soil indices like the Lability Index (LI), Carbon Pool Index (CPI), and Carbon Management Index (CMI) provide systematic assessments of soil quality and carbon dynamics, considering both quantity and quality of SOC. These indices are widely used globally in different ecosystems to evaluate management practices such as agriculture, conservation tillage, and land restoration (Nath *et al.*, 2015; Kumar *et al.*, 2024). LI measures labile SOC related to biological activity; CPI compares SOC stocks across sites; CMI detects management effects on soil quality. These indices promote better soil health and management worldwide (Kumar *et al.,* 2020).

Dragon fruit has shown adaptability to various agro-climatic conditions, including semi-arid and subtropical environments (Sahu *et al*., 2025). Its low water needs, heat tolerance, and suitability for marginal lands make it ideal for regions affected by climate change and resource scarcity (Jinger *et al*., 2024). The fibrous roots and drought resistance make it suitable for fragile Himalayan ecosystems. It can grow on degraded soils, sequester carbon, and improve soil structure, supporting sustainable land use and reducing degradation. Recently, the western Himalayan foothills and mid-hills have become new areas for dragon fruit cultivation due to demand, profitability, and government support. These soils are fragile and low in organic matter, requiring careful selection of accessions to boost productivity and restore soil carbon pools (Wakchaure *et al.*, 2021). Indexes like CPI, LI, and CMI help assess land suitability for sustainable development.

While awareness of dragon fruit's potential in fragile ecosystems grows, research on its effects on soil organic carbon (SOC) fractions and carbon dynamics remains limited (Kakade *et al*., 2020; Satish, 2023). Most studies have focused on yield and management; the impact on SOC fractions—labile, recalcitrant, and intermediate—is not well understood. This study is the first to quantify SOC fractions in northwest Himalaya, linking horticultural practices with soil sustainability. The main goal is to examine SOC fractions and the soil carbon management index across different dragon fruit accessions, hypothesizing (a) that accessions influence SOC dynamics, and (b) that LI and CMI vary among accessions.

2 | MATERIALS AND METHODS

2.1 | Study Site

This experiment was conducted at the CSIR-Institute of Himalayan Bio-resource Technology experimental site in Palampur, Himachal Pradesh. The experimental site falls in the mid-hill range of the northwestern Himalaya. The site is characterized by high rainfall in the monsoon season and moderate temperatures in the winter season. The site is situated at 32°0'05″ N latitude and 76°34'10″ E longitude, at an elevation of 1390 m above mean sea level. The mean annual rainfall in Palampur is 2690 mm. Summer temperatures range from 9.2 °C to 35.4 °C, and winter temperatures range from 3.0 °C to 20.7 °C.

2.2 | Experimental Setup

Seven accessions of dragon fruits of three varieties, viz. pink-skinned with pink flashed, pink-skinned with white flashed, and yellow-skinned with white flashed, were collected from different locations. The three varieties of dragon fruit, viz. pink-skinned with pink pulp, pink-skinned with white pulp, and yellow-skinned with white pulp, were collected from Gujarat, Bangalore, and locally grown on a farmer's field (Kangra, HP). Five accessions were collected from Bangalore and Gujarat, two accessions were grown from the seeds (obtained from farmers' fields), and these fruits were collected from Rajasthan. However, the cuttings of other accessions were collected from Bangalore and Gujarat. The names of the accessions were Pink Gujrat (PG), White Gujrat (WG), Yellow Gujrat (YG), Pink Bangalore (PB), White Bangalore (WB), Local Pink Pulp (LPP), and Local White Pulp (LWP). The experiment was carried out from 2024 to 2025. These accessions were planted in the field in randomized block design (RBD). The plant-to-plant spacing was 1.5m, and the row-to-row spacing was 2.5m (Fig. 1). All the accessions were planted with four replications in the field. Before planting, pits were prepared and filled with a soil–sand–FYM mixture in a 1:1:2 ratio at the time of planting. In addition, 10 kg of FYM was applied annually to each dragon fruit plant. The soil was analyzed before the plantation of dragon fruit to assess the basic soil properties. The results showed a pH of 6.24, SOC of 1.28%, bulk density of 1.05 g cm^{-3} and clay loam texture.

HIGHLIGHTS

- Significant accession-specific variation exists in soil organic carbon fractions among dragon fruit cultivars in the northwestern Himalaya.
- Carbon Management Index effectively discriminates among accessions based on current SOC status, validating its utility as an assessment tool for horticultural systems.
- Accessions YG, WB, and PB show distinct SOC profiles with higher active carbon pools, while PG demonstrates higher passive pools, establishing baseline values for future temporal monitoring studies.

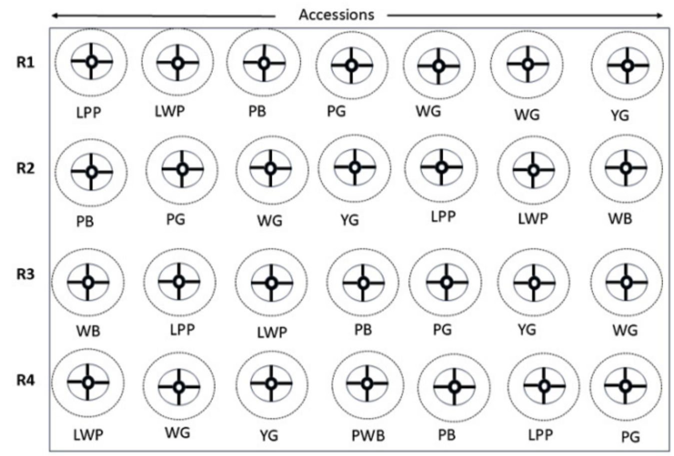

FIGURE 1 Layout of the dragon fruit experiment

2.3 | Soil Sampling

The samples were collected from all accessions of four replications. The soil samples were collected from 0-30 cm soil depth with the help of an auger, as the maximum roots are confined to 30 cm soil depth only in dragon fruit. Four plants were planted around the four directions of a square-shaped concrete pole; soil samples were collected from each direction to cover all four plants, and then all four samples were mixed to obtain a composite sample of about 500 grams. A total of 28 samples were collected from each replication of all seven accessions, and then these four samples were composited to make a single representative sample of one accession in a replication. The experiment was laid out in four replications, so the total number of composite samples was 7 accessions × 4 replications = 28. However, the subsamples were four samples from one pole × 7 accessions × 4 replications = 112. All four plants of an accession were planted around the square-shaped concrete pole (pole in the middle of all four plants), and the distance between one pole and another pole was 1.5 meters. The soil samples were collected within the periphery of each pole to avoid contamination and variability among the samples within the accessions. Additionally, the soil samples were also collected from the open control plot (without dragon fruit), which was adjacent to the dragon fruit plots. Historically, both lands (the dragon fruit plantation site and the open field) had remained barren for approximately 10 years. Prior to this period, some medicinal plants, such as

Curcuma aromatica, were cultivated in the area. Therefore, an adjacent barren field with a similar land-use history was selected as the reference site for soil sampling. The soil samples were air-dried in shade, ground and sieved for the analysis of various C fractions. Open plot existed at the adjoining site also served as the control plot or reference for comparison of dragon fruit accessions for the soil carbon fractions.

2.4 | Analysis For Different Carbon Fractions or Pools In Dragon Fruit Accessions

Five, ten, and twenty milliliters of concentrated sulfuric acid (H_2SO_4) were used in the Modified Walkley and Black Method to determine the various Soil Organic Carbon (SOC) fractions. This corresponds to three acid aqueous solution ratios of 0.5:1, 1:1, and 2:1, which correspond to twelve N, eighteen N, and twenty-four N H_2SO_4 (Chan *et al.*, 2001; Ghosh *et al.*, 2010). The total amount of soil organic C can be divided into four different portions with diminishing oxidizability by oxidizing it with different acid concentrations. According to Chan *et al.,* (2001), the sum of these four fractions represents the total amount of organic carbon found in the soil layer.

SOC can be divided into two groups by separating it into distinct fractions according to their oxidizability: the stable or resistant fraction (Fractions 3 and 4) and the easily oxidizable or labile portion (equivalent to Fractions 1 and 2). For tracking soil quality and determining the soil's potential to store carbon, SOC fractions with varying stability are useful indicators (Blair *et al*., 1995; Chan *et al*., 2001; Baretto *et al*., 2011). While the stable fractions (Fractions 3 and 4) are least affected by management techniques and show only slight variation, the readily oxidizable or labile fractions (Fractions 1 and 2) are more responsive to management practices and exhibit significant variability across treatments. Thus, studying these four fractions in any ecosystem would reasonably indicate the ecosystem's capacity to store and sequester C in soil and its long-term sustainability.

The oxidizability of soil carbon is linked to the active carbon pool (ACP) and the passive carbon pool (PCP), which are computed from four distinct fractions. As the name implies, the passive C pool is the stable, resistant, and less reactive pool that is more difficult to oxidize and extract (Fractions 3 and 4). In contrast, the ACP is the sum of Fractions 1 and 2, which are the easily oxidizable, labile, and active parts. The distribution of carbon between the active and passive pools directly affects the physical, chemical, and biological characteristics of soil and influences the retention of carbon in the atmosphere (Bayer *et al*., 2004). Following standard procedure, the Lability Index (LI), Carbon Pool Index (CPI), and Carbon Management Index (CMI) were computed (Blair *et al*.,1995). The LI and CPI are important parameters for the derivation of CMI. While CPI, as an independent indicator, is not frequently utilized in SOC research, the Lability indicator primarily sheds light on the type or oxidisability of the SOC fractions. According to Sainepo *et al.* (2018), the CMI is commonly recognized as a measure of soil deterioration or improvement in response to changes in land use. It efficiently tracks short-term changes in soil C pools and accounts for both the quantity and quality of SOC (Blair et al., 1995; Benbi *et al*., 2008).

2.5 | Statistical Analysis

The data were checked for adherence to key statistical assumptions prior to the performing ANOVA. The normality of data was tested using Shapiro-wilk test, while homogeneity to variances (homoscedasticity) among the treatments was assessed using levene's test. The different accessions of dragon fruit for carbon fractions and pools, carbon pool index, lability index and carbon management index were compared using analysis of variance (ANOVA). The means comparison in posthoc analysis were performed using Tukey's Honest Significant Difference (HSD) test at a significance level ($p \geq 0.05$) for randomised block design (RBD). Correlation analysis between the different soil C fractions, LI and CMI was also carried out using Pearson's correlation coefficient method. The data for all parameters were analysed using R statistical software (version 4.5.1).

3 | RESULTS AND DISCUSSION

3.1 | Labile Carbon Fractions

The different carbon fractions showed significant variation ($p<0.05$) among all accessions of dragon fruit in the northwestern Himalaya. Significantly ($p<0.05$) higher very labile carbon (Fig. 2) was observed in YG (3.84±0.19 mg g^{-1}) accession, which was statistically at par with WB (3.79±0.23 mg g^{-1}) and PB (3.65±0.22 mg g^{-1}) accessions. Other accessions followed the trend: PG (3.28±0.18 mg g^{-1}) > LWP (2.94±0.15 mg g^{-1}) > LPP (2.76±0.13 mg g^{-1}) > WG (2.60±0.15 mg g^{-1}). Significantly ($p<0.05$) lower very labile carbon was recorded in OC (2.43±0.11 mg g^{-1}) compared to other accessions.

Accession YG (2.83±0.15 mg g^{-1}) also had significantly ($p<0.05$) higher labile carbon (*Fig. 2*), which was statistically at par with WB (2.74±0.16 mg g^{-1}) and PB (2.68±0.13 mg g^{-1}). After PB, higher labile carbon was recorded in PG (2.42±0.11 mg g^{-1}), followed by LWP (2.02±0.12 mg g^{-1}), LPP (1.86±0.11 mg g^{-1}), and WG (1.62±0.08 mg g^{-1}). The minimum labile carbon was recorded in OC (1.15±0.06 mg g^{-1}) when compared to all other accessions.

The active carbon pool (sum of very labile and labile carbon) showed significant variation among accessions ($p<0.05$). Accession YG (6.67±0.39 mg g^{-1}) showed the highest active pool (Table 1 and Fig. 2), which was statistically at par with WB (6.53±0.29 mg g^{-1}). Other accessions followed the pattern: PB (6.33±0.38 mg g^{-1}), PG (5.70±0.34 mg g^{-1}), LWP (4.96±0.24 mg g^{-1}), LPP (4.62±0.24 mg g^{-1}), and WG (4.22±0.21 mg g^{-1}). OC (3.58±0.17 mg g^{-1}) had the lowest active carbon pool among all treatments.

The present study reveals significant accession-specific variation in soil organic carbon fractions among seven dragon fruit accessions in three-year-old plantations in the northwestern Himalaya. All dragon fruit accessions exhibited higher SOC fractions compared to adjacent open field conditions (OC) with similar land-use history, with differences ranging from 18% to 86% depending on the fraction and accession.

The observed SOC fractions under different dragon fruit accessions fall within or near the agronomically expected ranges reported for subtropical orchard and other perennial systems (Kumar et al., 2020; Kaushal *et al*., 2022). The very labile and labile C fractions (2.4–3.8 mg g^{-1} and 1.1–2.8 mg g^{-1}, respectively) are comparable to values reported in tropical fruit-based systems such as mango orchards in eastern India (Ankit *et al.*, 2024) and subtropical orchard systems (Kumar *et al*., 2020).

Accessions YG, WB, and PB demonstrated 46-86% higher active carbon pools (6.33-6.67 mg g^{-1}) compared to open field conditions (3.58 mg g^{-1}). These differences suggest that these accessions are currently associated with soils having higher proportions of readily decomposable carbon sources, which are critical for maintaining short term soil fertility (Sahu *et al.*, 2025). The very labile and labile fractions represent portions of organic matter that are most readily available for microbial decomposition and nutrient cycling, with rapid turnover rates that support a continuous nutrient supply (Kumar *et al.*, 2020).

The observed accession-specific differences in labile pools could be attributed to variations in litter quality, root exudates, and biomass turnover patterns characteristic of different genotypes (Kaushal *et al*., 2022). However, without measurements of root systems, litter composition, or decomposition rates, the specific mechanisms driving these differences cannot be definitively established from the current dataset.

TABLE 1 Soil organic carbon pools (mg g^{-1}) and carbon management indices (Mean±SE) under different dragon fruit accessions.

Accessions	Active pool	Passive pool	Carbon pool index	Lability index	Carbon management index
OC	3.58±0.17^{g}	5.88±0.34^{d}	1.00±0.05^{d}	1.15±0.07^{b}	114.73±5.16^{g}
LPP	4.62±0.24^{e}	6.99±0.34^{c}	1.23±0.06^{c}	1.20±0.07^{b}	147.67±7.24^{e}
LWP	4.96±0.24^{d}	7.86±0.46^{b}	1.35±0.07^{b}	1.18±0.05^{b}	159.55±8.30^{d}
PG	5.70±0.34^{c}	8.66±0.39^{a}	1.52±0.09^{a}	1.20±0.06^{b}	182.42±10.98^{c}
WG	4.22±0.21^{f}	7.12±0.35^{c}	1.20±0.06^{c}	1.13±0.06^{b}	134.93±6.07^{f}
YG	6.67±0.39^{a}	7.81±0.41^{b}	1.53±0.09^{a}	1.39±0.07^{a}	212.34±10.19^{a}
PB	6.33±0.38^{b}	7.86±0.47^{b}	1.50±0.07^{a}	1.35±0.06^{a}	202.75±12.21^{b}
WB	6.53±0.29^{ab}	8.11±0.39^{d}	1.55±0.09^{a}	1.34±0.06^{a}	207.85±9.35^{ab}
p-value	0.001	0.001	0.005	0.62	0.0001

Different letters indicate significant differences ($P < 0.05$). Data with the same letters in the superscript do not differ significantly.

3.2 | Non-labile Carbon Fractions

Significantly ($p \leq 0.05$) higher less labile carbon (Fig. 3) was recorded in YG (2.91±0.18 mg g^{-1}), which was statistically at par with PB (2.88±0.13 mg g^{-1}) and WB (2.82±0.15 mg g^{-1}). Other accessions followed the trend: PG (2.58±0.13 mg g^{-1}) > LWP (2.24±0.11 mg g^{-1}) > LPP (1.97±0.09 mg g^{-1}) > WG (1.74±0.10 mg g^{-1}). OC (1.26±0.08 mg g^{-1}) had the least labile carbon compared to other accessions.

Non-labile carbon (Fig. 3) ranged from 4.62 to 6.08 mg g^{-1}, with significantly (p WG (5.38±0.24 mg g^{-1}) > WB (5.29±0.29 mg g^{-1}) > LPP (5.02±0.29 mg g^{-1}) > PB (4.98±0.26 mg g^{-1}) > YG (4.90±0.24 mg g^{-1}). OC (4.62±0.25 mg g^{-1}) showed the lowest non-labile carbon when compared to all other accessions. Non-labile carbon (Fig. 3) ranged from 4.62 to 6.08 mg g^{-1}, with significantly (p WG (5.38±0.24 mg g^{-1}) > WB (5.29±0.29 mg g^{-1}) > LPP (5.02±0.29 mg g^{-1}) > PB (4.98±0.26 mg g^{-1}) > YG (4.90±0.24 mg g^{-1}). OC (4.62±0.25 mg g^{-1}) showed the lowest non-labile carbon when compared to all other accessions.

The passive pool (sum of less labile and non-labile carbon) showed significant ($p \leq 0.05$) variation (Table 1 and Fig. 3), with the highest value in accession PG (8.66±0.39 mg g^{-1}), followed by WB (8.11±0.39 mg g^{-1}), PB (7.86±0.47 mg g^{-1}), LWP (7.86±0.46 mg g^{-1}), YG (7.81±0.41 mg g^{-1}), and LPP (6.99±0.34 mg g^{-1}). The minimum passive carbon pool was recorded in OC (5.88±0.05 mg g^{-1}) when compared to all other accessions.

Significant variation was also observed in non-labile carbon fractions among dragon fruit accessions, revealing distinct carbon quality profiles. The non-labile carbon pool (4.6–6.1 mg g^{-1}) falls within ranges reported for stabilized organic matter in long-term fruit orchard soils in India and Southeast Asia (Bhattacharyya et al., 2019; Zhou et al., 2022).

Accession PG showed 3% higher stable carbon pools (8.66 mg g^{-1}) compared to the next highest accessions, while maintaining relatively lower active pools. This contrasts with the YG, WB, and PB accessions, which exhibited higher active: passive ratios. These distinct profiles suggest accession-specific differences in carbon partitioning patterns: YG/WB/PB show profiles that favor active carbon pools (potentially supporting short-term nutrient cycling), while PG and LWP show profiles with higher stable carbon accumulation (potentially favoring long-term carbon retention) (Kaushal *et al.*, 2022).

The estimated contribution of active and passive pools to total SOC in this study—with active fractions comprising approximately 35-45% and passive fractions 55 65%—follows typical distributions reported for perennial orchard soils (Wakchaure *et al*., 2021; Meena *et al*., 2020). Similar partitioning patterns have been documented in perennial and agroforestry systems, indicating that both pools play important roles in soil fertility and carbon storage potential (Meena *et al.*, 2020). However, it is important to note that these spatial differences reflect the current soil organic carbon (SOC) status of the existing plantation, rather than the actual carbon accumulation rates over time. Without pre-planting baseline measurements or temporal monitoring, we cannot distinguish whether these differences reflect plant-driven carbon inputs or pre-existing soil heterogeneity, even though uniform land-use history suggests minimal initial variation.

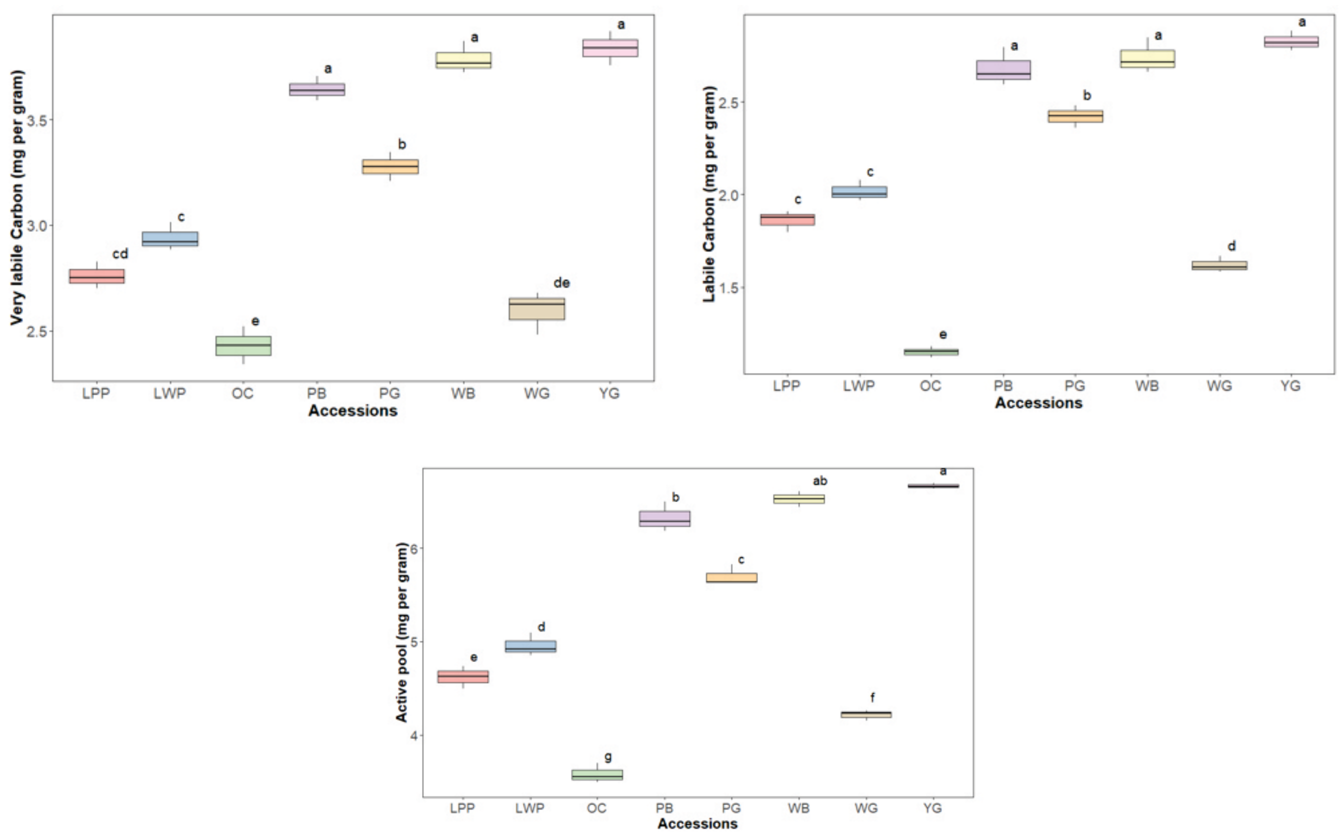

FIGURE 2 Active carbon pools (mg g^{-1}) under different accessories of dragon fruit (mean±se).

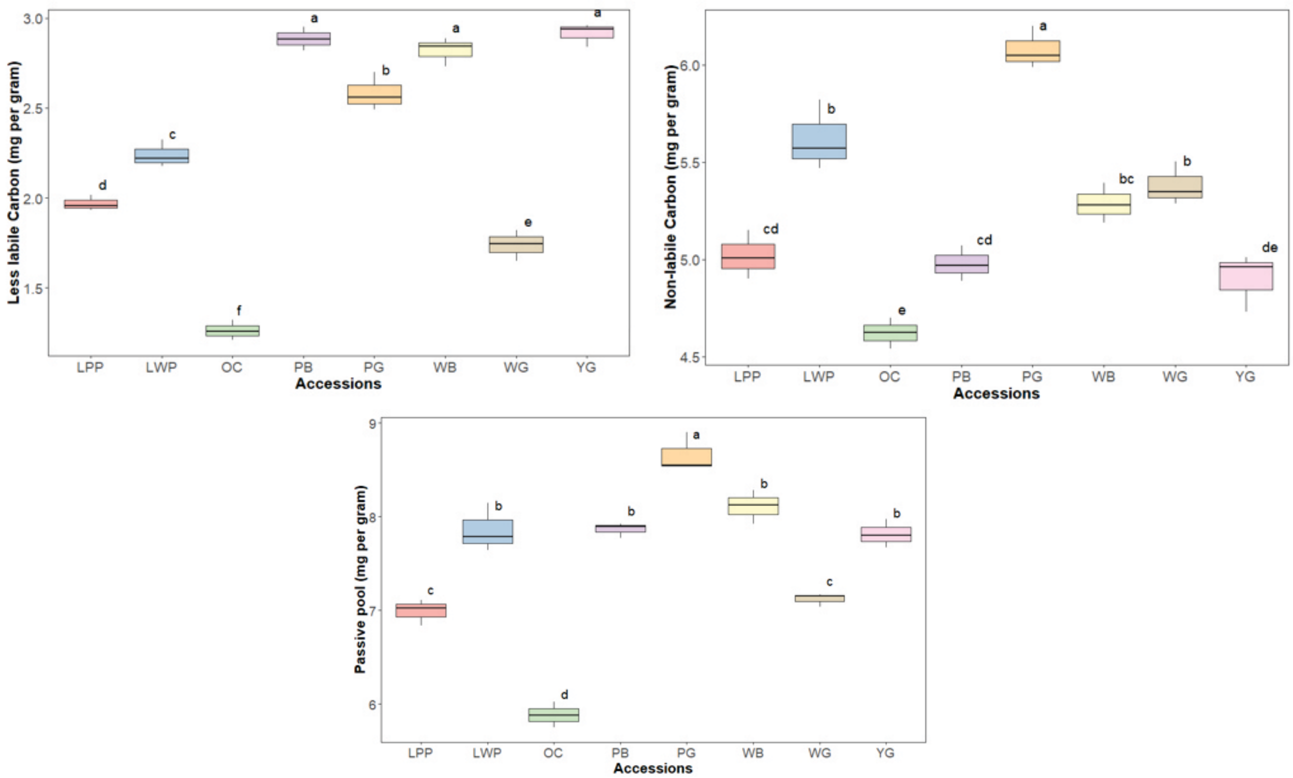

FIGURE 3 Passive carbon pools (mg g^{-1}) under different accessions of dragon fruit (mean±se)

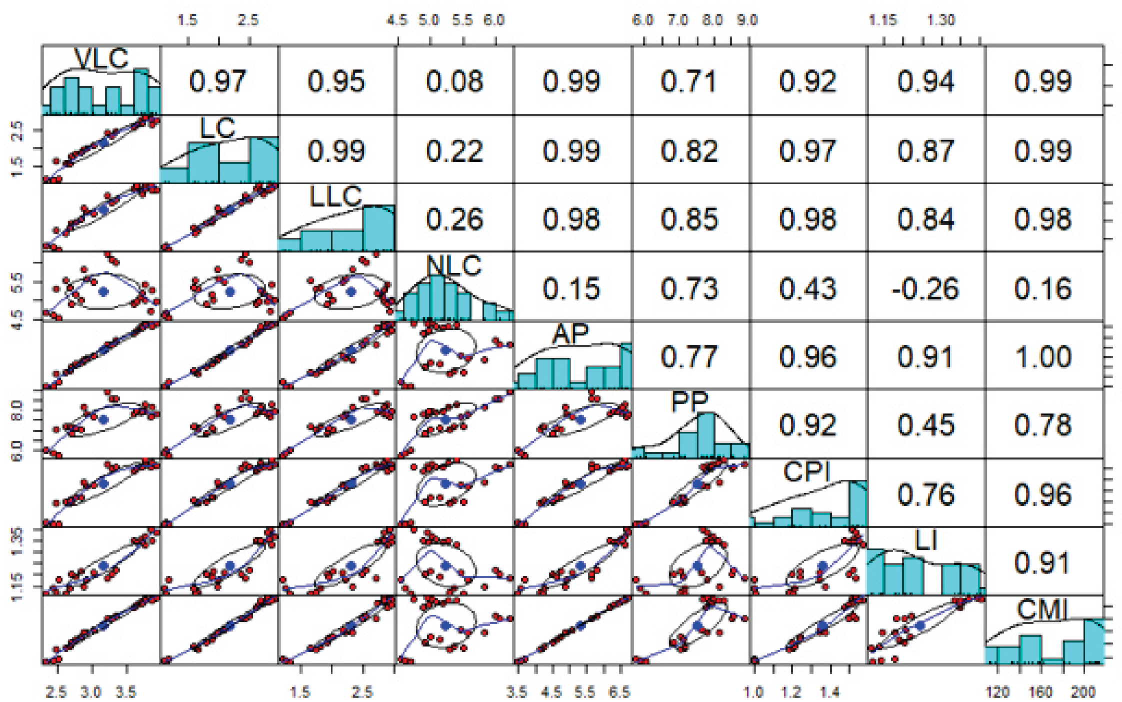

FIGURE 4 Correlation between SOC fractions, lability index, carbon pool index and carbon management index under different accessions of dragon fruit

3.3 | Lability, Carbon Pool and Management Index

The lability index (LI) did not differ significantly (p=0.62) among all accessions; however, higher LI (Table 1) was recorded in YG (1.53±0.07), followed by PB (1.35±0.06), WB (1.34±0.06), PG (1.20±0.06), LPP (1.20±0.07), LWP (1.18±0.07), and OC (1.15±0.07). The minimum lability index was recorded in WG (1.13±0.06) when compared to all other accessions.

Different dragon fruit accessions significantly influenced the carbon pool index (CPI) (Table 1). A significantly (p≤0.05) higher CPI was calculated for accession WB (1.55±0.09), which was statistically comparable to YG (1.53±0.09), PG (1.52±0.09), and PB (1.50±0.07). After PB, CPI was recorded in LWP (1.35±0.07), followed by LPP (1.23±0.06) and WG (1.20±0.06). The minimum CPI was recorded in OC (1.00±0.05) when compared to all other accessions.

Carbon management index (CMI) varied significantly (p≤0.05) among all dragon fruit accessions. Significantly higher CMI (Table 1) was observed in YG (212.75±10.19) accession, which was statistically at par with WB (207.85±10.98). Other accessions followed the trend: PB (202.75±12.21) > PG (182.42±10.98) > LWP (159.55±8.30) > LPP (147.67±7.24) > WG (134.93±6.07). A significantly lower CMI was recorded in OC (114.73±5.16) compared to other accessions.

The carbon management indices (LI, CPI, and CMI) proved sensitive to accession-specific differences in SOC status, validating their utility as discriminatory tools for assessing soil carbon quality in horticultural systems of this region (Kumar *et al*., 2024). CMI values ranged from 135 to 212 among dragon fruit accessions, with YG demonstrating the highest value (212.34±10.19), representing an 85% higher CMI compared to open-field conditions.

The strong positive correlation between labile carbon fractions and CMI (r = 0.99) demonstrates that labile pools are the primary drivers of variation in these management indices under dragon fruit systems (Jinger *et al*., 2024). This finding aligns with research on agroforestry and horticultural systems, in which labile fractions have been identified as sensitive indicators of soil quality differences (Sahu, 2025). The carbon pool index (CPI), which normalizes soil carbon pools relative to a reference condition, proved particularly useful for comparing accession performance. Accessions WB, YG, PG, and PB showed statistically similar CPI values (1.50-1.55), indicating comparable total carbon pool sizes relative to the baseline despite differences in carbon quality distribution.

In contrast, non-labile carbon showed weak or no correlation with CPI, LI, and CMI, underscoring the limited sensitivity of stable SOC pools for detecting differences in current carbon status. While non-labile carbon is important for long-term storage capacity, its weak association with management indices confirms that it cannot serve as a reliable indicator for discriminating among treatments at this temporal scale (Prasad *et al*., 2016). The lability index (LI) did not differ significantly (p=0.62) among accessions, suggesting that while absolute quantities of labile fractions varied, the relative proportions of oxidizable fractions remained similar. This indicates that accession effects primarily influenced carbon pool sizes rather than fundamental carbon quality characteristics.

3.4 | Relationship Between Carbon Fractions With CPI, LI, and CMI

Correlation analysis was performed to establish relationships (Fig. 4) between different carbon fractions, carbon pool index, lability index, and carbon management index. The very labile carbon pool showed a strong positive correlation with labile carbon (0.97), less labile carbon (0.95), AP (0.99), PP (0.71), CPI (0.92), LI (0.94), and CMI (0.99), but was weakly correlated with non-labile carbon (0.08).

Labile carbon showed strong positive correlation with less labile carbon, AP (0.99), PP (0.82), CPI (0.97), LI (0.87), and CMI (0.99). Less labile carbon had strong positive correlation with AP (0.98), PP (0.85), CPI (0.98), LI (0.84), and CMI (0.98). Non-labile carbon did not show strong relationships with AP (0.15), CPI (0.43), LI (-0.26), or CMI (0.16).

Active carbon pool was strongly correlated with PP (0.77), CPI (0.96), LI (0.91), and CMI (0.99). Passive carbon pool had strong relationships with CPI (0.92) and CMI (0.78). Carbon pool index showed positive relationships with LI (0.76) and CMI (0.96). Lability index had a strong relationship with carbon management index (0.91).

The distinct SOC profiles observed among accessions provide valuable information for accession selection based on management objectives. Accessions YG, WB, and PB, with their higher active carbon pools and CMI values, appear to maintain greater proportions of readily available carbon, potentially supporting enhanced short-term soil fertility and nutrient cycling processes (Kumar *et al*., 2020).

These characteristics may be advantageous in systems prioritizing rapid nutrient turnover and biological activity. Conversely, accessions PG and LWP, which demonstrated higher passive: active ratios, may offer advantages for systems prioritizing stable carbon retention. The higher non-labile pools in these accessions suggest potential for maintaining carbon in more recalcitrant forms, though whether this translates to enhanced long-term sequestration would require temporal validation (Dheri & Nazir, 2021).

It is crucial to emphasize that these observations represent baseline characterization at a single time point and spatial comparisons with adjacent land. They do not demonstrate temporal carbon accumulation or sequestration rates. Future temporal monitoring with repeated measurements is essential to: (1) validate whether observed accession-specific differences persist over time, (2) quantify actual carbon sequestration rates under different accessions, (3) distinguish plant driven carbon inputs from soil processes, and (4) establish whether initial differences in active pools translate into differential stable carbon accumulation over longer time scales.

The establishment of these baseline values, however, provides an important foundation for future research. This study represents the first quantification of SOC fractions among dragon fruit accessions in the northwestern Himalaya, establishing reference values for the region and identifying promising candidates (particularly YG, WB, and PB) for evaluation in long-term carbon dynamics studies (Kumar *et al.,* 2024).

4 | CONCLUSIONS

This study reveals significant accession-specific variation in soil organic carbon fractions in the northwestern Himalaya.. Accessions YG, WB, and PB exhibited 46-86% higher active carbon pools compared to adjacent barren land with similar land-use history, while PG showed 3% higher stable carbon pools. Carbon Management Index values ranged from 135 to 212, with YG demonstrating the highest value.

These distinct SOC profiles suggest that accession selection influences current soil carbon distribution patterns, with YG/WB/PB maintaining higher proportions of readily available carbon pools (potentially supporting short-term nutrient cycling) and PG/LWP showing higher stable carbon retention (potentially favoring long-term storage). However, these spatial differences represent current SOC status rather than demonstrated carbon sequestration rates.

Carbon Management Index and Carbon Pool Index proved sensitive to accession-specific differences, validating their utility as discriminatory tools for horticultural system assessment in this region. The strong correlation between labile fractions and CMI (r = 0.99) confirms that labile pools are the primary drivers of variation in management indices.

The observed patterns establish baseline values for future temporal monitoring, which is essential to: (1) validate whether accession-specific differences translate into differential carbon sequestration over time, (2) distinguish plant-driven effects from pre-existing soil heterogeneity, and (3) quantify actual sequestration rates. This study provides the first regional assessment of SOC fractions in dragon fruit systems and identifies YG, WB, and PB as promising candidates for evaluation in long-term carbon dynamics trials.

From a practical perspective, accessions YG, WB, and PB are recommended as candidates for systems prioritizing short-term soil fertility and active carbon cycling, while PG and LWP may be suitable for evaluation in systems emphasizing stable carbon retention. However, definitive recommendations for carbon sequestration or long-term soil carbon management await validation through multi-year temporal monitoring studies that quantify actual carbon accumulation rates and elucidate underlying mechanisms.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

DATA AVAILABILITY STATEMENT

The authors confirm that the data supporting the results of this study is available within the manuscript.

AUTHOR'S CONTRIBUTION

AK: Conceptualization, Data curation, writing original draft, SSS: Reviewing and Editing, Formal data Analysis. SKY: Supervision, Visualization and Investigation.

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