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Assessment of Soil Physicochemical Properties Across Different Land Use and Land Cover Types in South Delhi, India

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Keywords

Land use land cover;
Soil quality;
Soil degradation;
Carbon sequestration;
Water management

Abstract

This study investigates the influence of various land use and land cover (LULC) types on key soil properties, including moisture content, pH, electrical conductivity, bulk density, and total carbon content. Using normalised radar chart analysis, we analyzed soil properties across three soil depths (0–10, 10–20, and 20–30 cm). The results reveal clear patterns in soil health indicators associated with specific LULC categories. Agricultural soils consistently exhibited the highest moisture content at all depths, indicating enhanced water retention while maintaining moderate total carbon and bulk density levels. In contrast, forest soils showed the highest total carbon values throughout the soil profile, particularly at the surface (normalized value =1.0), demonstrating significant organic matter accumulation. Scrub forest soils showed higher carbon content in deeper layers, indicating greater carbon storage potential in the subsoil. Settlement and degraded soils showed signs of degradation with high bulk density, elevated electrical conductivity, low moisture content, and low total carbon, particularly in degraded areas. Moreover, settlements had the highest pH levels, likely due to human activity. These findings emphasize that natural and semi-natural land covers, including forests and scrub forests, improve carbon sequestration and soil quality. In contrast, urban and degraded landscapes suffer from compaction, salinization, and reduced organic matter. The study highlights the importance of preserving and restoring vegetative cover to enhance soil carbon storage and overall soil health, particularly in rapidly urbanizing and degraded areas.

1. Introduction

Soils are essential natural resources that support the production of food, feed, fiber, and bioenergy while also playing a key role in maintaining environmental quality (Palm *et al*., 2007). The functionality and health of soil rely on the dynamic balance of its biophysical and chemical properties (Adhikari and Hartemink, 2016). Unconventional land management practices may lead to a decline in essential soil nutrients and overall soil quality, ultimately impacting agricultural production, food security, and livelihoods. The expanding population and rising socio-economic demands pressure land use cover, leading to unanticipated and unchecked land-use alterations. The primary outcomes of improper land use changes include land degradation and deterioration of soil quality due to the loss of vegetative cover (Kebebew et al., 2022).

Land use and land cover (LULC) changes, particularly the conversion of natural ecosystems into agricultural or urban land, can significantly impact the soil's physical and chemical properties. For instance, Choudhary and Saxena (2015) found that converting forested areas into croplands results in higher bulk density, decreased organic matter, and lower soil pH. In a similar study, Koga *et al*. (2020) found that converting forested land to cropland reduces soil carbon reserves. These changes present significant challenges in developing nations, where land degradation is a leading factor in food insecurity, poverty, and social conflict (FAO, 2017). Soils are crucial reservoirs of terrestrial carbon and essential nutrients, such as nitrogen, vital for soil fertility and ecosystem health (Bünemann *et al*., 2018; Lal et al., 2015). Therefore, monitoring and managing the impacts of land use changes is essential. Vegetation restoration significantly reduced soil bulk density while increasing soil porosity. Changes in soil properties differ across various land use types. Furthermore, vegetation's age and growth status considerably impact soil properties (Qiu et al., 2022).

Rapid urbanization, infrastructure development, and land use changes are increasingly impacting soils in urban and peri-urban regions, such as South Delhi, India. These human activities often cause significant changes in soil physicochemical properties, including pH, electrical conductivity, organic carbon content, moisture levels, bulk density, and porosity. Such characteristics are vital for soil fertility and productivity and essential ecosystem functions like carbon sequestration, water management, and pollution control. This study evaluates and compares the physicochemical properties of surface soils at three depths, 0–10, 10–20, and 20–30 cm, across various LULC categories in South Delhi. Soil samples from settlements, forests, scrub forests, agricultural lands, and degraded land were collected and analyzed to identify trends in soil degradation or enhancement resulting from natural phenomena and anthropogenic activities. Insights will support sustainable land use, urban green space development, and soil conservation, ultimately promoting environmental sustainability in urbanizing areas.

2. Material and methods

2.1. Study area

South Delhi is one of 11 districts in the National Capital Territory of Delhi (Fig 1). This historically, economically, and culturally significant area has its headquarters at M.B. Road in Saket, bordered by the Haryana state, with Gurgaon and Faridabad to the south. The district includes three subdivisions: Saket, Hauz Khas, and Mehrauli. While it has a sizeable portion of rural land, it is primarily urban, with 42 villages (18 in Hauz Khas, 11 in Mehrauli, and 13 in Saket). South Delhi experiences a humid subtropical climate, characterized by extreme weather conditions. The Delhi Tourism Portal states that summers have high temperatures and humidity, often with heatwaves, with temperatures from 25 to 46°C. The monsoon season continues until early September, bringing an average rainfall of about 660.1 mm (IMD, 2020). Winters are cold, with temperatures dropping in November, potentially reaching as low as 2°C in January, accompanied by cold waves, smog, and fog (Delhi Tourism, 2024). South Delhi encompasses a range of LULC types, including settlements, agricultural land, forests, scrublands, and barren terrain. This variety provides a unique chance to explore soil variability across different levels of land use intensity. Despite its ecological and urban significance, scientific research on the spatial distribution of soil quality parameters in this area remains limited.

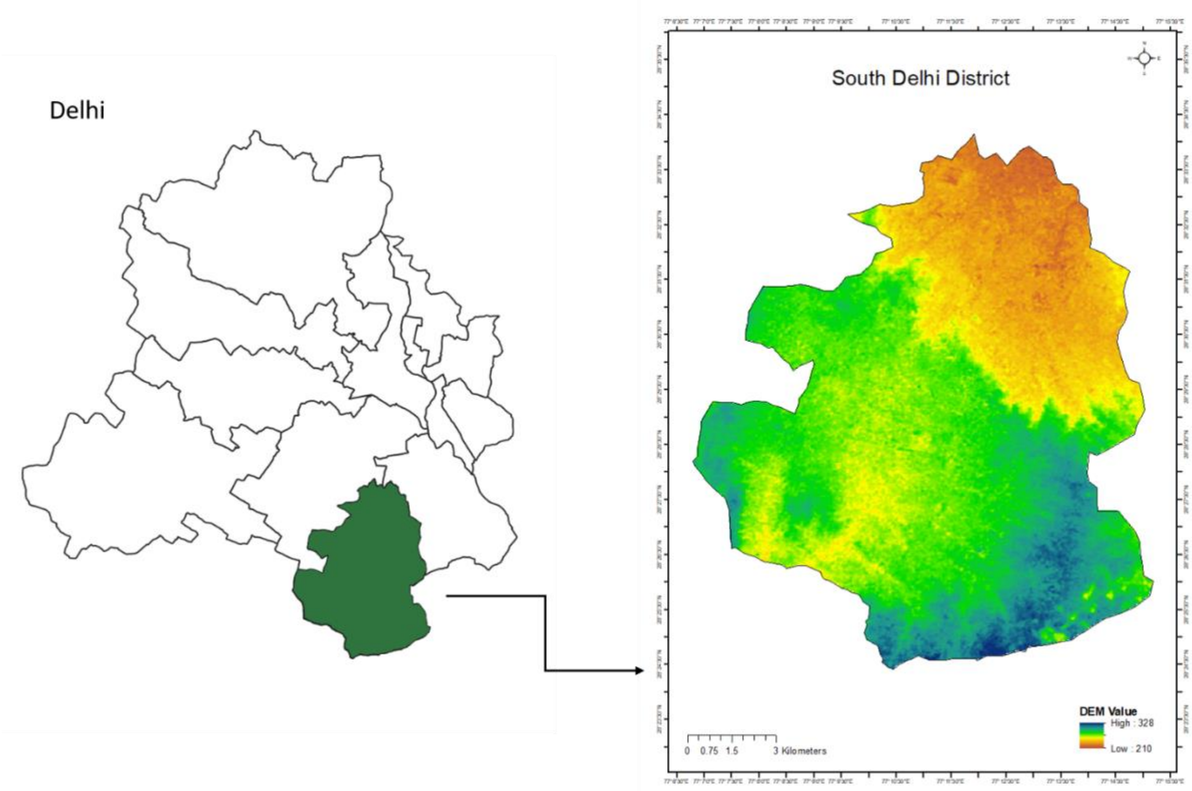

Fig 1. The study area, South Delhi District

2.2. Sample collection and preparation

Five dominant LULC categories were identified: Agriculture, Forest, Scrub forest, Settlement, and Degraded land (Fig 2). After removing litter, soil samples were collected from three depths: 0-10, 10-20, and 20-30 cm. Before analysis, plant debris and contaminants were removed from samples stored at 4°C in the laboratory. The soil was air-dried, crushed with a mortar and pestle, and sifted through a 2 mm sieve.

***2.2.1. Bulk density*:** Soil samples were collected using a core sampler with a sharp edge, minimizing compaction. After trimming excess soil and labelling, fresh weights were recorded. Samples were oven-dried at 105°C for 24 hours, then cooled and weighed. Bulk density (g/cm³) was calculated as the ratio of dry mass to core volume (Blake and Hartge, 1986)**.**

$$Bulk\ density = \frac{dry\ soil\ mass}{Volume\ of\ the\ cylinder(cm^3)} \times 100$$

The Volume of the cylinder is:

$$V = \pi \times r^2 \times h$$

Where: π= 3.1416; r= radius (cm); and h= height of the cylinder (cm)

***2.2.2. Water holding capacity*:** To measure the soil's water holding capacity, Whatman No. 1 filter paper was placed in a perforated brass box and weighed (W1). Then, 10 g of soil was added, and the box was submerged overnight in 1 cm of distilled water. After 12 hours, the box with saturated soil was weighed again (W2). The soil was dried at 105ºC and weighed (W3). The water retained in the filter paper (W4) was calculated using the relevant formula (Piper, 1966).

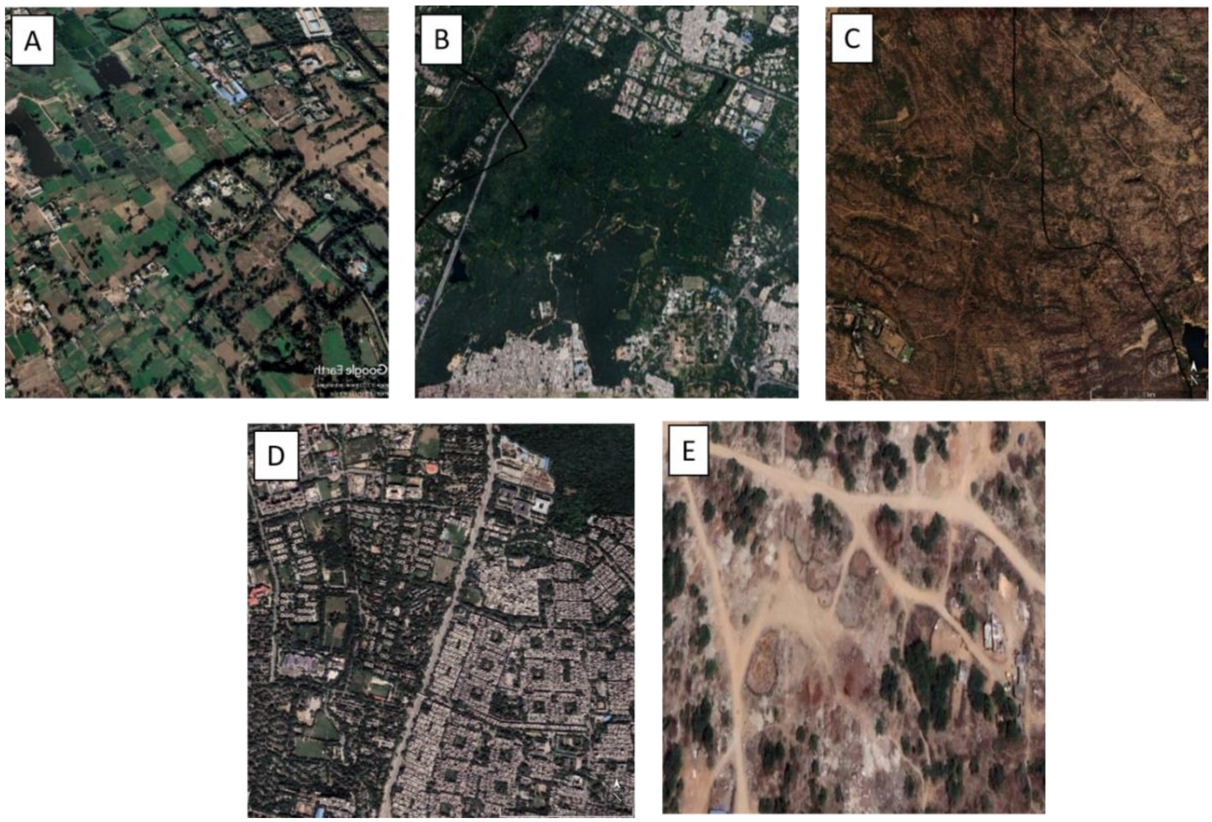

Fig 2. Google Earth imagery of South Delhi shows the distribution of major LULC types: (A) agricultural fields, (B) forest, (C) scrub forest, (D) settlement, and (E) degraded land, highlighting the region's diverse landscape and land use intensity.

***2.2.3. pH and electrical conductivity*:** 5 g of air-dried soil was placed in a beaker, and 25 mL of deionized water was added to create a suspension. This mixture was stirred with a glass rod, allowed to stand for 30 minutes, and stirred every 10 minutes. After the equilibration phase, the pH and electrical conductivity meters were calibrated, and the electrode was inserted into the suspension for measurement after 30 seconds. After the reading, the electrode was rinsed with deionized water to prevent contamination (Estefan *et al*., 2013).

***2.2.4. Particle density*:** Soil particle density was measured using a pycnometer. A clean pycnometer containing 10 g of dried soil was filled with boiled and cooled water. After boiling to remove air bubbles, the weight was recorded. The empty pycnometer was weighed with water to calculate soil density through water displacement (Bandyopadhyay et al., 2012).

$$Particle\ density = \frac{10}{W_2 + 10 - W_3}$$

Where: Weight of empty bottle = W1g; Weight of bottle + Water = W2g; Weight of bottle + Soil + Water = W3g; Soil weight 10 g

***2.2.5. Soil porosity*:** As explained in the method above, particle density is used with bulk density to calculate soil porosity. Then, using the formula, the soil porosity was measured (Estefan *et al*., 2013).

$$Porosity = \left[100 - \left(\frac{Bulk\ density \times 100}{Particle\ density}\right)\right]$$

***2.2.6. Moisture content*:** Following Estefan et al. (2013), the lid of the drying container was weighed and tared using a digital weighing scale to assess the moisture content. Then, 10 g of moist soil was added, and its mass was recorded. The container was covered and dried at 105°C for 24 hours. Afterwards, it was sealed, cooled in a desiccator for two hours, and weighed.

2.2.7. Total soil carbon: The total carbon content in soil was measured using an Elemental Analyzer 3000A. Soil samples were air-dried, ground, and sieved to create a uniform powder. About 25–30 mg of the sample was weighed and placed in a tin capsule, then combusted at high temperatures in pure oxygen. The resulting carbon dioxide (CO_2) was detected and quantified. Calibration used sulphanilamide for accuracy, and blank runs helped with background correction. TC was reported as a percentage of dry soil weight (Ghosh *et al*., 2018).

2.3. Radar chart: A radar chart, also known as a spider chart or web chart, is a graphical method for displaying multivariate data across multiple variables. This study visualizes differences in soil properties, including moisture, pH, electrical conductivity, bulk density, and total carbon, across various LULC types. Normalized data ensures that values measured on different scales are adjusted to a standard range, typically from 0 to 1, which allows for a fair comparison. For instance, the highest value for a property across all samples is normalized to 1.0, while the lowest is set at 0.0. This visualization technique effectively highlights soil quality indicators' relative strengths and weaknesses for each land use category.

3. Results

Radar charts depicting normalized soil properties at three depth levels (0–10 cm, 10–20 cm, and 20–30 cm) illustrate the impact of various LULC types on key soil parameters, including moisture content, pH, electrical conductivity, bulk density, and total carbon. At the 0–10 cm depth, agricultural soils presented the highest moisture content (normalized value = 1.0) alongside moderate pH readings, total carbon, and bulk density (Fig 3A). Forest soils had the peak total carbon (1.0), indicating organic matter accumulation on the surface, but displayed low moisture, electrical conductivity, and bulk density. Scrub forest soils exhibited intermediate total carbon and bulk density levels, characterized by low moisture and pH values. Settlement areas recorded the highest pH (1.0) and a bulk density of 0.816, reflecting anthropogenic compaction. Conversely, degraded land soils had the lowest total carbon (0.0) and moisture values, with maximum electrical conductivity and bulk density (1.0), indicating soil degradation and salinization.

At the 10–20 cm depth, agricultural soils preserved their high moisture levels and moderate total carbon content (Fig 3B). Forest soils had the highest total carbon and negligible electrical conductivity and bulk density values. Scrub forest soils exhibited a significant increase in total carbon (0.527), suggesting deeper carbon retention. Settlement and degraded land soils remained compacted, characterized by high bulk density and electrical conductivity, confirming ongoing structural degradation.

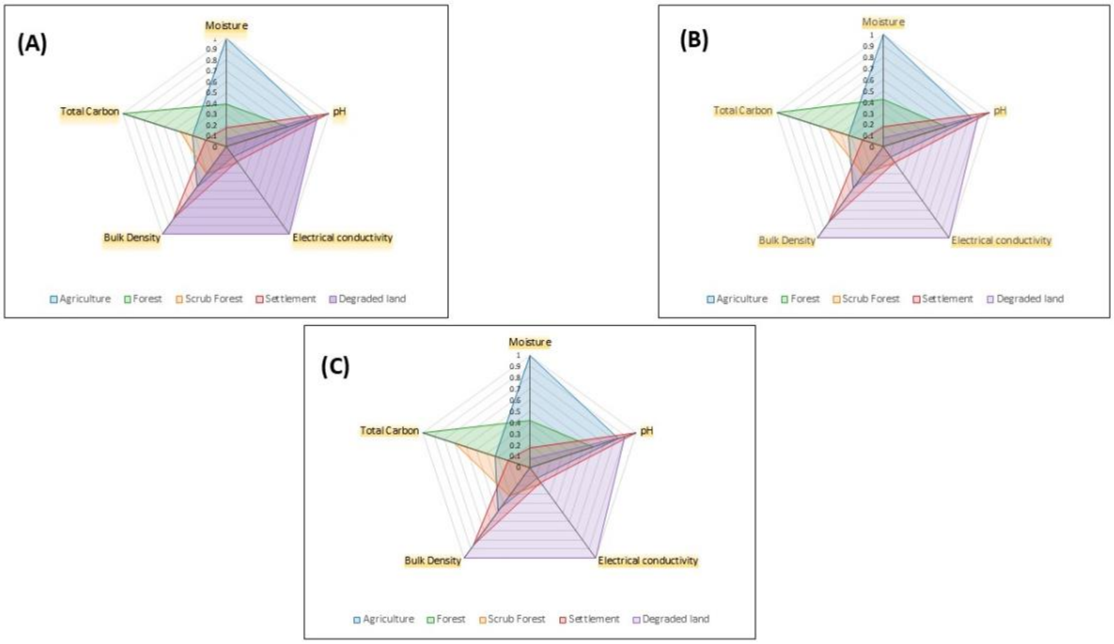

Fig 3. Radar chart showing Soil Organic Carbon (SOC) variation across land use and land cover types at different soil depths: (A) 0–10 cm, (B) 10–20 cm, and (C) 20–30 cm.

In the 20–30 cm layer, agricultural soils maintained stable moisture and carbon values throughout the depths (Fig 3C). Forest soils upheld high total carbon levels (1.0), while scrub forest soils revealed an additional rise in carbon content (0.703), emphasizing organic matter's vertical movement and stabilization. Settlement and degraded land displayed high bulk density (1.0) and low carbon values, especially in degraded land areas (total carbon = 0.0), indicating persistent degradation and lack of biological input.

Soil physical properties, including water holding capacity, porosity, and particle density, vary across different LULC types. Fig 4 (A) and (B) show that forest soils exhibit the highest water holding capacity at 28.34% and porosity at 54.64%, attributed to increased organic matter and root biomass that enhance soil structure. In contrast, settlement areas show the lowest water holding capacity at 17.87% and porosity at 41.90%, likely due to soil compaction from human activities. The particle density is lowest in forest soils at 2.57 g/cm³ and highest in degraded land at 2.675 g/cm³, reflecting variations in mineral composition and organic matter content as shown in Fig 4 (C). These results highlight the considerable impact of land use on soil physical properties, affecting water retention and overall soil health.

To examine essential soil physicochemical properties, Pearson correlation heatmaps as shown in Fig 5 (A), (B), and (C) were created using PAST software for three depths, i.e., 0–10 cm, 10–20 cm, and 20–30 cm. These heatmaps illustrate relationships between moisture content, pH, electrical conductivity, bulk density, and total carbon. Red shades indicate strong positive correlations, while blue shades denote strong negative correlations. At 0–10 cm, the heatmap reveals a strong negative correlation between total carbon, bulk density, and electrical conductivity, suggesting that higher organic matter content leads to less compact and less saline soils. Moisture content positively correlates with total carbon and negatively correlates with electrical conductivity and bulk density, indicating that organic-rich soils retain more water. At greater depths (10–20 cm and 20–30 cm), similar, less pronounced trends are observed, likely due to reduced influence of surface vegetation and organic matter inputs. These visualizations support previous findings from radar charts and highlight the interconnectedness of soil compaction, salinity, and water retention across different depths, influenced by natural factors and land use practices.

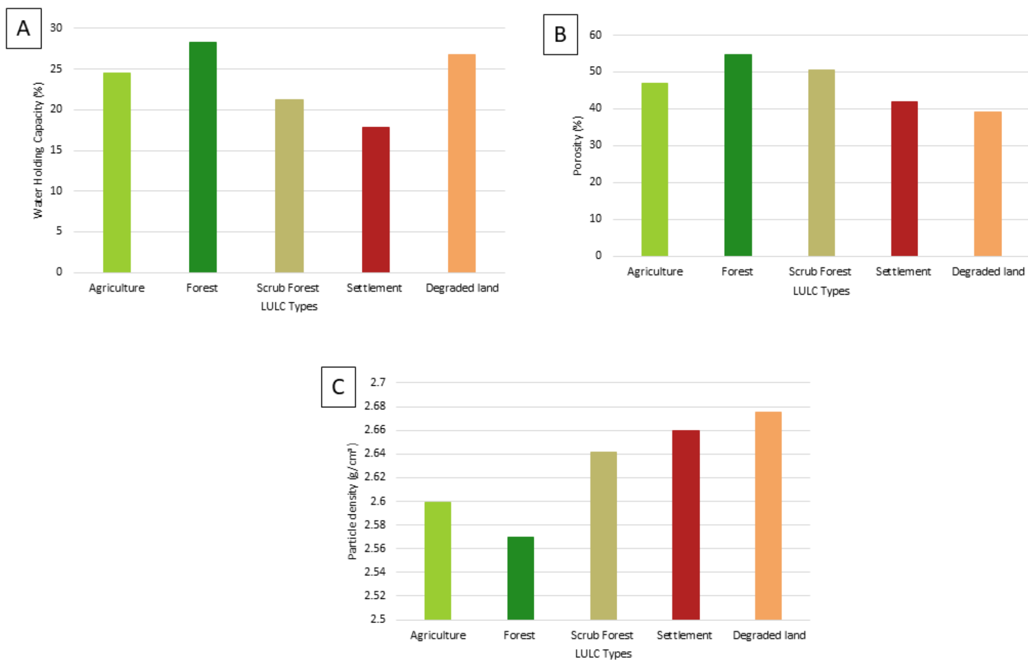

Fig 4. Visual comparison of soil physical properties, i.e., (A) Water Holding Capacity, (B) Porosity, and (C) Particle Density across different LULC types

Radar charts displaying normalized values of soil physicochemical parameters at three depths (0–10 cm, 10–20 cm, and 20–30 cm) demonstrate the significant impact of LULC types on soil properties (Fig 3). At a 0–10 cm depth, agricultural soils exhibited the highest moisture content (normalized to 1.0), likely due to irrigation and soil management practices. These soils also had moderate pH, total carbon, and bulk density values, aligning with Hammad *et al*. (2020), who observed greater moisture retention and moderate carbon levels in cropland compared to forest and degraded land. Forest soils showed the highest total carbon content (normalized to 1.0), indicating surface organic matter accumulation. These soils also exhibited low moisture, bulk density, and electrical conductivity. Gandhi and Sundarapandian (2017), along with Kaur and Kaur (2016), reported that forest soils generally have high surface SOC levels, with low compaction and salinity, which they linked to the undisturbed state of these ecosystems. Scrub forests exhibited moderate carbon and bulk density levels, characterized by low moisture and pH, indicating semi-natural conditions with moderate litter and structural diversity. Settlement areas had the highest pH (1.0) and increased bulk density (0.816), pointing to human-induced soil compaction. Degraded land exhibited the lowest carbon and moisture levels and the highest bulk density and electrical conductivity (normalized to 1.0), signifying severe degradation and salinization. Similar patterns were observed in degraded arid regions, as reported by Cao *et al*. (2018) and Rittl *et al*. (2017), who emphasized that poor land use management contributes to reduced carbon stocks, increased soil compaction, and salt buildup.

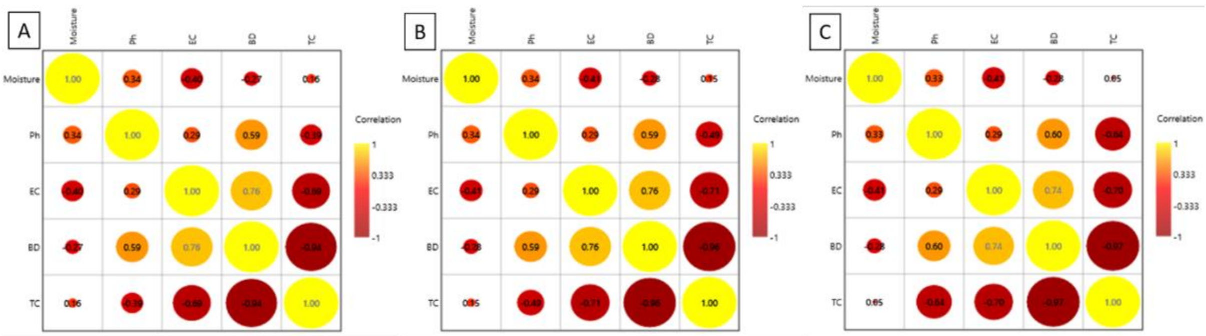

Fig 5. Correlation Matrix of soil properties at different depths (A) 0-10 cm, (B) 10-20 cm, and (C) 20-30 cm

At depths of 10–20 cm and 20–30 cm, agricultural soils showed higher moisture levels, likely due to routine irrigation; however, total carbon content was still lower than that of forest soils. Conversely, forest soils consistently exhibited high carbon levels at all depths, highlighting their capacity for long-term carbon storage. Similar findings were reported by Ghimire *et al.* (2023) and Guo and Gifford (2002), who noted that deep-rooted plants and minimal soil disturbance in forests play a crucial role in building soil organic carbon at greater depths. Settlement and degraded lands consistently had high bulk density and low total carbon across all depths, aligning with the findings of Rittl *et al.* (2017) and Kaur and Kaur (2016), which indicate that urbanization and vegetation loss negatively impact subsurface soil quality. The soil physical data (Fig 4) further supports the insights from the radar chart. Forest soils exhibited the highest water-holding capacity (28.34%) and porosity (54.64%), indicating better soil structure and higher organic matter content. These traits enhance moisture retention and biological activity, aligning with findings from Gandhi and Sundarapandian (2017) and Kaur and Kaur (2016) for forests in the Eastern Ghats and Himalayas. In contrast, settlement areas showed the lowest water holding capacity (17.87%) and porosity (41.90%), primarily due to compaction caused by construction activities and trampling. Degraded lands showed the highest particle density (2.675 g/cm³) and bulk density, indicating mineral dominance and low organic input. Similar trends of structural degradation and compaction were reported by Cao et al. (2018) in semi-arid forested regions.

Correlation heatmaps (Fig 5) across three depths showed strong negative correlations between total carbon and bulk density and electrical conductivity, particularly at the surface. This highlights the importance of organic matter in enhancing soil structure and mitigating salinity. Moisture content correlated positively with total carbon and negatively with electrical conductivity and bulk density, indicating that organic-rich soils retain more water and resist compaction. These patterns weaken with depth due to reduced surface influence, consistent with findings by Jobbágy and Jackson (2000) and supported in Hammad et al. (2020), which attribute surface carbon accumulation to litterfall and minimal soil disturbance. The data confirm that natural and semi-natural lands, such as forests and scrub areas, preserve better soil quality through improved carbon retention, reduced compaction, and increased water availability. In contrast, settlement and degraded lands show signs of human-caused damage, including compaction, salinity, and loss of organic content. Although agricultural areas perform better than degraded soils, their carbon storage remains limited due to practices such as tillage and residue removal, as highlighted by Guo and Gifford (2002).

4. Conclusions

The results show how different LULC types impact soil properties at various depths. Forests and scrub forests have better soil quality, especially in total carbon content. The high carbon levels in forest soils at all depths suggest that much organic matter is added and that the soil is not disturbed much, which helps store carbon over time. Additionally, scrub forest soils have more carbon as you go deeper, which may mean that organic material and carbon move down and stabilize in the deeper soil layers. This highlights the importance of plants in increasing soil carbon storage, particularly in natural and semi-natural areas. These results emphasize the crucial role of land cover in maintaining vital soil functions. Natural forests are critical for storing organic carbon, whereas urban areas and degraded land show clear signs of damage. This suggests that restoring and protecting soil, especially in areas without forests, can improve carbon capture, reduce soil compaction, and enhance soil quality, ultimately leading to better land management. It is crucial to regularly check soil health and employ conservation methods, particularly in rapidly growing urban areas like South Delhi, to protect ecosystem services, enhance carbon storage, and ensure that agriculture remains productive while the environment remains stable. Future land use plans should prioritize soil conservation for sustained ecological and agricultural health.

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6. Declarations

Conflict of interest: The authors declared that there are no competing or conflicting interests.

Consent to participate: This article does not contain any studies involving human participants performed by authors.

Ethics approval: This article does not contain any studies with human participants or animals performed by any authors.

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