COMMUNITY URBAN PARKS AS CARBON SINKS: EVALUATING THE ROLE OF THE URBAN PARK IN CARBON SEQUESTRATION AND ENVIRONMENTAL SUSTAINABILITY UNDER ARID CONDITIONS

Daniyal Hussain[1], Ghulam Yasin[1], Akash Jamil[2], Gulab Hussain[1], Ghulam Yasin[1], Muhammad Farooq Azhar[1], Abdullah A. Alarfaj[3], Mansour Shrahili[4], Mohammad Javed Ansari[5], Shafeeq Ur Rahman[6*]

[1] Department of Forestry and Range Management, FAS &T, Bahauddin Zakariya University, Multan 61000, Pakistan

[2] Department of Range Management, Forestry and Wildlife, Cholistan University of Veterinary and Animal Sciences, Bahawalpur.

[3] Department of Botany and Microbiology, College of Science, King Saud University, P. O. Box.2455, Riyadh, 11451, Saudi Arabia. aalarfajj@ksu.edu.sa

[4] Department of Statistics and Operations Research, College of Science, King Saud University, P.O. Box 2455, Riyadh 11451, Saudi Arabia. msharahili@ksu.edu.sa

[5] Department of Botany, Hindu College Moradabad (MJP Rohilkhand University Bareilly) India-244001. mjavedansari@gmail.com

[6] Water Science and Environmental Engineering Research Center, College of Chemical and Environmental Engineering, Shenzhen University, Shenzhen, 518060, China.

malikshafeeq1559@gmail.com

[*]**Corresponding author:**

Prof. Dr. Shafeeq Ur Rahman

E-mail: malikshafeeq1559@gmail.com

ABSTRACT

Urban parks and forests are essential elements of urban ecosystems, providing vital ecosystem services including climate regulation, air purification, and carbon sequestration. Green spaces significantly mitigate the ecological impacts of urban development by functioning as terrestrial carbon sinks. This research, carried out in Multan, Pakistan, evaluated carbon densities across 10 parks classified as small, medium, large, and urban forests. Aboveground and soil carbon densities were measured, along with associated variables such as biodiversity and soil bulk density. Large and medium-sized parks demonstrated the highest aboveground carbon densities, measuring 32.56 Mg ha^{-1} and 23.48 Mg ha^{-1}, respectively. In contrast, urban forests recorded 15.45 Mg ha^{-1}, while small parks had 11.77 Mg ha^{-1}. This disparity is primarily attributed to the presence of dense, well-managed tree plantations. Total carbon densities, encompassing aboveground biomass and soil carbon, varied from 63 Mg ha^{-1} to 82.72 Mg ha^{-1}. Large parks exhibited the highest density at 82.72 Mg ha^{-1}, followed by urban forests at 80.75 Mg ha^{-1}, small parks at 66.12 Mg ha^{-1}, and medium-sized parks at 63.13 Mg ha^{-1}. The findings underscore the essential function of urban green spaces in carbon sequestration. Enhancing carbon storage in arid environments necessitates prioritizing the plantation of high-biomass tree species and increasing tree density in urban parks to promote sustainable urban ecosystems. This study can help city authorities to design parks to support climate resilience goals amplifying ecological and socioeconomic benefits. Thus leading Pakistan's commitment to carbon neutrality and SDG 11 (Sustainable cities)

Key Words: Biomass, carbon sequestration, urban ecosystem, soil carbon, tree diversity

1. Introduction

Carbon dioxide (CO_2) has been recognized as a major driver of climate change globally. The concentration of CO_2 in the atmosphere has increased from 280 ppm at the beginning of the Industrial Revolution to the present level of 426 ppm (Zhang *et al* 2024). Vegetation in urban areas especially in arid environments has become increasingly important in improving urban ecosystem resilience both to regulate urban microclimates and mitigate global climate change. Vegetation in urban areas may be an undervalued carbon sink (Nowak and Crane, 2002), however, it is a beneficial component of urban design and provides many socioeconomic and biophysical benefits, including the provision of recreational services, aesthetic value and improvement of biodiversity (Pasher *et al* 2014). Therefore, improving urban green infrastructure not only diminishes the ecological footprints of cities but also improves the quality of life of urban dwellers (Gómez-Baggethun and Barton, 2013). It was hypothesized that in arid urban environments, parks that are left more natural with limited human intervention and well-established trees tend to store much more carbon, both in the vegetation above ground and in the soil, compared to parks that are heavily managed.

The Intergovernmental Panel on Climate Change acknowledged the existence of five carbon pools in the terrestrial environment that entail biomass. These pools consist of aboveground biomass, belowground biomass, litter, woody debris, and soil organic matter. Vashum and Jayakumar (2012) stated that the above-ground biomass is the most important component of all carbon pools. The urban green zones can sink carbon in three main ways. First, plants transform carbon into biomass and then sequester it. Second, the presence of soil contributes significantly to carbon sequestration. Third, urban vegetation helps to reduce the need for cooling systems by providing shade and ventilation, which reduces heat generation within residential structures (Nowak *et al* 2013).

The ability of urban vegetation to store carbon is strongly shaped by the local climate, especially factors like rainfall patterns, drought frequency, and temperature (Jha and Srivastava, 2018). In arid climatic zones, long droughts and low rainfall can slow down plant growth, which limits how much carbon is stored in both the plants and the soil (Li *et al* 2024). On the other hand, when there is enough rainfall, vegetation tends to grow more actively, increasing the overall carbon storage capacity (Jha and Srivastava, 2018).

The climate also plays a key role in determining which types of trees are suitable for certain zones. For example, drought-tolerant species are more adapted to arid zones (Ryan, 2011). While these trees may grow more slowly than those in temperate or tropical climates, they are more resilient and can support long-term carbon storage in different ways (Rowland *et al* 2021). However, the intense heat common in arid cities can speed up the breakdown of organic matter in the soil, which may reduce the benefits gained from carbon stored in tree biomass (Conant *et al* 2011).

As a natural carbon sink, urban vegetation is essential in offsetting carbon dioxide (CO_2) emissions (Yasin *et al* 2024). Since atmospheric CO_2 has been linked to global climate warming (Salmond *et al* 2016), it is important to study how effectively vegetation can store carbon. Reliable estimates of carbon stock are vital to evaluating the variation of carbon budget caused by land cover change and significant to carbon accounting and trading to achieve the projected carbon emission reduction (Shen *et al* 2018).

Trees play a significant role in sequestering carbon and act as a sink in urban areas as well (Amoatey and Sulaiman, 2020). Due to their impressive growth rates, trees have a great potential to absorb CO_2 and effectively help in mitigating climate change (Byrd *et al* 2018). The amount of carbon sequestered by a tree can be determined by calculating the biomass accumulated below and above the ground level of the tree. The biomass is predominantly found in stems, roots, branches and small amounts in leaves (Zubair *et al* 2022).

Urban parks play a crucial role by providing numerous ecological services, such as carbon sequestration, air filtration, and climate moderation (Vieira *et al* 2018; Song *et al* 2020). Urban parks are essential components of terrestrial ecosystem carbon sinks, alleviating the adverse ecological effects of urbanization (Lahoti *et al* 2020). Enhancing green spaces in a country like Pakistan through urban parks is essential for achieving carbon neutrality and promoting sustainable development.

Previous studies on urban carbon sequestration have largely concentrated on temperate or non-arid regions (Shadman *et al* 2022; Bhera *et al* 2022; Ariluoma *et al* 2021; Havu *et al* 2021). Therefore, there is a gap in understanding of how park management practices affect carbon storage in arid urban environments (Moon et al. 2024). In Pakistan, and particularly in rapidly expanding cities like Multan, there is a notable lack of empirical research linking urban park design to carbon dynamics. This study seeks to fill these gaps by measuring carbon stocks across a range of park types within Multan's arid landscape and assessing how factors such as park size, vegetation composition, and horticultural practices influence carbon sequestration efficiency.

This study analyzed the effects of contemporary management practices regarding carbon density in urban parks. For this study, Multan City was selected, and an analysis of multiple functional parks was conducted. The study examined the aboveground biomass carbon as well as soil carbon concentration along with related parameters. The study aimed to achieve the following specific objectives: (a) identifying variations in carbon storage among different functional urban parks and urban forests and (b) comparing carbon storage across various functional urban parks and urban forests to identify significant indicators influencing carbon storage. This research was carried out in various urban parks in Multan, and the findings provide valuable insights for achieving sustainable development goals in the arid region. Based on the above objectives, the following hypotheses were formulated to guide our present study:

Hypothesis 1: Urban parks with larger surface areas possess significantly higher carbon storage capacity compared to smaller parks.

Hypothesis 2: Vegetation type and density within parks significantly influence their overall carbon sequestration potential.

Hypothesis 3: Soil organic carbon varies significantly with land-use intensity and park management practices.

2. Materials and Methods

2.1. Study area and Sample design

The city of Multan is located in the southern region of Punjab, Pakistan and is known for its history and cultural heritage. Located between 71° 00′ 54″ E to 72° 58′ 43″ E longitude and 29° 27′ 21″ N to 30° 45′ 30″ N latitude, it is the oldest region in South Asia. It has significant economic and heritage value. The area has a diverse topography with agricultural lands and various historical landmarks, resulting in a dynamic and multifaceted area. Multan has seen unusual weather in recent years, with temperatures ranging from -1°C (30°F) to 52°C (126°F). Precipitation is about 186 mm (7.3 in), and heat waves are frequent in May and June. Table 1 demonstrates our attempt at distinguishing urban parks and urban forests by their scale and characteristics.

2.2. Park Classification

In Multan City, according to the datasheet provided by the Pakistan Horticulture Authority (PHA) for 2024, the number of constructed park areas was 89, and PHAPHA managed all these parks managed all these parks. Of these, 68 parks were developed, 2 were underdeveloped, and 19 were non-developed. The parks were categorized into three classifications: small (less than 1 acre), medium-sized (1 to 3 acres) and large (greater than 3 acres). Out of these 68 developed parks, 32 were small, 16 were medium-sized, and 20 were large parks. Small parks were located in the centre of the residential colonies, medium-sized parks in the market and near the Multan Metro stations whereas the large parks were located in the city centre.

An 8-acre urban forest is located within the university campus. The lottery method of simple random sampling was adopted to select the parks for sampling from each park category. Sampling was done from 9 urban parks (3 from each category) as well as from urban forests for the estimation of carbon stocks.

Table 1. Key attributes of various urban parks and urban forests

Functional parks	Park name	Longitude	Latitude	Area/hectare	Characteristics
Small Parks	Rotary Park	30.2093193 N	71.4748219E	0.41	In front of metro station.
	Illyas Town Park	30.2236458 N	71.4838532 E	0.12	In the center of buildings.
	Fatima Jinnah Park	30.2472 N	71.4791 E	0.4	Surrounding by different buildings.
Medium Parks	Gol-Bagh Park	30.131717 N	71.282302 E	1.11	In the center of market.
	Jalal Park	30.2282 N	71.4765 E	0.6	Surrounded by colony and commercial markets
	Model Town Park	30.2338 N	71.4651 E	1.3	In the housing society
Large Parks	Dogar Park	30.1875 N	71.4488 E	1.78	In the Centre of city.
	Madni Park	30.1211.52 N	71.3053.64 E	2.51	Surrounded by many commercial buildings.
	Muzaffarabad Park	30.2361N	71.4917 E	1.9	In between the market
Urban Forest	Bio Park	30.2675 N	71.5019 E	10.12	In the BZ. University.

2.3. Data Collection

Field survey and inventory of the selected parks and urban forest was carried out between March and June 2024. A non-destructive approach was applied to estimate carbon stocks. Keeping in mind the size of functional parks and urban forest, different ways were used for data collection. For example, for small and medium-sized parks, the total park area was investigated. As the area of these parks was very small, all the trees were easily counted and measured. For large parks and urban forests, quadrates of areas of 15*15 m and 20*20 m were used. The number of quadrants depended on the park area. GPS was used to record the latitude and longitude values, whereas the characteristics of parks were noted with visual observations, such as their surroundings. Data regarding growth parameters (diameter at breast height (DBH) and tree height) was measured by using a calliper and a clinometer. To minimize the error, all the vegetation parameters were measured two times. For soil carbon estimation, soil sampling was randomly done at 0-40 cm soil depth from selected parks and urban forests under the tree canopy by a soil sampler having 200 cm^3 and 52 cm dimensions. Sampling was done in cardinal directions, and a composite sample was made. Overall, 36 soil samples from each park category and urban forest were collected. Once sampling was completed, soil samples were packed into zip-locked plastic bags and labelled appropriately.

2.4. Biomass carbon and tree density estimation

As tree height and DBH were considered the main parameters for the estimation of biomass, therefore species-specific allometric equations published in the literature were used for the estimation of biomass and carbon of each surveyed tree (Jo *et al* 2019). Species-specific equations were used to ensure the carbon calculated in the present study can reflect the actual carbon storage. The carbon stock of the tree was determined by applying a standard factor of 0.5 to the biomass, as outlined by the Intergovernmental Panel on Climate Change (Prommer *et al* 2020). The allometric equations used in this study are presented in Table 2.

Tree density and diversity indices were calculated using the following equations, as explained by Nandal et al. (2023b).

$$\text{Tree density (ha}^{-1}) = \frac{\text{Total number of trees of a specific species}}{\text{Total area (ha)}} \quad (1)$$

$$Ds = \frac{\Sigma n(n-1)}{N(N-1)} \quad (2)$$

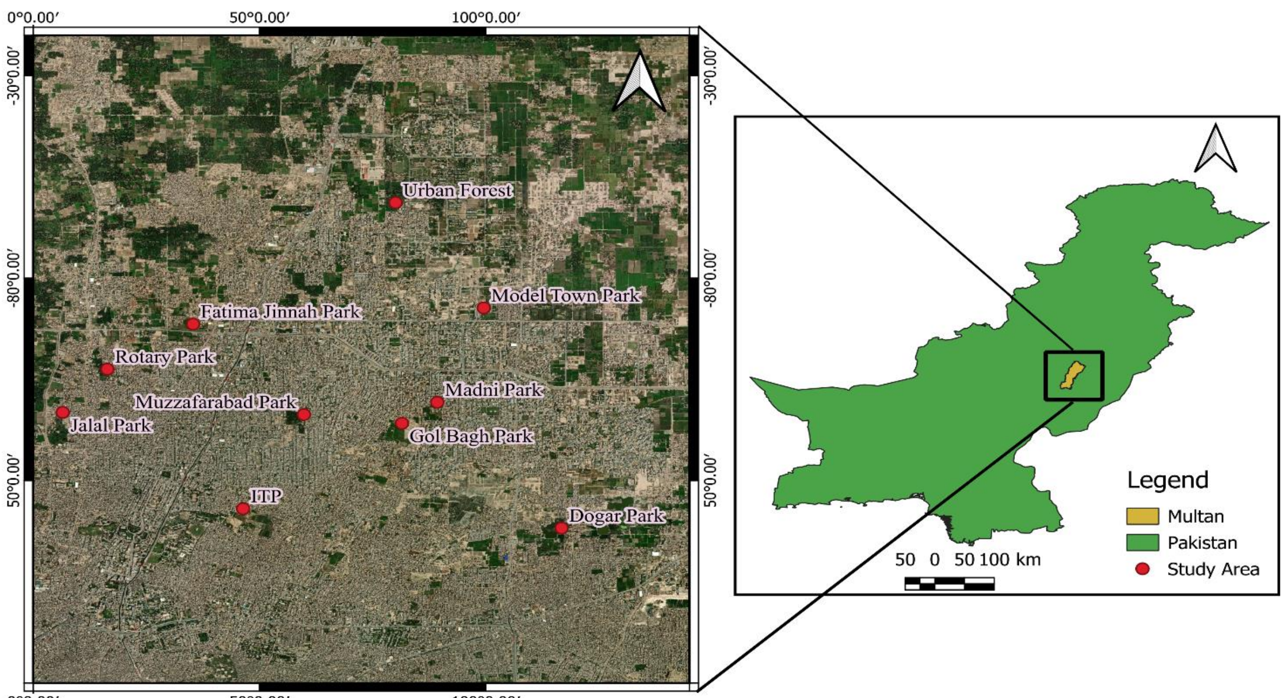

Figure 1. Location map of the study area showing the distribution of urban parks of Multan.

2.5. Soil carbon estimation

The soil samples were brought to the laboratory of the department of Forestry and Range Management, BZU. The samples were sieved to eliminate the stones; however, small roots were kept. Subsequently, the samples underwent milling for additional analysis. The categorization of soil carbon storage includes both inorganic carbon storage and organic carbon storage. Organic carbon, which comes from decomposed plant material, indicates how much carbon is stored through vegetation. In contrast, inorganic carbon—mainly in the form of carbonates—is more common in arid soils like those in Multan, where organic matter is low and mineralization happens quickly. Including both types provides a more complete picture of how carbon behaves in Multan's soils. The estimation of soil organic carbon (SOC %) was conducted using the standard method outlined by Walkley and Black (1934). The soil's inorganic carbon was removed from organic carbon indirectly by using the HCL solution method (Zhang *et al* 2024). The soil carbon stock on a hectare basis was later determined by multiplying the values of SOC %, BD and soil depth as described by Gogoi *et al*. (2021).

Table 2. Allometric equations applied for the estimation of tree biomass

Tree species	Equations used for biomass estimation	References
Azadirachta indica	$AGB = 0.213 \times DBH^{2.109}$	Nandal *et al* 2023b
Albizzia procera	$LnY = -3.1114+0.9719 \times \ln D^2H$	Brown *et al* 1989
Alstonia scholaris	$LnY = -3.1114+0.9719 \times \ln D^2H$	Brown *et al* 1989
Callistemon viminalis	$AGB = 0.0509 \times \rho \times DBH^2 \times H$	Nath *et al* 2019
Dalbergia sisoo	$Y = -11.0369 + 3.6005 \times DBH$	Lodhiyal and Lodhiyal, 2003
Albizzia lebbek	$AGB = -0.2976+0.4172D$	Singh *et al* 2011
Eucalyptus camaldulensis	$LnY = -2.2660+2.4663 \times \ln D^2H$	Hawkins 1987

Ficus religiosa	AGB=−0.103+1.766(ln D)+0.508(ln H)	Pati *et al* 2022
Bouhinia variegata	AGB = 0.675 (ln (D^2 × H)) + 0.252	Pati *et al* 2022
Melia azaderach	AGB= 42.31+9.52×10^{-5}×D^2H	Nandal *et al* 2023b
Magifera indica	AGB= 2.886(PBG × NPB)$^{1.039}$	Ganeshamurthy *et al* 2016
Morus alba	ABG= −3.206+1.337 lnpD2H	Chaturvedi and Raghubanshi, 2013
Syzygium cumini	LogY = -1.2066+0.9872×logD^2H	Rai1984
Conocarpus erectus	AGB= 0.0509×ρ×DBH^2×H	Nath *et al* 2019
Ficus carica	AGB= 0.0509×ρ×DBH^2×H	Nath *et al* 2019
Ficus virens	AGB=−0.103+1.766(ln D)+0.508(ln H)	Pati *et al* 2022
Pongamia pinnata	AGB=1.187+1.107(lnD)+0.980(ln H)	Pati *et al* 2022
Terminalia arjuna	AGB= 0.0509×ρ×DBH^2×H	Nath *et al* 2019
Cassia fistula	AGB = 0.863 (ln (D^2 × H)) + 0.517	Pati *et al* 2022
Terminalia chubula	AGB= 0.0509×ρ×DBH^2×H	Nath *et al* 2019

2.6. Statistical analysis

Statistical analyses were performed utilizing Origin Pro 2024 and Statistics 10 software. One-way ANOVA and t-tests were utilized to assess whether the mean values of aboveground carbon and soil carbon exhibited significant variation across different functional urban parks and urban forests, assuming a normal distribution of independent samples. When the data did not conform to a normal distribution, the Kruskal-Wallis test was utilized, accompanied by post hoc tests for additional analysis.

3. Results

3.1. Growth parameters and tree density

In this study, we surveyed 8 families, 16 genera, and 25 species, including 16 deciduous species and 9 evergreen species. The dominant tree species were *Alstonia scholaris, Dalbergia sissoo, Pongamia pinnata, Ficus virens, Cassia fistula, Conocarpus erectus* and *Azadiracta indica*. We explored the distribution of diameter at breast height (DBH) and height of trees in different functional urban parks and urban forests (Figure 2). The trees in small parks were dominated by small to medium-sized trees (DBH 35cm-45cm and <15cm, H 15-25m), while medium parks and large parks were dominated by medium to large size trees (35-45cm,>45cm). The Urban forests were dominated by medium-sized trees (15-25cm, 25-35cm), as depicted in Figure 2A.

Trees having DBH greater than 45 cm were dominant in the large park (38.2%), followed by medium parks (30.1%), whereas the minimum percentage of trees with DBH > 45 cm was estimated in small parks (9.7%) (Figure 2A). Tree height varied significantly across all studied parks (Figure 2B). The trees having a height greater than 25m were dominant in the large park (39.5%), followed by medium parks (27.3%), urban forests (18.51%), and small parks (14.7%). All the parks have different ranges of tree sizes and DBH; however, large parks have trees with greater DBH and height than other categories of urban parks and urban forests.

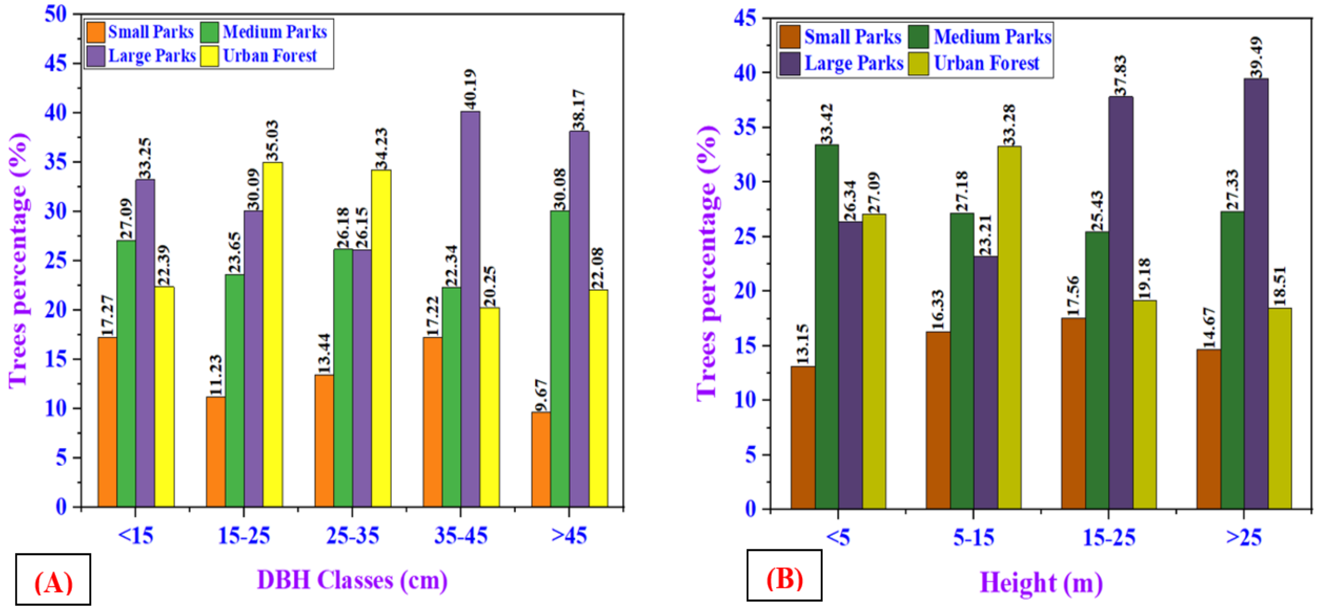

Figure 2 (A-B). The distribution of tree frequency in the study was classified by DBH (a) and height (b).

The differences between biodiversity and tree density were significant in different urban parks and urban forests (Figure 3). After the complete survey of all park categories, higher biodiversity was observed in the small parks with a value greater than 0.6. However, the lowest tree density was measured in small parks with a value of less than 300 trees per hectare (Figure 3B). In comparison to small parks, the biodiversity of the selected plots was low (<0.6) in both medium and large parks; however, the tree density of these parks was much higher than the small parks (>488.98 trees per hectare). The highest tree density was measured in urban forests (1244.7 trees per hectare) compared to the functional urban parks (Figure 3B).

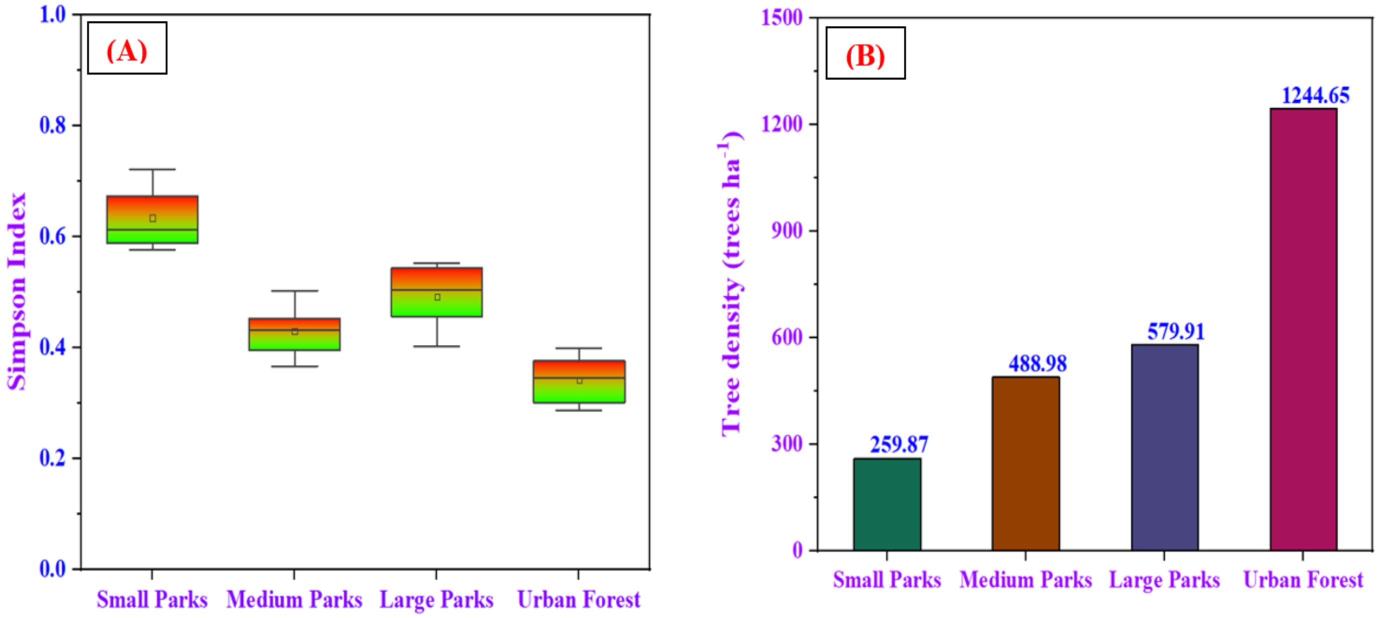

Figure 3 (A-B). Biodiversity and tree density in different urban parks and urban forests (df=3).

3.2. Carbon density and CO_2 sequestration.

The aboveground biomass and carbon density in the studied parks gradually increased with the increase of park scale (Figure 4A). The highest mean aboveground biomass and carbon density was estimated in the large parks (67.83 Mg ha^{-1} and 32.56 Mg ha^{-1}), followed by the medium-sized parks (48.92 Mg ha^{-1} and 23.48 Mg ha^{-1}) and urban forest (32.19 Mg ha^{-1} and 15.45 Mg ha^{-1}), whereas lowest mean carbon density amount was observed in the small parks (24.53 Mg ha^{-1} and 11.77 Mg ha^{-1}). The significance test revealed highly significant variations ($p < 0.05$) in aboveground tree biomass and carbon density when comparing small parks to other functional parks. The biomass and carbon density in the urban forest were significantly lower ($p = 0.016$, $p = 0.041$) than in medium-sized and large parks (Figure 4A). The sum of organic and inorganic soil carbon density ranged from 39.65 Mg ha^{-1} to 65.3 Mg ha^{-1} in the study area. The soil carbon density in the study area was highest (65.3 Mg ha^{-1}) in urban forests, as depicted in Fig. 4B, followed by small parks (54.35 Mg ha^{-1}), large parks (50.17 Mg ha^{-1}) and medium-sized parks (39.65

Mg ha^{-1}). The soil organic carbon density was slightly higher than the soil inorganic carbon density in the study area. The findings showed that the soil carbon density in medium-sized parks was significantly lower than that in urban forests, large parks, and small parks ($p = 0.034$, $p = 0.020$, and $p = 0.017$, respectively). On the other hand, small parks had a higher soil density, which was almost identical to that of large parks ($p = 0.716$), but it was lower than that of urban forests ($p = 0.030$).

Figure 4C demonstrates the total carbon density (biomass carbon + soil carbon), and it ranged from 63 Mg ha^{-1} to 82.72 Mg ha^{-1}. Overall, large parks have the highest total carbon density (82.72 Mg ha^{-1}), followed by urban forests (80.75 Mg ha^{-1}), small parks (66.12 Mg ha^{-1}) and medium-sized parks (63.13 Mg ha^{-1}). Figure 4 shows the contribution of studied parks and urban forests in CO_2 sequestration. The results depicted that the contribution of large parks was highest (39.1%) in CO_2 sequestration, followed by medium-sized parks (28.2%), whereas the contribution of small parks was lowest (14.1%), as depicted in Figure 4C.

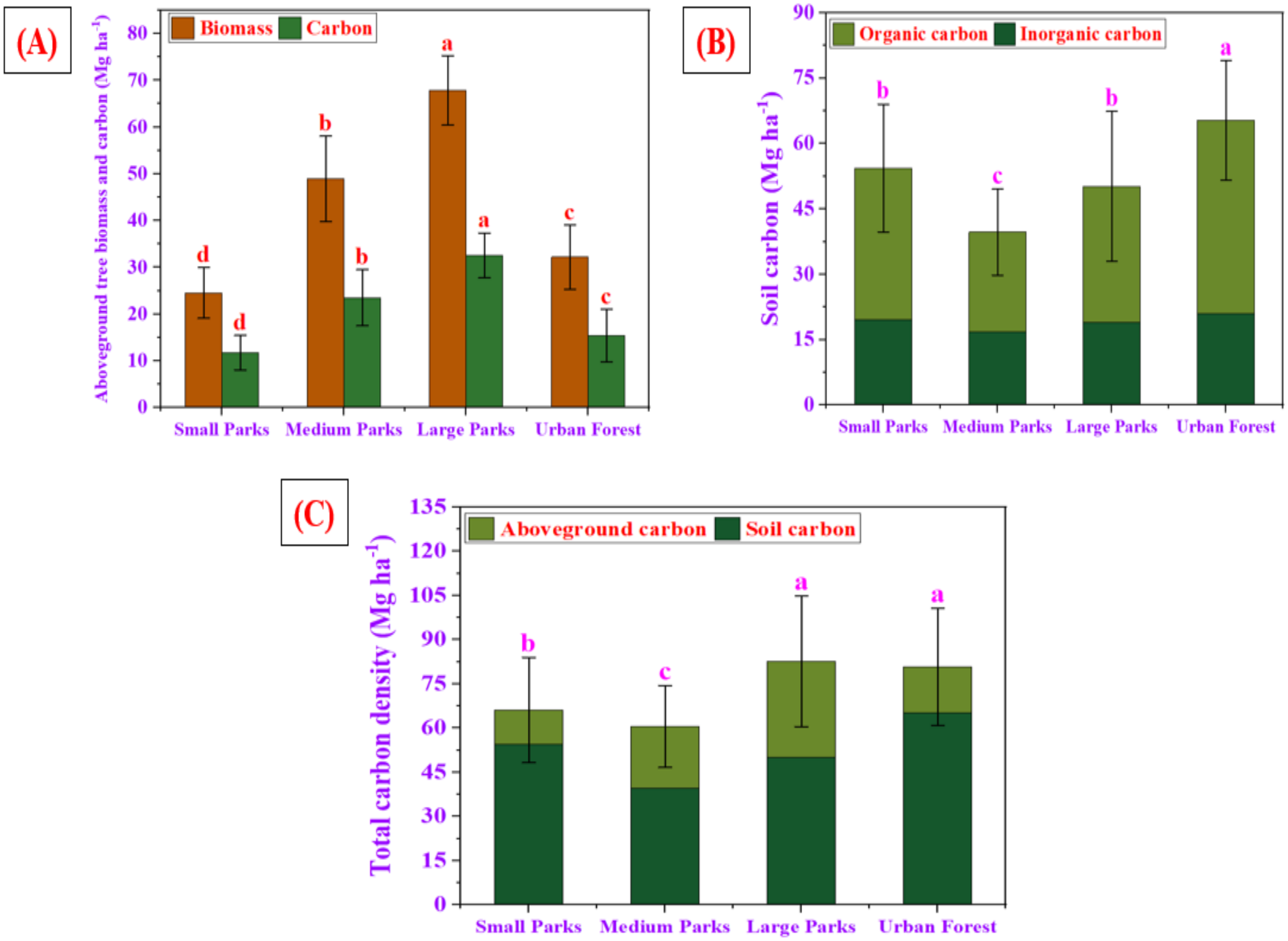

Figure 4. Aboveground carbon density; df=3, *$p < 0.0329$*(a), soil carbon density df=3, *$p < 0.0401$* (b), and total carbon density df =3, *$p < 0.0237$* (c) of different urban parks and Forest.

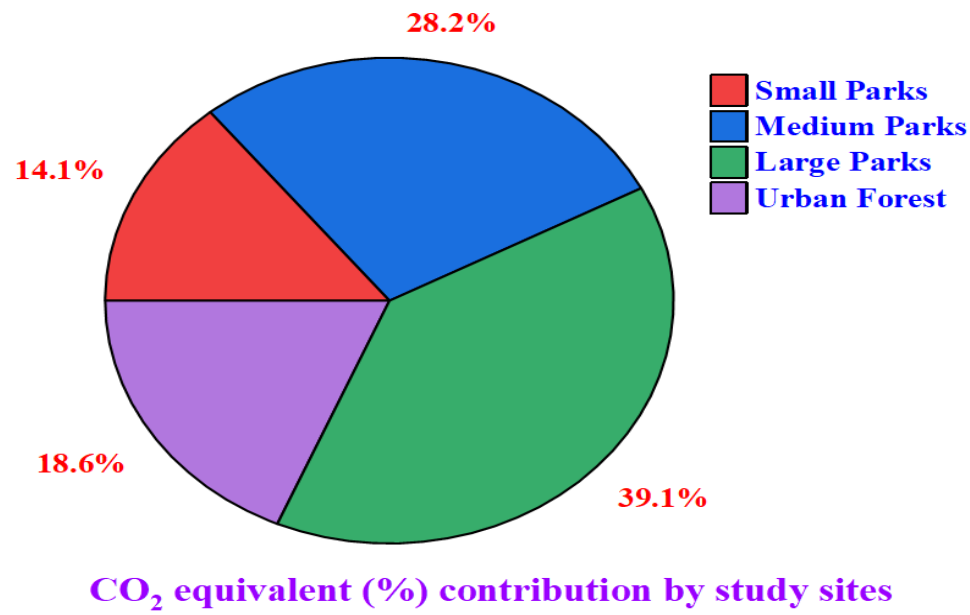

Figure 5. CO_2 equivalent (%) contribution of urban parks and urban forest.

3.3. Carbon sequestration contribution of trees and Principal Component Analysis (PCA)

The distribution of carbon sequestration among tree species in functional parks and urban forests reveals notable variations (Figure 6). *Dalbergia sissoo* contributed the greatest share (24.5%) in small parks, followed by *Alstonia scholaris* (21.7%) and *Bauhinia variegata* (12.7%), while *Cassia fistula* had the least share (5.3%). *Cassia fistula* and *Eucalyptus camaldulensis* were found as leading tree species (15.9% each) in medium parks, while storage of carbon was the least (2%) in the case of *Callistemon viminalis* (Figure 6). In large parks, *Eucalyptus camaldulensis* with 12%, *Dalbergia sissoo* with 11.4% and *Azadiracta indica* with the lowest share of 3% were significant contributors (Figure 6). The urban forests were dominated by *Morus alba* (18.3%), *Eucalyptus camaldulensis* (15.01%), *Mangifera indica* (14.3%) and had the least carbon stores in *Albizia lebbeck* (4.99%). Results suggest that the species *Dalbergia sissoo* and *Eucalyptus camaldulensis* play an important role in the potential carbon sequestration in urban green spaces.

The relationship between park types (small, medium, large parks and urban forests) and ecological variables, including carbon, biomass and tree characteristics, is visualized through the Principal Component Analysis (PCA) biplot (Figure 7). PC1 explains 67.16% of the variance and is strongly correlated with carbon storage, biomass, and tree height within a plot. These variables are closely associated with urban forests and large parks. The second principal component (PC 2), which explains 27.25%, reflects higher relevance for urban forests and is related to species diversity (SCD) and tree density (TD). PC1 variables are negatively associated with small parks in that they contribute little to carbon and biomass (Figure 7).

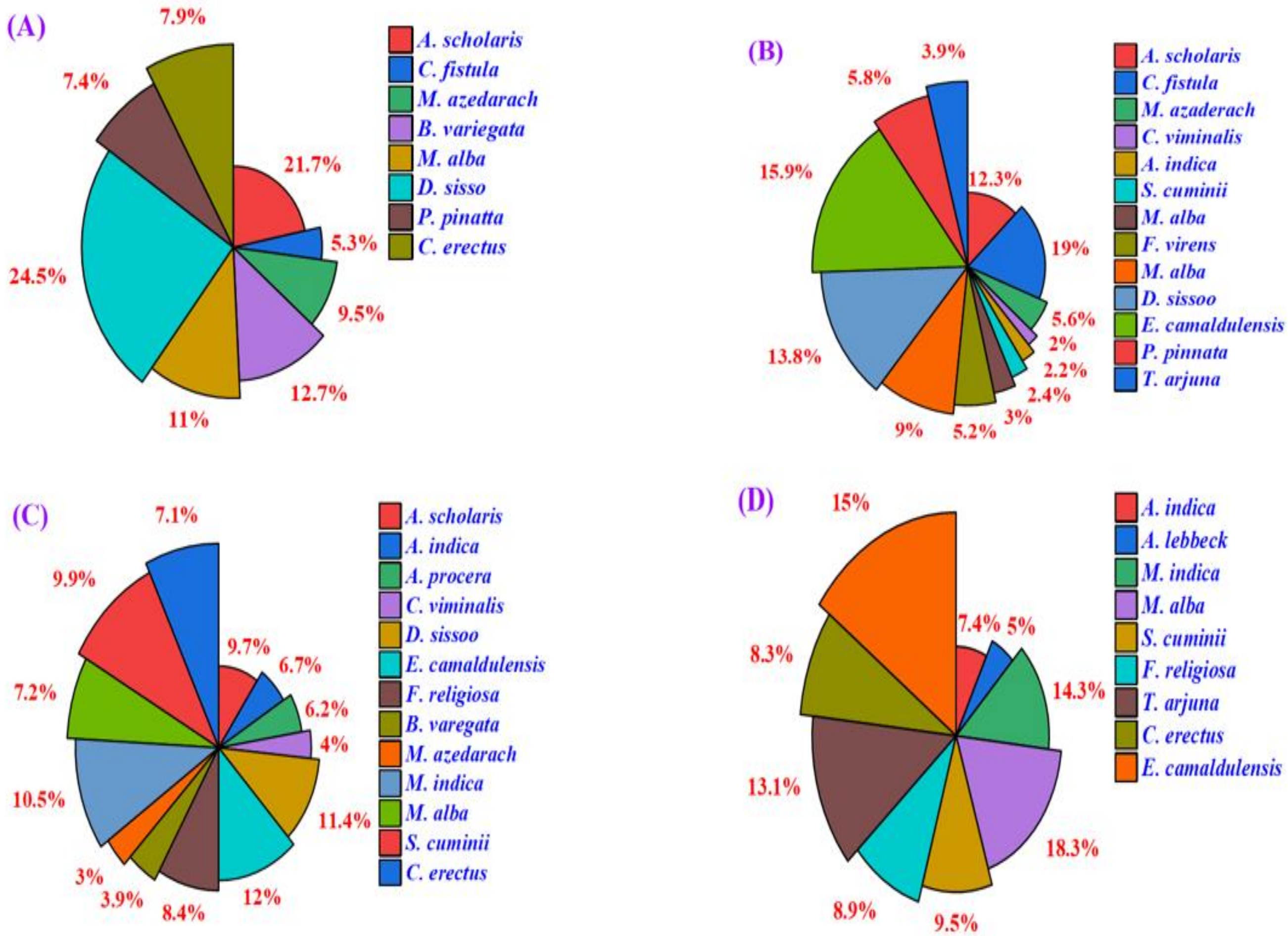

Figure 6. Carbon sequestration contribution by different tree species within urban parks and urban forests.

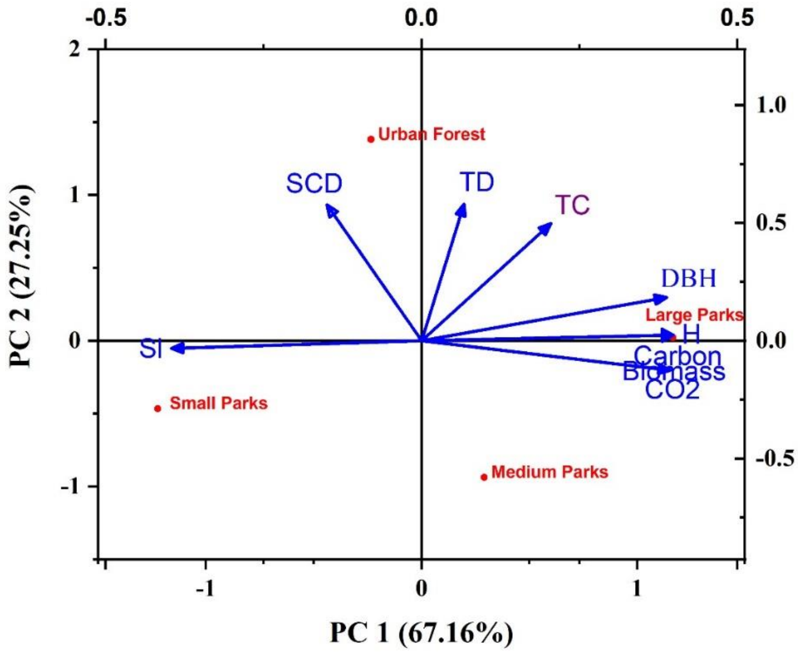

Figure 7. Principal Component Analysis (PCA) biplot between park types and studied variables

4. Discussion:

This study highlights a key relationship between the carbon sequestration potential among different types of urban parks in a metropolitan city in Pakistan. It was depicted that the size, management and types of vegetation in a specific park influenced the carbon sequestration potential of that urban space. Our study depicts a key association of park size in determining the carbon storage, tree height and biomass accumulation in an urban landscape. For instance, "Large parks" had shown the highest aboveground biomass and total carbon density (67.83 Mg ha^{-1} and 82.72 Mg ha^{-1}, respectively), thus contributing substantially to carbon sequestration (39%). On the other hand,, urban forests that are larger in size but lack management showed comparatively low aboveground biomass and total carbon density compared to medium and large urban parks. This shows that horticulturally managed urban spaces had more carbon sequestration potential.

Our results are in accordance with similar studies conducted in large metropolitan cities of the world. For example, studies carried out in large cities, i.e. Beijing (Wang *et al* 2021; Zhang *et al* 2024), Rome (Gratani *et al* 2016; Fares *et al* 2020), Pune (Shinde and Mahajan, 2015, Vijayalaxmi and Dnyanesh, 2021), Dhaka (Shadman *et al* 2022) revealed that managed large size parks depicted high carbon sequestration potential as compared to urban forests and small sized parks. This could be explained by the fact that urban forests normally are not much managed horticulturally (Wang *et al* 2021) and small-sized parks lack trees with greater size and density (Zhao *et al* 2020). The same reason was mentioned in a study conducted by Zhang *et al*. (2024), which reported higher carbon density in somewhat larger parks due to relatively greater tree size and density. While similar research in Pune and Rome displayed urban forests to have lower carbon sequestration value due to possible ongoing felling cycles (Vijayalaxmi and Dnyanesh, 2021; Gratani *et al* 2016).

The vegetation observed in the studied parks was mostly ornamental. Most dominant being the native trees such as *Alistonia Sochalirs and Melia Azaderach*. It was observed that *Alistonia Sochalirs* (21.5%) and *Delbergia sissoo* (35.9%) displayed the highest potential in terms of carbon sequestration. According to the literature, trees having faster growth rates, broad crowns and dense foliage results in higher carbon sequestration capacity (Jin *et al* 2023; Anjali *et al* 2021; Weissert *et al* 2017). The reported trees in the study depict the above-mentioned characteristics, thus explaining their higher carbon storage capacity. Moreover, various studies have shown local perennial horticultural trees have 50-100 times more biomass. Thus, it has more capacity to absorb CO_2 and has a greater chance of curbing global climate change effects (Ilakiya *et al* 2024).

It was seen that larger parks had trees with greater diameter (>45 cm) and height (25m). These results are concordant with studies of urban parks in China. As trees in those parks were quite old, having significant importance both culturally and historically (Zhang *et al* 2024; Wang *et al* 2021). Another reason for this fast growth could be credited to daily horticultural management practices (Singkran 2022). This allows the tree to grow faster and thus increase its carbon-storing potential (McPherson *et al* 2013). In our study, Urban forests and small parks displayed the lowest values for tree diameter and height. It is also visible in similar studies, which depict that urban forests might be involved in felling or thinning cycles (Vijayalaxmi and Dnyanesh, 2021; Gratani *et al* 2016) and small parks due to lack of park size have such lower values (Kurtz *et al* 2024).

The study depicts that smaller parks showed more diversity in terms of vegetation. It usually contrast with wider literature available that larger parks would tend to host a wider variety of species solely due to park size (Massoni *et al* 2018; Deane 2022). Nevertheless, many studies have shown that smaller parks can also exhibit higher tree diversity per unit area (Nielsen *et al* 2014; La Sorte *et al* 2023). Most of these studies have reasoned upon the fact that these small parks usually depict a higher edge effect, i.e. edge-to-interior ratio, thus creating diverse microhabitats (La Sorte *et al* 2023; Jasmani *et al* 2017).

Our study reveals significant variations in aboveground carbon density (ACD) and aboveground biomass (AGB) among various functional park categories. Large parks exhibited the highest values (32.56 Mg ha^{-1} for ACD and 67.83 Mg ha^{-1} for AGB). In contrast, the lowest was depicted by the small parks (11.77 Mg ha^{-1} and 24.53 Mg ha^{-1}). Our results concord with Devagiri *et al* (2013), which depicts similar AGB (20-65 Mg ha^{-1}) and ACD (9.4- 25.9 Mg ha^{-1}) values. This can be accounted for due to similar climatic factors prevalent and the origin of species. It can also be explained by the fact that large mature trees are most prevalent in large parks which increases the carbon storage values. In another similar study conducted in Delhi, the AGB values ranged from 18 to 60 Mg ha^{-1} (Snehlata *et al* 2021). The higher range of AGB in these parks also concords with our results and can be justified by the native trees and suitable subtropical growing climatic conditions. The smaller parks in both studies displayed the lowest values due to their smaller size and fewer large trees. However, in a similar study conducted in Beijing, the smaller parks displayed higher carbon storage values (23.88 $t{\cdot}hm^{-2}$). The authors link these higher values due to the extensive growth of shrubs and herbs alongside a few large trees (Zhang *et al* 2024). This is a testament to the role of shrubs and herbs in the carbon sequestration of urban spaces in metropolitan cities.

Most studies on carbon stock assessment in urban green spaces have placed verdict on parks to have the most potential for carbon sequestration. For example, Canedoli *et al* (2020) found urban parks to exhibit higher average SOC stocks (7.9 ± 2.4 kg m^{-2}) compared to urban non-parks (5.3 ± 2.5 kg m^{-2}), suggesting a strong role of urban parks in carbon sequestration. A similar study in South Korea assessed soil C stocks in various urban green spaces, including parks, roadsides, school forests, and riversides (Yoon *et al* 2016). It was observed that among all urban green spaces,, and parks depicted the highest soil carbon storage capacity. Our study, on the other hand, depicted urban forests to have the highest soil carbon density (39.65 Mg ha-1 to 65.3 Mg ha-1). This high-end values can be credited to higher tree density and more diverse vegetation. Other studies have also highlighted that intensive soil management practices often lead to soil-disturbing activities that would reduce the accumulation of soil organic content. (Bae and Ryu, 2015; Zou *et al* 2012; Zhang *et al* 2012; Nowak *et al* 2013) This reason could possibly explain the lower carbon storage capacity of small and medium parks. These same factors were also supported by Bae and Ryu (2015), in which the authors highlighted that the small and medium parks often have high public incoming. This affects the soil compaction due to trampling by visitors, with soil hardness reaching hundreds or even thousands of kilograms per cubic centimetre, affecting the aeration and ability of soils to supply water and fertilizer for plant roots (Zou *et al* 2012).

Our study highlights that the area of urban parks is undoubtedly an important factor influencing their carbon storage potential. Larger parks often support greater vegetation diversity and quantity, which naturally enhances carbon storage (Massoni *et al* 2018). As parks expand, they tend to form more self-sustaining ecosystems with less intensive management requirements (Sarı and Bayraktar, 2023; Ren *et al*

2013). However, our findings suggest that carbon sequestration efficiency (i.e., carbon density) is influenced more significantly by management practices than by park size. Accordingly, we classified urban parks into four distinct types, considering both size and management practices, to better understand their role in carbon sequestration.

Small Parks, located within densely populated urban areas, are typically under intensive management, including regular irrigation, fertilization, and seasonal planting (Zhang *et al* 2024; Vijayalaxmi and Dnyanesh, 2021). Despite significant variations in size, our results indicate minimal differences in carbon density within this group. By improving management strategies, small parks have the potential to greatly enhance carbon sequestration efficiency. Furthermore, introducing multi-layered vegetation—such as shrubs and grasses beneath tree canopies can rapidly improve carbon storage while also enriching biodiversity. Such strategies can simultaneously provide shade, reduce urban heat, and mitigate climate change effects by lowering air and surface temperatures (Massoni *et al* 2018; Yasin *et al* 2024).

Medium-sized parks often consist of naturally growing vegetation and require management practices focused on newly introduced species. Effective practices include proper fertilization, retention of organic matter (e.g., dead branches and fallen leaves), and artificial introduction of soil fauna like earthworms to enhance soil permeability and organic decomposition. By adopting such measures, medium-sized parks can significantly increase carbon density (Zou *et al* 2012; Zhang *et al* 2012; Nowak *et al* 2013).

Large Parks typically located in rural or peri-urban areas, large parks often consist of natural vegetation with minimal management. However, strategic interventions, such as reducing natural disturbances, conducting fire patrols, and prohibiting unauthorized tree-cutting, can further improve tree density and carbon sequestration efficiency (Zhang *et al* 2024; Gratani *et al* 2016).

The present research explains a crucial understanding of the biophysical elements of carbon sequestration in urban parks, but it acknowledges a significant limitation: the lack of experimental or survey-based data on park usage capability and human activities. This research gap limits a detailed knowledge of how social usage elements overlap with ecological procedures. Urban parks are inherently socio-ecological systems, where visitor behaviours like recreational activities, foot traffic, and maintenance practices may directly or indirectly affect carbon sequestration capability through mechanisms such as vegetation trampling, soil compaction, and sudden shift to microbial communities (Bisht *et al* 2024). For example, maximum user density in popular parks could increase soil compaction and reduce pore spaces and water penetration, thereby restricting root growth and microbial activities, which are crucial for soil organic carbon retention (Millward *et al* 2011; Sarah *et al* 2015). Similarly, trampling of understory vegetation or frequent mowing of lawns to accommodate recreational pores may demolish upper-ground biomass, a main element of carbon sequestration.

Existing research underlines the dual role of human activity: although excessive use can demolish ecological functions, tactical management practices may mitigate these effects. For instance, Setälä *et al*. (2016) stated that soil compaction in high-traffic areas of urban parks minimized carbon sequestration by 20% compared to undisturbed areas. On the other hand, selected strategies and restorative vegetation in heavily visited parks have been shown to balance usability with ecological resilience (Talal *et al* 2020). These results suggest that visitor density cannot estimate carbon sequestration capacity alone; rather, it is the intermediate among usage patterns, management practices, and vegetation type that outlines overall capacity.

To address these study gaps, future research must adopt a comparative approach by analyzing parks across gradients of user density. Such findings could integrate methodologies such as user surveys, pedestrian counters, and spatial soil/vegetation sampling to quantify how visitor traffic correlates with the carbon sequestration matrix. For instance, pairing LiDAR-oriented biomass measurement with soil core data from low- high-use areas within the same park could uncover the effects of human activities from biophysical variables. Moreover, leveraging geospatial methods to map visitation hotspots against carbon sequestration rates may disclose practice understanding for park design, like redirecting footpaths away from ecologically sensitive areas or promoting native vegetation in high-impact zones.

The oversight of human dynamics in the present study shows an opportunity for policymakers to implement adaptive management practices that correspond to recreational needs with ecological aims. For example, rotating event locations in parts that significantly preserve chronic soil compaction or incorporating carbon-friendly landscapes (e.g., replacing frequently mowed lawns with perennial meadows) could accelerate sequestration while maintaining visitor satisfaction. Moreover, community-based initiatives like citizen science programs assessing soil health could foster stewardship while generating localized data on human-ecological interactions.

The findings highlight the important role urban parks play in capturing and storing carbon—especially in arid cities like Multan. Larger parks with mature trees were found to store the most carbon, with some holding up to 82.72 megagrams (Mg) per hectare. Based on this, city planners should aim to include parks that are at least 5 hectares in size in new urban developments. Just 1,000 square meters of such green space can absorb about 8.27 Mg of carbon each year. That said, smaller parks (less than 2 hectares) still have value and shouldn't be ignored. With the right management, such as layered planting, improving soil health, and avoiding soil compaction, these smaller spaces can boost their carbon storage by up to 40%, even in crowded neighbourhoods.

5. Policy Recommendation

To get the most out of park spaces, municipal policies should require a minimum level of plant diversity. For example, at least 30% of the trees should be fast-growing native species such as *Alstonia scholaris* and *Dalbergia sissoo.* It's also important to limit the amount of hard surfaces like concrete paths and patios, as these reduce the space available for trees and plants to grow. For urban forests, stronger protections against illegal logging and encouraging natural growth can raise their carbon storage capacity by 25–30%. Designing parks to support climate goals, such as planting shade trees near homes to lower air conditioning use, can increase both environmental and social benefits. This approach supports Pakistan's efforts toward sustainable cities (SDG 11) and reaching carbon neutrality by 2050. Additionally, based on these findings, we have also suggested that urban park managers should balance ecological conservation with recreational access, for example, by:

- ✓ Zoning high-traffic areas and protecting core vegetated zones.
- ✓ Designing walking paths to minimize vegetation damage.

6. Periodically restoring compacted soils through mulching or aeration practices.**Conclusion**

Urban parks play a crucial role in mitigating climate change by acting as carbon sinks, particularly in arid regions where vegetation is limited. This study reveals that large parks in Multan, Pakistan, exhibit the highest carbon densities, reaching 82.72 Mg ha^{-1}, highlighting the significance of park size, tree diversity, and effective management in enhancing carbon sequestration. While urban forests store substantial soil carbon, their aboveground biomass accumulation remains lower than that of managed parks. Medium-sized parks contribute moderately, whereas small parks, despite their limited area, display notable biodiversity, suggesting that optimized management can enhance their carbon storage capacity. Tree species such as *Dalbergia sissoo* and *Eucalyptus camaldulensis* were identified as key contributors to carbon sequestration, accounting for 24.5% and 12.0% of the total sequestration, respectively. Soil carbon storage varied, with urban forests demonstrating the highest levels, but frequent soil disturbances in small and medium parks reduced their sequestration potential. The findings emphasize that increasing tree density, preserving mature trees, and reducing disturbances such as excessive pruning and soil compaction can significantly improve carbon sequestration. Additionally, integrating multi-layered vegetation and employing sustainable park management strategies can enhance the ecosystem services provided by urban green spaces. Future urban planning should focus on optimizing green infrastructure by prioritizing large parks while enhancing small and medium parks through mixed vegetation strategies. Furthermore, long-term monitoring programs and policy-driven initiatives should be implemented to ensure urban parks maximize their role in climate change mitigation and environmental sustainability.

Conflicts of interest

The authors declared that there are no conflicts of interest.

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