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Article

Carbon Storage in Tropical Laterites: Insights into Mineralogical Controls and Sequestration Potential

P. Deepthi, G. K. Indu*, Arunima M. Lal, Arun J. John, A. A. Ardra Krishna and Sneha Biju

Department of Geology, University College, Thiruvananthapuram 695034, India

*Correspondence: indugk@universitycollege.ac.in

ABSTRACT

Lateritic soils are widespread in the tropics but their role in carbon storage has not been well studied. This study reports petrographic, grain-size distribution, XRD, XRF, and total organic carbon (TOC) analyses of selected laterite samples from four representative profiles in Kerala, India, to assess their carbon sequestration potential. Our results show that carbon stocks in these laterites are between 10.4 and 457.6 t ha^{-1}, which is equivalent to 38.17 and 1679.39 t CO_2 equivalent ha^{-1}, with the highest values occurring in the Vilangara profile.The data reveal that iron- and aluminium-rich minerals such as goethite, gibbsite, and kaolinite play a central role in stabilising organic carbon through mineral-organic associations, enabling long-term carbon retention even under intense tropical weathering. Given their extensive distribution and demonstrated capacity for carbon storage, lateritic soils should be recognised as significant components of the global carbon cycle and integrated into future carbon accounting and climate mitigation strategies.

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Research Highlights

- Tropical laterites represent a significant terrestrial carbon sink.
- Mineralogy, profile thickness, and weathering intensity collectively control carbon sequestration.
- Fe–Al oxide-rich laterites exhibit enhanced carbon sequestration potential.

1. Introduction

Carbon sequestration is essential in combating global climate change by capturing atmospheric CO_2 and storing it in soils and plant biomass over the long term. Photosynthesis transforms atmospheric CO_2 into complex organic molecules, removing it from the active atmospheric cycle [1]. The terrestrial soil system holds about 2500 petagrams of carbon, which is over three times the carbon present in the atmosphere or in living biomass [2]. This soil carbon reservoir includes inorganic carbon (IC), formed by weathering of parent material and carbonate formation, and organic carbon (OC). Organic carbon accounts for approximately 60% of total soil organic matter, with the remainder comprising non-carbon elements such as hydrogen, oxygen, nitrogen, phosphorus, sulphur, potassium, calcium, and magnesium [3]. Proper management of soil carbon via carbon capture and storage (CCS) strategies is crucial for reducing greenhouse gas emissions, especially given the substantial rise in atmospheric emissions during the past century and their continued increase worldwide [4, 5].

The ability of terrestrial reservoirs to capture and store organic matter depends on the interplay of geological, environmental, and biological factors. Key geological influences include soil mineralogy, grain size, and overall geochemistry, which set the basic chemical and physical boundaries of the underground environment [6]. In highly weathered systems, a protective geological structure enables reactive iron and aluminium oxyhydroxides to chemically bind organic molecules [6], while fine-grained particles enhance physical protection by increasing surface area [7]. When combined with environmental factors such as climate, plant biomass input, and microbial activity, these geological factors ultimately determine whether terrestrial carbon is rapidly released into the atmosphere or sequestered in stable, long-term organo-mineral sinks (see Figure 1) [8].

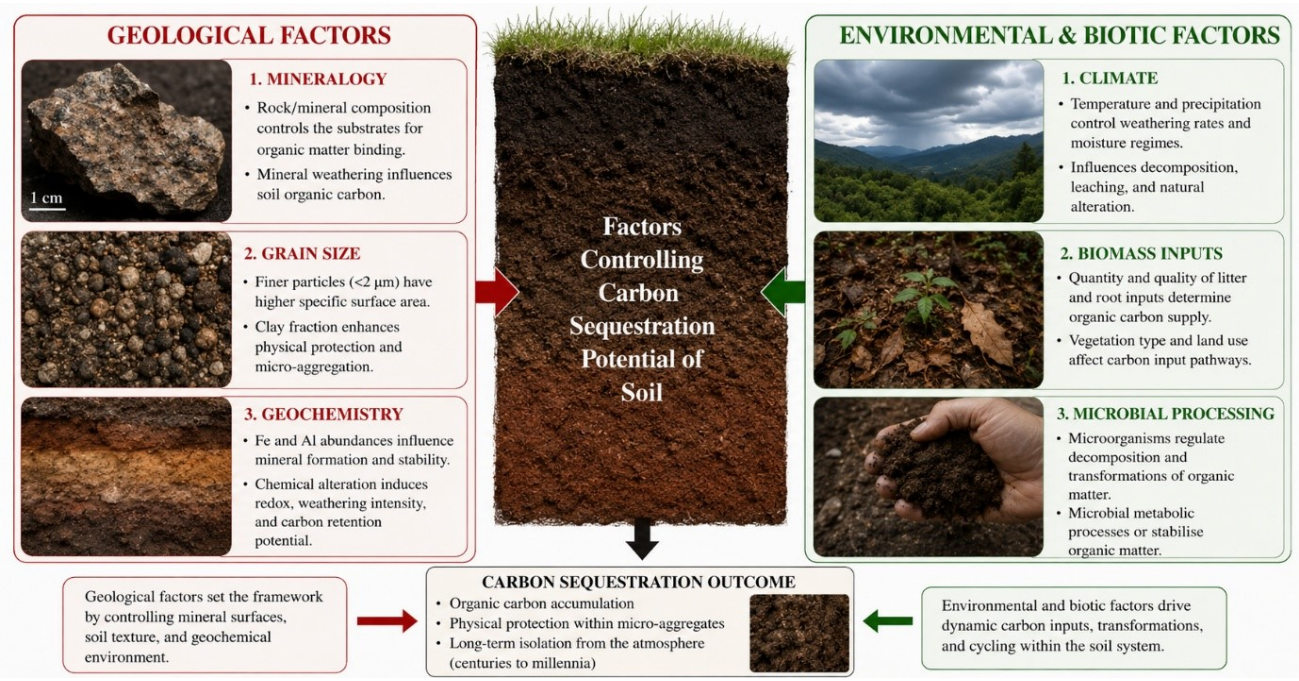

Figure 1. Schematic representation of geological, environmental and biotic factors controlling carbon sequestration potential of soil.

Globally, highly weathered lateritic terrains in tropical and subtropical regions represent a crucial yet understudied area for terrestrial carbon storage. Much of peninsular India lies within the hot tropical zone, where intense weathering forms extensive residual laterites [9–12]. Soil carbon sequestration in these sub-humid and semi-arid tropical areas offers two main benefits: reducing atmospheric carbon levels and restoring soil fertility in heavily degraded or nutrient-poor soils [1]. While labile organic carbon can be quickly decomposed by microbes, stable mineral-associated carbon can remain sequestered for centuries or even millennia [4]. These weathered soils contain minerals like goethite, hematite, and gibbsite, which have surface charges that allow them to trap and stabilise organic compounds through electrostatic attraction and covalent bonds [5, 6, 13]. Studies on India's western coast show that, despite high temperatures and rainfall promoting rapid carbon cycling, baseline organic carbon typically stabilises between 0.5% and 1.5%, thanks to mineral protection [6, 7]. Still, detailed data on the carbon storage potential and stabilisation processes of these lateritic soils are limited.

This study aims to evaluate the carbon sequestration potential of lateritic profiles over Tertiary and Precambrian terranes in India's Southern Granulite Terrain. The research involves determining particle size distributions, quantifying absolute carbon concentrations, and analysing mineralogical and geochemical features of weathered profiles. These analyses will be integrated to assess how mineral phases, grain size, and other factors influence long-term carbon storage.

2. Regional Geological Framework and Study Area

The Southern Granulite Terrain (SGT) in India is a heavily eroded, multi-phase crustal block primarily composed of high-grade metamorphic rocks dating from the late Archean to Neoproterozoic eras. It includes charnockites, khondalites, and migmatitic gneisses, intersected by major crustal shear zones such as the Palghat–Cauvery and Achankovil systems (see Figure 2) [14–16]. These features reflect ancient continental collisions associated with Gondwana's formation, while later Mesozoic mafic dykes and alkaline intrusions point to post-collision extension and continent fragmentation [15]. On its western boundary, this crystalline basement is overlain by Tertiary sedimentary layers deposited in down-faulted basins during Gondwanaland's breakup [2]. Kerala, as a southern extension of the SGT, has over 90% of its land composed of Precambrian crystalline rocks. The narrow coastal zone contains Mio-Pliocene Warkalli and Quilon Formations, heavily covered by lateritic profiles from long exposure to humid-tropical weathering. Intense leaching has altered the chemistry significantly, indicated by high CIA and WIP values, depletion of mobile elements like Ca, Mg, Na, K, and Si, and residual accumulation of Fe and Al sesquioxides. Consequently, minerals such as kaolinite, goethite, hematite, and, locally, gibbsite dominate, forming reactive surfaces that stabilise soil organic carbon through organo-mineral associations [8, 12, 17].

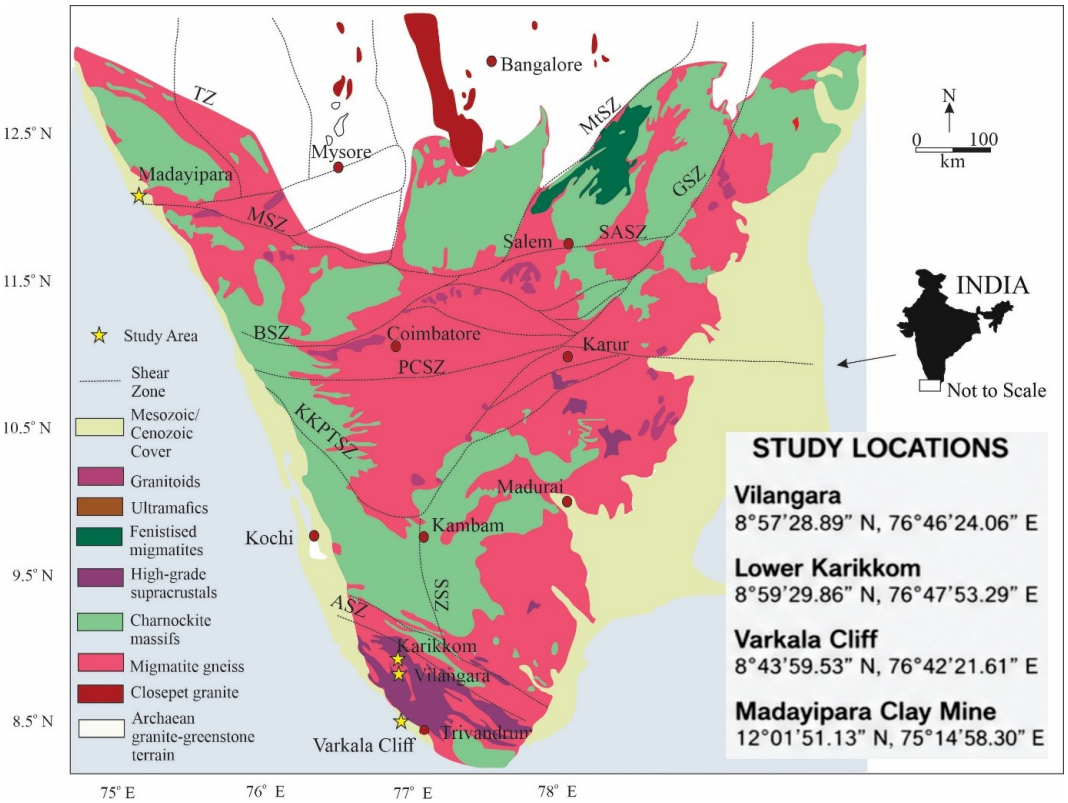

Figure 2. Geological map of SGT (modified after Kumar et al. [18]) showing the sampling locations.

This study examines four key lateritic locations in Kollam, Thiruvananthapuram, and Kannur districts to capture differences in parent lithology, stratigraphy, and weathering conditions. Location 1 (Vilangara, Kollam) and Location 2 (Lower Karikkom, Kollam) are in the crystalline midland terrain formed over Precambrian crystalline rocks. Location 3 (Varkala Cliff, Thiruvananthapuram) is the type area of the Mio-Pliocene Warkalli Formation, featuring sandstones, variegated clays, and lignite-rich carbonaceous clays capped by mature laterites [12]. Location 4 (Madayipara Clay Mine, Kannur) lies on the Tertiary Cheruvathur Formation, similar to the Warkalli beds, mainly comprising silty laterites rich in kaolinite, with lesser goethite and gibbsite [17]. These sites collectively represent the development of laterite across different geological settings in Kerala, making them ideal for this research. The Tertiary laterites have developed over ferruginous detrital sandstones, whereas the Precambrian laterites have formed over crystalline metamorphic rocks, mainly garnet-biotite gneiss (GBG). These contrasting geological setting contributed to the mineralogical and geochemical characteristics of the laterites. Laterite profiles over crystalline rocks are dense, with a moderately hardened ferruginous crust at the surface. The dark brown upper layer gradually grades into softer, pink to buff-coloured laterite with depth. In laterites formed on pyroxene granulites, meta-ultramafic rocks, and gneisses, the preservation of relict foliation parallel to the bedrock suggests an *in situ* residual origin. Laterites on Tertiary sedimentary rocks feature a thick, strongly indurated ferricrete cap, usually 2–5 m thick, which grades into soft laterite containing relict gritstone fragments and ultimately into a variegated clay horizon, indicating a mature residual weathering profile developed over detrital sedimentary rocks [19]. Figure 3 displays photos from each sampling location.

Figure 3. Different sampling locations (**a**) Vilangara, (**b**) Karikkom (laterites developed over Precambrian rocks) (**c**) Varkala and (**d**) Madayipara (laterites developed over Tertiary sediments).

3. Methodology

A total of 21 laterite samples were collected from four lateritic terrains in Kerala, India, namely Vilangara, Karikkom, Varkala, and Madayipara, selected to encompass variations in parent lithology and geomorphological setting. Representative lateritic samples were examined using 30 µm-thick thin sections on a Leica polarising microscope at the Department of Geology, University College, Thiruvananthapuram, to identify mineralogical constituents and textural features relevant to weathering processes. Grain-size distribution was determined using ASTM standard sieves after sample preparation involving carbonate removal with 10% HCl, washing with distilled water, and oven drying at 70 °C. Dry sieving was performed using a mechanical Ro-Tap sieve shaker, and grain-size parameters were calculated following Folk and Ward [20]. These analyses were conducted at the Department of Geology, University College, Thiruvananthapuram.

Mineralogical analysis was performed using XRD on powdered samples with a Rigaku MiniFlex diffractometer (SAIF, University College, Thiruvananthapuram) to identify mineral phases, with results compared to the RRUFF database. Major-element compositions were measured by XRF analysis of pressed powder pellets to assess elemental abundances, especially Fe and Al, at NCESS, Thiruvananthapuram. Total Organic Carbon (TOC) content was determined at the Central Soil Analytical Laboratory, Thiruvananthapuram, employing the Walkley–Black wet oxidation method, a standard procedure for estimating organic carbon in soils and sediments [21]. The TOC data were integrated with mineralogical, textural, and geochemical parameters to understand the factors influencing carbon sequestration in tropical lateritic systems.

4. Results

4.1. Petrographic Composition and Textural Evolution of Laterite

Petrographic features and grain-size distribution offer valuable insights into weathering intensity and the processes behind laterite formation. Figure 4 displays photomicrographs of the studied laterite samples under crossed polars. Petrographic analysis shows a framework mainly composed of quartz grains within a ferruginous-aluminous matrix (Figure 4a–c). These quartz grains are mostly subangular to subrounded and vary in size, while the reddish-brown Fe–Al-rich matrix acts as the main cementing agent, filling the intergranular spaces. The dense, interconnected ferruginous fabric, along with abundant iron-rich coatings and aggregates, indicates advanced lateritization with extensive leaching of silica and mobile elements, leading to residual iron and aluminium enrichment. The gradual development of Fe–Al-rich zones around relic quartz grains signifies intense chemical weathering and parent material transformation. These microstructures are typical of mature tropical laterites, characterised by secondary minerals such as hematite, goethite, kaolinite, and gibbsite [22]. The close association between quartz grains and the ferruginous matrix suggests that iron and aluminium oxides play a key role in maintaining the stability of the lateritic framework.

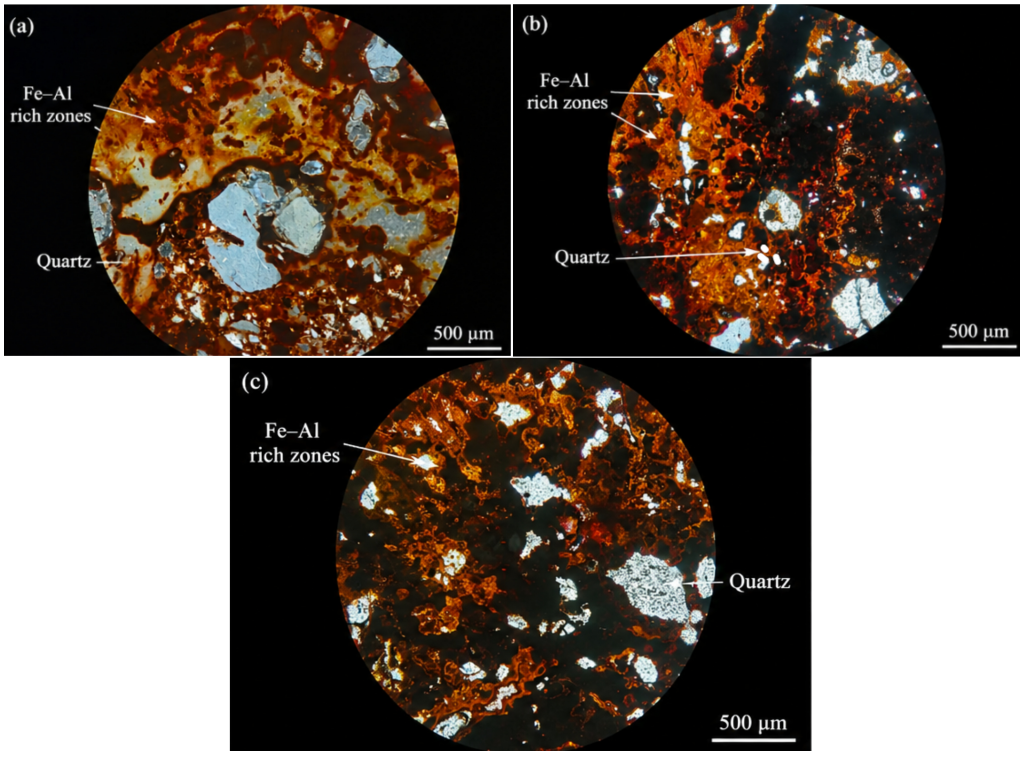

Figure 4. Photomicrographs of laterite samples showing the distribution of quartz grains within an Fe–Al matrix. (**a**–**c**) under crossed polars. (**a**) VL-1; (**b**) ML-1 and (**c**) WL-1.

Grain-size analysis reveals that the studied laterites are mainly coarse-textured, with mean grain sizes between 0.24 and 1.05 Φ (Figure 5a, Table 1), mostly falling within coarse to medium sand categories. The coarsest samples are from the Varkala and Karikkom profiles, while Madayipara samples are relatively finer. The particle-size distribution is predominantly coarse lateritic material, making up about 99.5% of the sediment, with clay content remaining very low (0.12–0.89%; Figure 5b). The scarcity of clay and the dominance of quartz-rich coarse fractions suggest extensive desilicification and residual concentration of resistant minerals during long-term tropical weathering. Petrographic analysis supports these findings, showing abundant sand-sized quartz grains dispersed within a fine ferruginous matrix. The presence of coarse quartz grains alongside Fe–Al-rich cement indicates the selective preservation of resistant quartz and the concurrent formation of secondary iron and aluminium oxides, a common feature in highly weathered lateritic profiles formed under humid tropical conditions [23, 24].

4.2. Mineralogical and Geochemical Characterisation of Laterite Profiles

The mineralogy and major-element distributions across the four studied profiles, Vilangara (VL), Karikkom (KL), Varkala (WL), and Madayipara (ML), reveal highly consistent weathering trends across both Precambrian and Tertiary terrains (Figure 6). XRD fingerprints show that all profiles share a core structural skeleton built of residual quartz ($2\theta \sim 26.6°$) and secondary kaolinite ($2\theta \sim 12.3°$ and 24.9°), documenting a uniform regional pathway of silicate alteration under humid tropical conditions. As intense chemical leaching removes silica, this baseline framework is accompanied by a shared proliferation of secondary iron and aluminium minerals. Goethite is consistently present across all sites ($2\theta \sim 35°$–$36°$ and 59°–60°), coexisting with prominent gibbsite peaks ($2\theta \sim 18.2°$ and 21.8°) that mark an advanced, widespread state of high-grade laterization across the region. Localised variations from this core mineralogy are minor and environmentally specific, such as a trace illite peak near $2\theta \sim 8.9°$ at the base of the crystalline profile in VL-8, pointing to unweathered micaceous precursors.

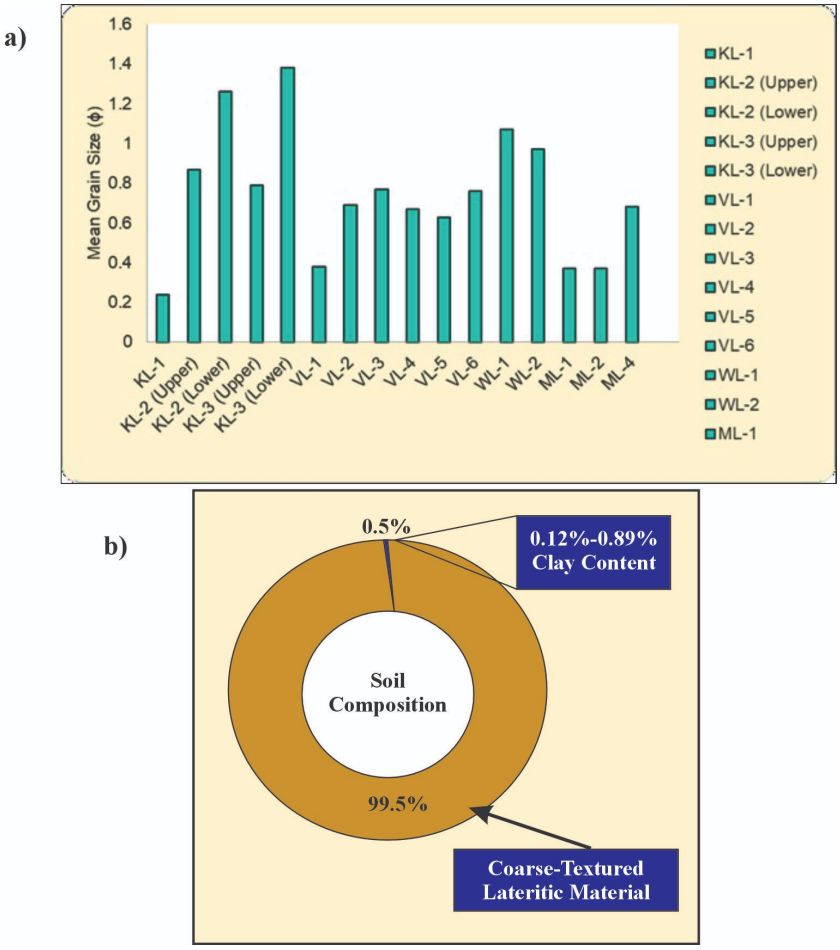

Figure 5. (**a**) Mean grain size (Φ) variations in laterite samples from the four study locations. (**b**) Schematic representation of overall textural composition showing the predominance of coarse-textured lateritic material over clay-sized fractions, highlighting the coarse-grained nature of the laterite profiles.

Table 1. Distribution of grain size fractions in the studied laterite samples from Kerala.

Sample No	Coarse Sand (%)	Medium Sand (%)	Fine Sand (%)	Total Sand (%)	Clay (%)	Mean Grain Size (ϕ)
KL-1	75.98	8.21	15.66	99.84	0.16	0.24
KL-2	55.73	12.26	31.82	99.81	0.19	0.87
KL-3	59.18	13.20	27.62	100.00	0.00	0.79
VL-1	74.35	6.72	18.68	99.75	0.25	0.38
VL-2	64.44	9.35	26.13	99.93	0.07	0.69
VL-3	58.15	12.57	29.03	99.75	0.25	0.77
VL-4	63.68	10.41	25.86	99.95	0.05	0.67
VL-5	64.76	10.31	24.33	99.41	0.59	0.63
VL-6	61.15	10.25	27.98	99.38	0.62	0.76
WL-1	47.51	11.76	40.52	99.79	0.21	1.07
WL-2	52.12	13.82	33.37	99.31	0.69	0.97
ML-1	74.54	6.67	18.54	99.75	0.25	0.37
ML-2	74.82	6.43	18.50	99.75	0.25	0.37
ML-4	63.87	9.47	26.34	99.67	0.33	0.68
ML-6	57.89	6.30	35.74	99.94	0.06	0.73

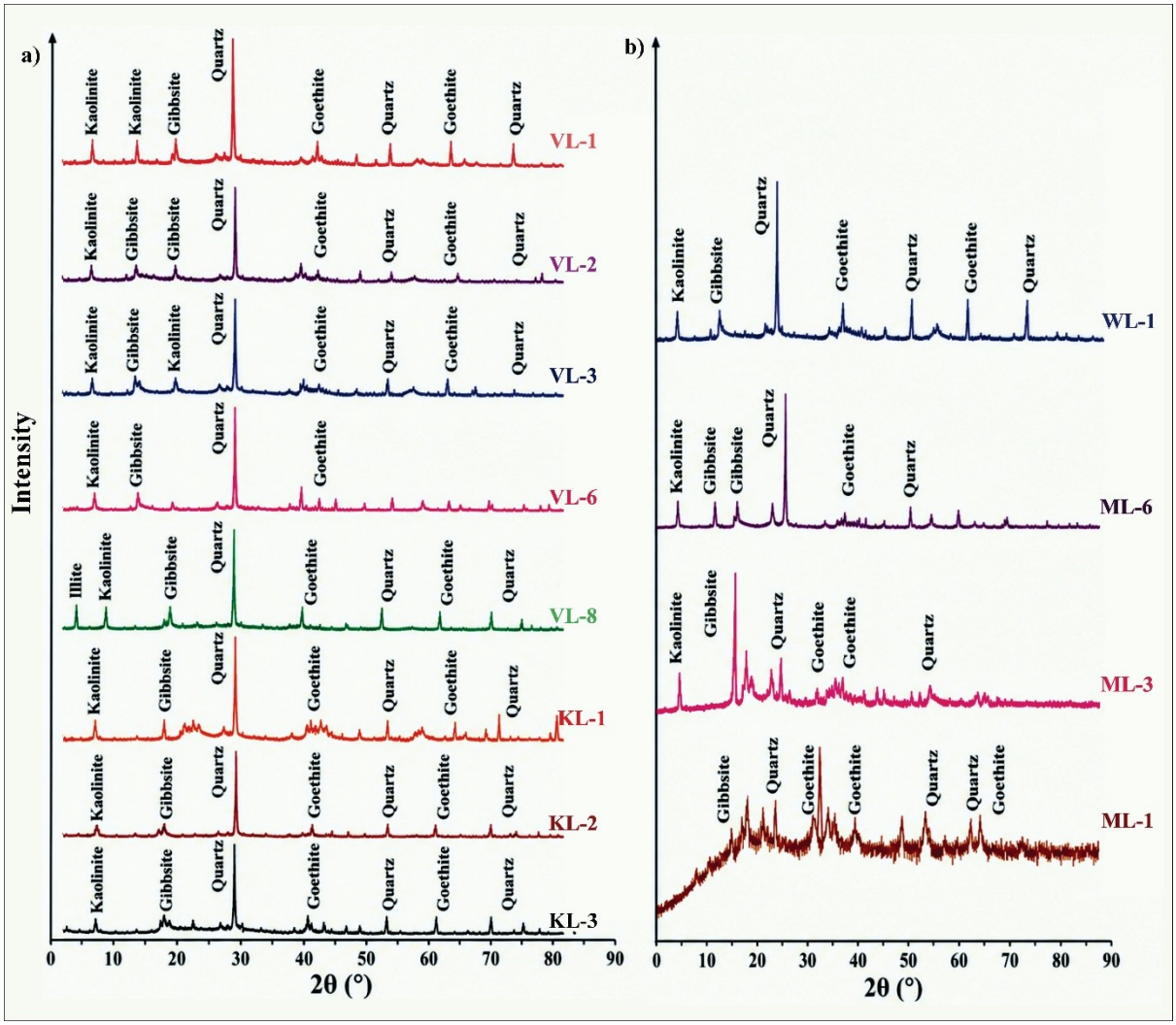

Figure 6. Representative XRD diffractograms of laterite samples from Vilangara, Karikkom, Varkala and Madayipara.

The geochemical profiles of the investigated laterites exhibit a clear trend of surface iron enrichment, reflecting ongoing lateritization and residual concentration under prolonged tropical weathering (Figure 7; Table 2). The top horizons consistently display higher Fe_2O_3 levels and Fe/Al ratios compared to the deeper layers, pointing to a preferential buildup of iron oxides near the surface. This pattern is most prominent in Madayipara, where the ferricrete cap (ML-1) exhibits an extraordinary Fe_2O_3 content of 51.70% (36.16% Fe) and an Fe/Al ratio of 2.52, indicating intense ferruginization and advanced laterite development. Iron content diminishes systematically from 34.30% Fe_2O_3 in ML-2 to below 10% in the lower horizons, with a significant decrease in Fe/Al ratios. Similar but less intense enrichment trends are observed in the Vilangara and Varkala profiles, where the uppermost horizons have Fe_2O_3 contents of 15.59% and 14.07%, respectively, along with the highest Fe/Al ratios within their profiles. The decrease in iron levels downward suggests ongoing mobilisation and reprecipitation of iron during weathering, leading to the formation of iron-rich surface layers.

Aluminium levels remain fairly constant across the profiles, typically ranging from 23.79% to 40.80% Al_2O_3. This consistency suggests that aluminous phases are not highly mobile and tend to persist under tropical weathering conditions. The Karikkom profile exhibits the least ferruginization, with Fe_2O_3 concentrations between 5.67% and 8.40% and Fe/Al ratios from 0.25 to 0.34, indicating a more aluminous composition and a less mature stage of laterite formation. Overall, the Fe/Al ratios reveal differences in laterite maturity within the study areas: Madayipara shows a well-developed ferricrete system, whereas Vilangara, Karikkom, and Varkala have Fe/Al ratios below one, signifying co-occurring iron and aluminium enrichment. This vertical geochemical differentiation is typical in tropical lateritic profiles, where intense leaching removes silica and mobile cations, leaving iron and aluminium oxides to accumulate residually, forming ferruginous crusts and distinct weathering horizons [23, 25].

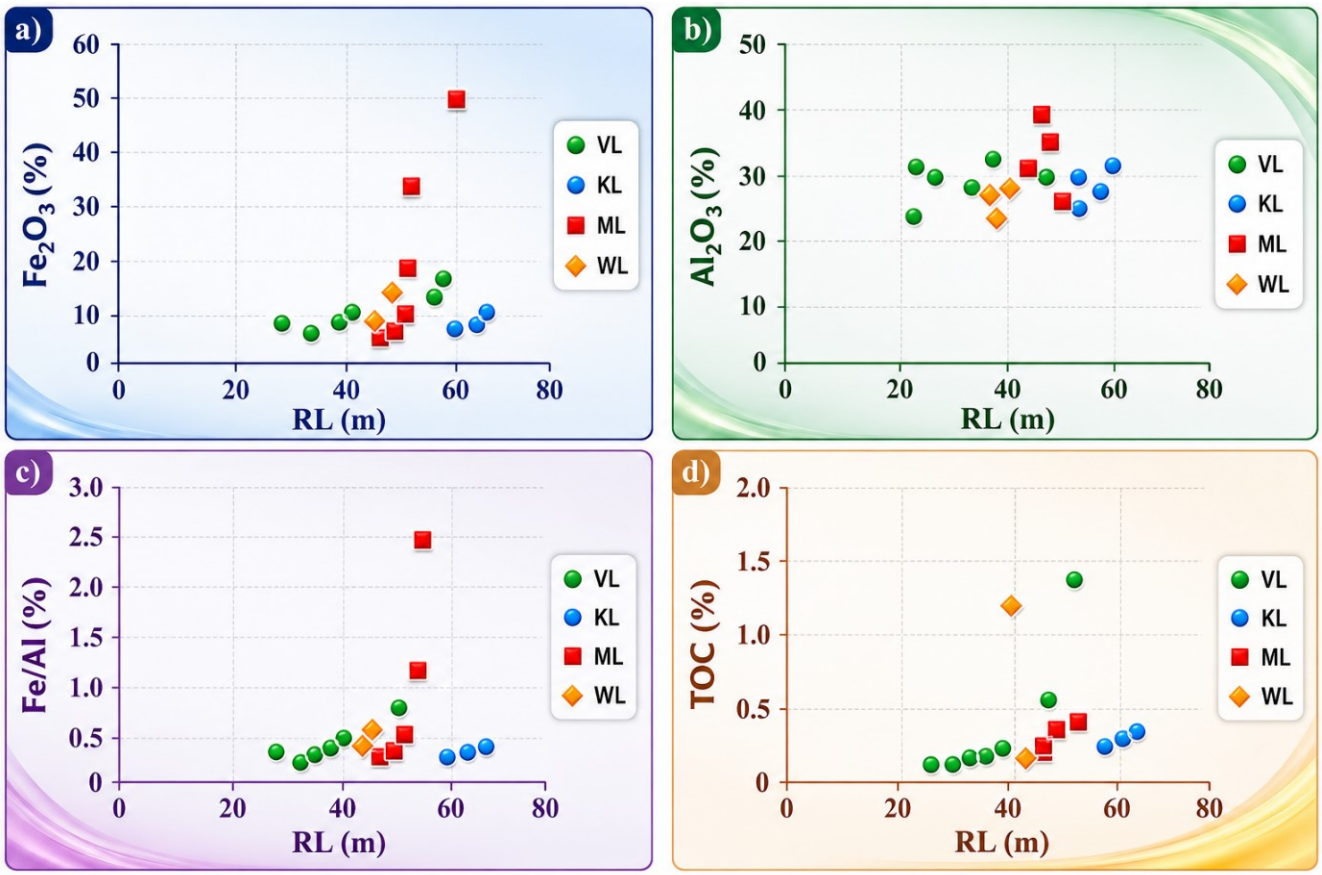

Figure 7. Geochemical variations along the elevational gradient of the studied laterite profiles. Scatter plots showing the relationship between relative elevation (RL) and (**a**) Fe_2O_3 content, (**b**) Al_2O_3 content, (**c**) Fe/Al ratio, and (**d**) total organic carbon (TOC).

Table 2. Vertical distribution of Fe_2O_3, Al_2O_3, elemental Fe and Al contents, and Fe/Al ratios in laterite profiles from Vilangara (VL), Karikkom (KL), Madayipara (ML), and Varkala (WL).

Sample	Fe_2O_3	Al_2O_3	Fe%	Al%	Fe/Al
VL-1	15.59	25.31	10.90365	13.39658	0.813912
VL-2	11.68	30.98	8.168992	16.39771	0.498179
VL-3	9.54	32.44	6.672276	17.17049	0.38859
VL-4	9.21	33.32	6.441474	17.63628	0.36524
VL-5	9.08	29.85	6.350552	15.79961	0.401944
VL-6	7.06	30.08	4.937764	15.92134	0.310135
VL-7	5.25	32.06	3.67185	16.96936	0.216381
VL-8	6.66	23.79	4.658004	12.59205	0.369916
KL-1	8.4	32.47	5.87496	17.18637	0.341838
KL-2	6.21	27.89	4.343274	14.76218	0.294216
KL-3	5.67	30.57	3.965598	16.1807	0.245082
ML-1	51.7	27.1	36.15898	14.34403	2.520838
ML-2	34.3	36.3	23.98942	19.21359	1.248565
ML-3	17.1	40.8	11.95974	21.59544	0.553809
ML-4	9.39	32.1	6.567366	16.99053	0.386531
ML-5	7.11	29.2	4.972734	15.45556	0.321744
ML-6	8.81	30.5	6.161714	16.14365	0.38168
WL-1	14.07	29.31	9.840558	15.51378	0.634311
WL-2	8.55	24.05	5.97987	12.72967	0.469759

4.3. Total Organic Carbon and Carbon Stocks in the Laterite Profiles

Total Organic Carbon (TOC) is a standard measure of organic matter in soils and sediments, serving as an important indicator of terrestrial carbon sequestration [26, 27]. To estimate carbon storage in laterite profiles, TOC values were converted into soil organic carbon (SOC) stocks by considering bulk density and layer thickness. In this study, a uniform bulk density of 1.6 g cm^{-3} was applied across all laterite horizons, based on published data for ferruginous tropical lateritic soils and weathered regoliths [24, 28]. SOC stocks were calculated from measured TOC values using bulk density and sampling depth, following established methods from the literature [29]. The calculation is expressed by the formula: in the literature [29].

$$\text{SOC Stock } (\text{t ha}^{-1}) = \text{TOC } (\%) \times \text{Bulk Density } (\text{g cm}^{-3}) \times \text{Layer Thickness (m)} \times 100. \quad (1)$$

The corresponding carbon dioxide equivalent (CO_2-eq), representing the amount of atmospheric CO_2 associated with the stored carbon, was estimated using the molecular weight ratio of CO_2 to carbon:

$$CO_2 \text{ equivalent } (\text{t ha}^{-1}) = \text{SOC Stock } (\text{t ha}^{-1}) \times \frac{44}{12}. \quad (2)$$

The TOC values and carbon stocks clearly indicate greater carbon accumulation in surface layers than in deeper layers. The highest TOC (1.43%) was found in the top horizon of the Vilangara profile (VL-1), with a carbon stock of 457.6 t ha^{-1} and a CO_2 equivalent of 1679.39 t ha^{-1}. Similarly, the surface horizon of Varkala (WL-1) showed a TOC of 1.30%, resulting in a carbon stock of 249.6 t ha^{-1} (916.03 t CO_2 ha^{-1}). The upper horizons of Madayipara (ML-1) and Karikkom (KL-1) had lower TOC values of 0.32% and 0.25%, respectively, with corresponding carbon stocks of 112.64 t ha^{-1} and 48.0 t ha^{-1} (Figure 8).

A consistent decrease in organic carbon with depth is observed in all profiles (Table 3). In the Vilangara section, TOC decreases from 1.43% at the surface to 0.50% in the second horizon, then gradually declines across subsequent layers to 0.08% in the basal horizon (VL-8), with an estimated carbon stock of 25.6 t ha^{-1}. Similar decreasing trends are seen in the Karikkom, Madayipara, and Varkala profiles, where TOC values stabilise around 0.12%–0.23% in deeper layers. This pattern suggests that fresh organic inputs are mainly near the surface, while organic matter diminishes with depth due to reduced biological activity and limited incorporation. Despite this reduction, deeper horizons still retain significant carbon because of their thickness and the stabilising influence of iron- and aluminium-rich minerals typical of tropical laterites.

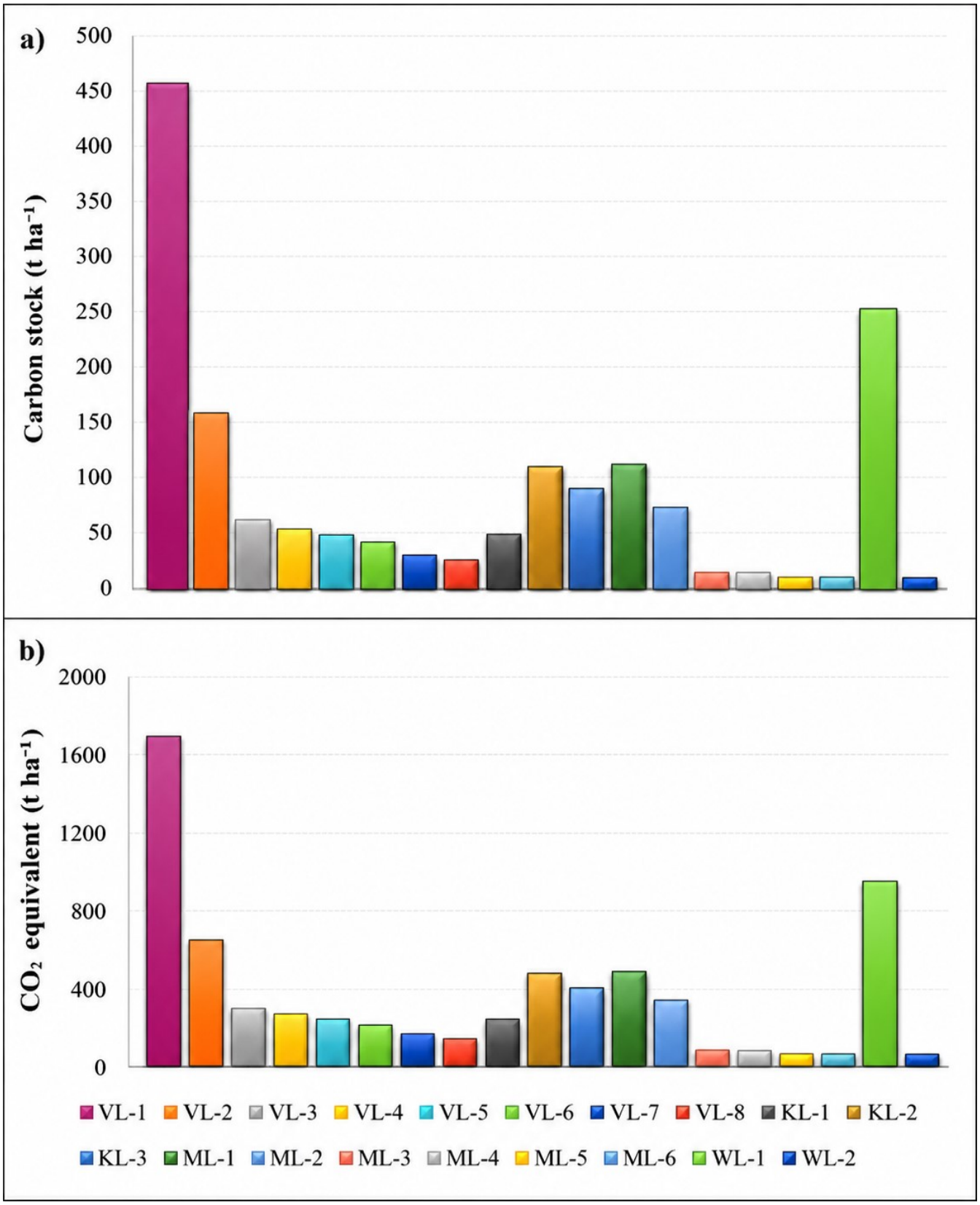

Figure 8. Variations in carbon stock and CO_2-equivalent storage across laterite profiles developed under contrasting geomorphological and geological settings. (**a**) Carbon stock estimates and (**b**) corresponding CO_2-equivalent.

Table 3. Profile thickness, total organic carbon (TOC), carbon stock (t ha^{-1}), and CO_2-equivalent sequestration potential (t ha^{-1}) of the investigated laterite profiles, highlighting variations in carbon storage capacity across different lateritic terrains.

Sample	Thickness (m)	TOC (%)	Carbon Stock (t ha^{-1})	CO_2 Equivalent (t ha^{-1})
VL-1	2	1.43	457.6	1679.392
VL-2	2	0.5	160	587.2
VL-3	2	0.19	60.8	223.136
VL-4	2	0.17	54.4	199.648
VL-5	2	0.15	48	176.16
VL-6	2	0.13	41.6	152.672
VL-7	2	0.09	28.8	105.696
VL-8	2	0.08	25.6	93.952
KL-1	1.2	0.25	48	176.16
KL-2	3	0.23	110.4	405.168
KL-3	3	0.19	91.2	334.704
ML-1	2.2	0.32	112.64	413.3888
ML-2	1.5	0.31	74.4	273.048
ML-3	0.5	0.19	15.2	55.784
ML-4	0.5	0.2	16	58.72
ML-5	0.4	0.2	12.8	46.976
ML-6	0.7	0.12	13.44	49.3248
WL-1	1.2	1.3	249.6	916.032
WL-2	0.5	0.13	10.4	38.168

5. Discussion

5.1. Laterites as Long-Term Carbon Sinks: Controls, Mechanisms, and Environmental Significance

This study shows that Kerala laterites serve as effective long-term carbon sinks, with carbon storage influenced by mineral composition, geochemical features, and profile structure. While laterites typically have lower TOC than peatlands or volcanic soils, their widespread presence in tropical areas and the abundance of iron- and aluminium-rich minerals make them significant for terrestrial carbon sequestration. Secondary minerals like goethite, hematite, kaolinite, and gibbsite offer reactive surfaces that facilitate the formation of stable organo-mineral complexes through adsorption and co-precipitation, helping to protect organic matter from microbial breakdown and supporting its long-term preservation [30, 31].

Among the investigated profiles, the Madayipara laterites exhibit the highest Fe_2O_3 concentrations (up to 51.7 wt.%, which suggests strong ferruginisation and an abundance of reactive mineral surfaces that favour carbon stabilisation. Iron oxides are increasingly recognised as crucial factors in controlling mineral-associated organic carbon in tropical soils because they effectively immobilise organic compounds and slow their decomposition [31–33]. Additionally, kaolinite and gibbsite support carbon retention by providing adsorption sites for organic molecules, particularly under acidic and highly weathered environments [30]. Therefore, the combined role of Fe and Al-rich minerals is a key mechanism in maintaining carbon in these laterites.

The vertical distribution of TOC shows a consistent decline with depth across all profiles (Figure 9), reflecting reduced organic matter inputs below the biologically active surface horizons where litter decomposition and root activity are concentrated [33]. However, carbon storage is not determined solely by TOC concentration. Profile thickness exerts an equally important influence, as demonstrated by the Vilangara profile, where the thick lateritic succession results in the highest cumulative carbon stock despite decreasing TOC with depth. Conversely, the thinner Varkala profile, although enriched in surface organic carbon, stores comparatively less carbon overall. These observations highlight the importance of considering both organic carbon concentration and profile geometry when evaluating carbon sequestration potential.

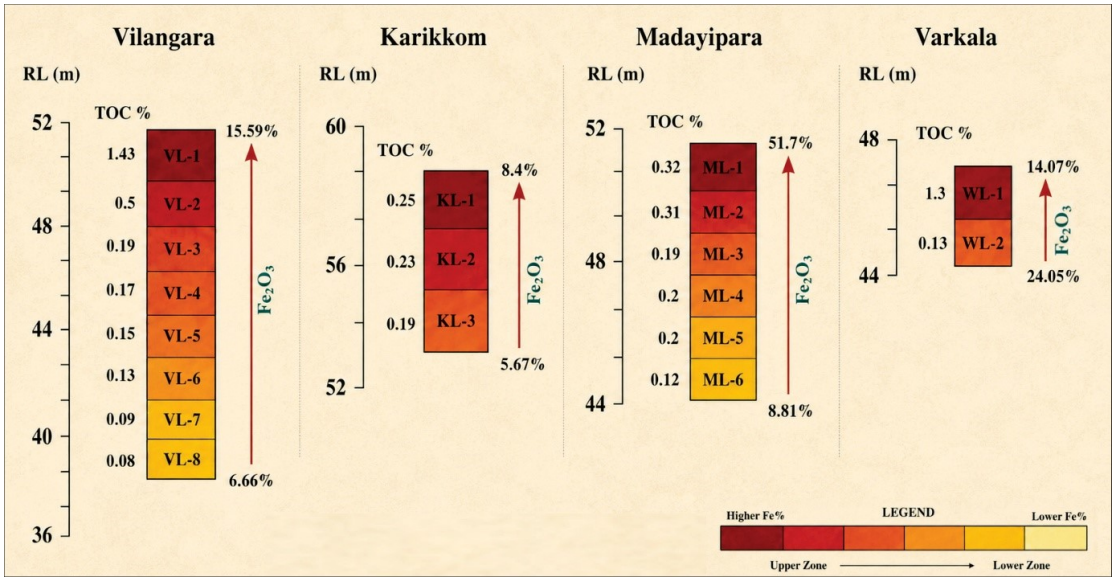

Figure 9. Profile-wise variation of total organic carbon (TOC%) and Fe_2O_3 content (%) along the relative elevation (RL) gradient in the laterite sequences of Vilangara, Karikkom, Madayipara, and Varkala.

Notably, all four study sites share similar cultivation-based land use, implying broadly comparable inputs of plant-derived organic matter and agricultural residues. Therefore, the observed differences in TOC and carbon stocks are attributed primarily to variations in mineralogical composition, weathering intensity, and profile thickness rather than to differences in land-use practices. Overall, the current study indicates that carbon storage in Kerala laterites is dominated by mineral-associated stabilisation processes, supported by abundant Fe–Al oxides and substantial profile thickness (Figure 10).

5.2. Laterites as Long-Term Carbon Sinks: Global Perspective, Controls, and Environmental Significance

Lateritic soils are widely distributed across tropical and subtropical regions, including India, Brazil, Africa, Southeast Asia, and Australia, where prolonged chemical weathering under warm, humid climatic conditions has produced highly evolved Fe- and Al-rich regoliths. Although these soils generally contain lower total organic carbon (TOC) than peatlands or volcanic soils, they are important long-term carbon sinks because of their widespread occurrence and capacity to stabilise organic matter through mineral-organic interactions [31, 34, 35].

The effectiveness of laterites to serve as carbon reservoirs heavily depends on mineral-associated organic matter (MAOM), which is the most durable form of soil organic carbon. In highly weathered tropical soils, reactive Fe and Al (hydr)oxides offer numerous sorption sites for organic substances, aiding the development of stable organo-mineral complexes with extended residence times [35]. MAOM is much more resistant to microbial breakdown than particulate organic matter because organic molecules are strongly bonded to mineral surfaces. Furthermore, seasonal changes in groundwater levels and redox conditions can lead to the dissolution and reprecipitation of iron oxides, further promoting carbon stabilisation through ongoing mineral-organic interactions [34, 36].

Globally, SOC stocks in highly weathered tropical soils generally range from 20 to 200 t C ha^{-1} in the top metre, though substantial variation exists due to factors like climate, vegetation, land use, mineralogy, and sampling depth [29, 37]. Research on Brazilian Oxisols has shown that Fe- and Al-oxides play a key role in carbon preservation by forming stable organo-mineral complexes, enabling significant carbon storage even with low organic carbon levels [34]. Similar processes have been observed in other tropical regions, highlighting that mineral-associated organic carbon is a major, persistent part of the global soil carbon reservoir [37, 38].

The Kerala laterites examined in this study conform to this global pattern. Carbon stocks range from 10.4 to 457.6 t ha^{-1}, with the highest values recorded in the thick Vilangara profile (2 m profile). Across all profiles, TOC declines with depth, reflecting reduced organic matter inputs below the biologically active surface horizons where litter accumulation and root activity are concentrated [33]. However, carbon storage depends not only on TOC concentration but also on profile thickness. The Vilangara profile illustrates this relationship clearly: despite decreasing TOC with depth, its thick lateritic succession stores the highest cumulative carbon. Conversely, the thinner Varkala profile has relatively high surface TOC but contributes a smaller overall carbon reservoir. The strong association between carbon accumulation and iron-rich horizons indicates that ferruginous minerals provide effective mechanisms for long-term carbon stabilisation through adsorption and organo-mineral complex formation. Consequently, lateritic landscapes should not be regarded merely as residual weathering products but as active geochemical reservoirs capable of storing substantial amounts of carbon over extended timescales.

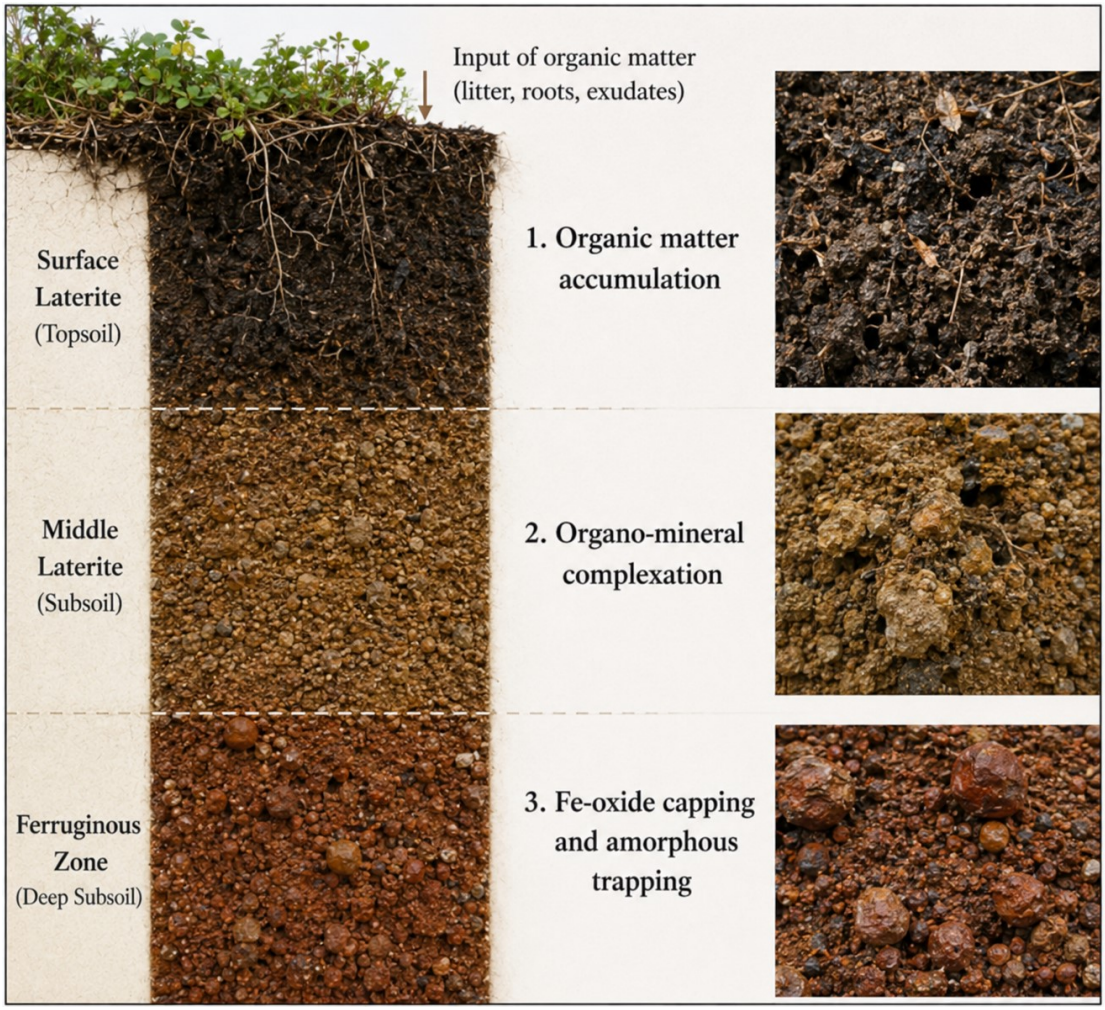

Figure 10. Schematic representation of carbon stabilization pathways in tropical laterites, showing organic matter accumulation, organo–mineral complexation, Fe-oxide-mediated protection, and long-term carbon preservation within lateritic horizons.

Given their extensive distribution across the tropics, lateritic terrains are an under-recognised component of the global terrestrial carbon cycle. Incorporating these landscapes into regional and global carbon inventories could improve estimates of ecosystem carbon storage and strengthen climate change mitigation strategies.

5.3. Laterites in the Context of Global Soil Carbon Storage

Soil organic carbon storage varies significantly across different soil types, influenced by factors like climate, vegetation, parent material, mineralogy, hydrology, and pedogenic processes. Histosols and peatlands are among the largest terrestrial carbon stores because waterlogged and anaerobic conditions inhibit microbial decomposition, enabling the accumulation of large organic matter quantities [39]. Likewise, volcanic Andisols have high carbon storage potential thanks to short-range-order minerals such as allophane and imogolite, along with stable Al-humus complexes that effectively shield organic matter from breakdown [40].

Table 4 outlines typical ranges of soil organic carbon (SOC) stocks and main stabilisation mechanisms across major soil orders relevant to this study. Organic soils and volcanic ash soils lie at the high end of the global SOC spectrum, where waterlogging and mineralogy facilitate significant organic matter buildup [41, 42]. Conversely, Aridisols hold smaller SOC stocks due to limited moisture availability [43]. In between, tropical soils rich in kaolinite and Fe-/Al-oxides—such as Alfisols, Ultisols, and Oxisols/Ferralsols—maintain moderate SOC levels through mineral association mechanisms within thick weathering profiles [44, 45]. The Kerala laterites examined here fall into this group, with SOC stocks ranging from 10.4 to 457.6 t C ha^{-1}, similar to values for global Oxisols and tropical Ultisols [46, 47]. Notably, the highest values reflect profile thickness and Fe-oxide complexation rather than organic matter content, indicating that lateritic carbon sequestration differs from the organic matter preservation pathways in Histosols and the allophane stabilisation found in Andisols.

Table 4. Comparative overview of carbon storage potential and stabilisation mechanisms in different soil types.

Soil Type	Typical SOC Stock (t C ha^{-1})	Dominant Carbon Stabilisation Mechanism	References
Histosols/Peat soils	>500 (often 600–800 in deep profiles)	Waterlogging and anoxia suppress microbial decomposition; physical protection in fibric/hemic materials	Aide et al. [41]; Köchy et al. [42]
Andisols	200–800	Short-range-order minerals (allophane, imogolite, ferrihydrite) and Al-/Fe–humus complexation	Georgiou et al. [37]
Mollisols	150–500 (84–116 in upper 0–50 cm; >300 in deep grassland profiles)	High belowground biomass inputs; aggregate occlusion; stable humification	Łabaz et al. [48]
Alfisols	80–250	Clay–organic associations (smectitic/mixed-clay matrices); aggregate protection	Georgiou et al. [37]
Ultisols	50–250	Fe–Al oxide interactions and kaolinite-mediated mineral-associated organic matter	Kirsten et al. [44]; Vaughan et al. [47]
Oxisols /Ferralsols	40–300 (high SOC in deep, geochemically stable landforms)	Strong Fe–Al (oxyhydr)oxide-mediated stabilization; deep mineral-organic associations	Reichenbach et al. [45]; Marques et al. [46]; Kirsten et al. [44]
Kerala laterites (this study)	10.4 (0.5m)–457.6 (2m)	Fe–Al oxide complexation and profile thickness over deeply weathered saprolite	Present study
Aridisols	10–80 (≈42 at 0–25 cm; ≈225 at 0–100 cm when calcareous)	Limited biomass inputs and moisture; in many profiles, $CaCO_3$-bound (inorganic) carbon dominates	Sharma et al. [43]

6. Conclusions

Laterites are important yet overlooked terrestrial carbon sinks in the tropics. Beyond environmental and ecological factors, the carbon storage potential of laterites is controlled by grain size and mineralogical content, particularly the abundance of Fe–Al oxides. Tropical laterites in the south-western part of India are extensively developed over Precambrian crystalline rocks and tertiary sedimentary sequences. Irrespective of parent material, laterites are coarse-grained, with a small clay fraction around 0.12 to 0.89%. Yet they show relatively higher amounts of SOC, up to 457.6 t ha^{-1}. Mineralogical analysis reveals that laterites consist mainly of quartz, kaolinite, gibbsite and goethite. Petrographic examination also reveals an abundant iron- and aluminium-rich matrix enclosing relict quartz grains. The close association between organic carbon and Fe–Al phases shows that iron and aluminium oxides are key in controlling carbon stabilisation in laterites. The data indicate that carbon storage in laterites is influenced not only by inputs of organic matter but also by mineralogical and textural characteristics that modulate carbon preservation. The findings suggest that laterites are potentially significant carbon sinks in the tropics.

Author Contributions

P.D.: Writing—original draft, Formal analysis & Data curation. G.K.I.: Conceptualisation, Methodology, Investigation, Writing—review & editing, Supervision. A.M.L., A.J.J., A.A.A.K. and S.B.: Writing—review & editing.

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Data Availability Statement

All data used in this work are presented in the paper.

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Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Use of AI and AI-assisted Technologies

The authors used AI-assisted tools for grammatical editing and language refinement of the manuscript. The authors reviewed and approved all content and are fully responsible for the accuracy and integrity of the work.

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