CARBON STOCK EVALUATION IN NATIVE AND EXOTIC TREE SPECIES USING MULTIPLE ALLOMETRIC EQUATIONS: INSIGHTS FROM INDIA'S GREENEST UNIVERSITY

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ABSTRACT

Understanding the dynamics of tree carbon stock in urban green spaces is critical for sustainable ecosystem management and climate change mitigation. This study evaluates carbon stock in native and exotic tree species at India's greenest university (Maharshi Dayanand University) using four different allometric equations. A total of 5742 trees (22.81 trees/ha) were analysed, representing 56 species from 28 families. Tree parameters showed substantial variation. Diameter at breast height (DBH) ranged from 10.21 cm (*Citrus limon*) to 24.29 cm (*Ficus benghalensis*), with an average of 16 cm. Basal area (BA) ranged from 0.008 m²/tree to 0.046 m²/tree, with an average of 0.020 m²/tree. Biomass ranged from 20.22 kg/tree (*Pterospermum acerifolium*) to 194.82 kg/tree (*Casuarina equisetifolia*), with an average of 70.35 kg/tree, totalling 403.95 Mg. In comparison, the mean total carbon (TC) was 35.17 kg/tree, giving a total of 201.97 Mg and 0.80 Mg/ha. The dominant families, Fabaceae (112.31 kg/ha) and Moraceae (146.02 kg/ha) contributed significantly to carbon storage, while families like Lauraceae (0.19 kg/ha) and Moringaceae (0.34 kg/ha) showed minimal contributions. Equation A [$AGB = \exp(-2.409 + 0.9522 \ln(D^2 H \rho))$] gave the maximum values of carbon stock. Statistical analysis revealed significant variation between equations (one-way repeated measures ANOVA, $p < 0.0001$). Pearson correlation analysis highlighted the number of trees, DBH, and BA as the strongest predictors of biomass and carbon stock ($r > 0.6$). Native trees showed greater carbon stocks. These findings highlight the superior carbon storage of native trees and the role of allometric equations in precise carbon estimation, aiding urban carbon management.

Keywords: *urban trees, ecosystem management, allometric equations, carbon assessment*

INTRODUCTION

Forests and trees help mitigate climate change by sequestering atmospheric carbon dioxide (CO_2), one of the main greenhouse gases responsible for global warming [1, 2]. Trees serve as significant carbon sinks, storing carbon in their biomass and soil. Urban trees absorb carbon through direct CO_2 absorption during photosynthesis and store carbon in their biomass (trunks, branches, roots, and leaves) [3, 4]. Additionally, it has been reported that trees in large cities like New York City and Toronto significantly help reduce CO_2 emissions. In New York City alone, urban forests remove approximately 200000 tons of CO_2 annually [5]. In addition to carbon sequestration, trees in urban contexts reduce the urban heat island effect by providing shade and cooling through evapotranspiration [6]. The growing recognition of these benefits has prompted many cities and institutions to include trees in their sustainability strategies, specifically analysing the carbon storage capacity of urban forests to improve future urban greening programs. However, the ability to sequester carbon varies among tree species depending on their growth habits, biomass distribution, and degree of local adaptation [7]. While exotic species are regularly introduced for quick development and economic advantages, native species are usually praised for their resistance and ecological integration [8]. This dichotomy has sparked debate about their respective roles in sustainable landscaping and carbon sequestration strategies. It is estimated that 7.1 billion metric tons of carbon is sequestered annually in India's forest ecosystems [9]. However, despite their importance in local carbon management, little is known about tree plantations in institutional and metropolitan environments. Given the increasing emphasis on urban greening and carbon offsetting through tree planting efforts, this gap is crucial. Particularly in urban and semi-urban environments, a methodical assessment of the carbon sequestration capability of native and invasive species could provide useful information for afforestation tactics. The increasing importance of urban greening has attracted substantial attention worldwide, especially in higher education institutions [10, 11]. The diversity of tree species on institutional campuses, such as those at universities, provides an unparalleled opportunity for such research [12]. A campus with a balanced mix of native and exotic species provides a controlled environment for such experiments. Internationally, the University of Tasmania (UTAS) has achieved carbon neutrality and is a leader in encouraging sustainable practices [13]. At the same time, the Shanghai Institute of Technology (SIT) in China has adopted innovative methodologies for carbon stock estimation to support its green campus programs [14]. In India, Panjab University (PU) in Chandigarh and Maharshi Dayanand University (MDU) in Rohtak have carried out carbon stock assessments as part of their green programs [4, 15]. Cotton University in Assam, located in a biodiversity-rich zone, is working on carbon storage in the northeastern region [16]. Carbon stocks are estimated using various methodologies, such as direct biomass measurements, remote sensing, and modelling. While destructive sampling and Light Detection and Ranging (LiDAR) provide accurate data, they can be expensive and time-consuming. Allometric equations, which relate tree size factors (such as diameter at breast height (DBH) and height (H)) to biomass, are a more practical and cost-effective option [17].

Previously, the carbon stocks of the dominant tree species at MDU were investigated, while other tree species were excluded from the analysis [15, 18]. This study focuses on filling a gap in understanding the dynamics of carbon stock in institutional settings by comparing native and exotic tree species. The research aims to provide actionable insights into sustainable carbon management strategies by analysing the performance of different allometric equations. The objectives of this study are: a) estimate the carbon stock for 56 tree species, b) estimate which allometric equation gives the highest carbon stock, c) assess which parameters affect the carbon stock, and d) compare carbon stock in native and exotic trees using different statistical methods. To address these objectives, the study proposes the following hypotheses: a) the different allometric equations will show significant differences in carbon stock values, b) native tree species will store more carbon than exotic species, and c) statistical analysis will reveal significant differences in carbon stocks between native and exotic species.

EXPERIMENTAL

Study site

The study was conducted at MDU, Rohtak, Haryana, India (Figure 1). Recognized as India's cleanest and greenest government university in 2018, MDU is located within the National Capital Region (NCR). The campus covers approximately 250 hectares and is located in a subtropical climatic zone, with temperatures ranging from 2 °C to 47 °C. The university has a diverse vegetation, including plantations of herbs, shrubs, and trees, as well as an herbal garden with various plant species. The campus is also home to approximately 60 tree species, predominantly from the Fabaceae and Moraceae families. Among these, *Eucalyptus globulus* and *Pongamia pinnata* are particularly abundant [19].

Data processing and analysis

Trees were sampled to determine a range of quantitative factors, including DBH, H, and basal area (BA). Measurements were taken using a measuring tape for circumference at breast height (CBH) and a Haga altimeter for tree H. To calculate DBH, the value of CBH was divided by π (3.14). The tree density, relative density, and BA were determined using the following formulas:

$$\text{Density (trees ha}^{-1}) = \frac{\text{Total tree count}}{\text{Total area (hectares)}} \tag{1}$$

$$\text{Relative density (trees ha}^{-1}) = \frac{\text{Total tree count of a particular species}}{\text{Total area (hectares)}} \tag{2}$$

$$\text{Basal area}\left(\text{m}^2\text{ha}^{-1}\right) = \frac{(\text{DBH})^2 \times \pi \times \text{tree density}}{4} \tag{3}$$

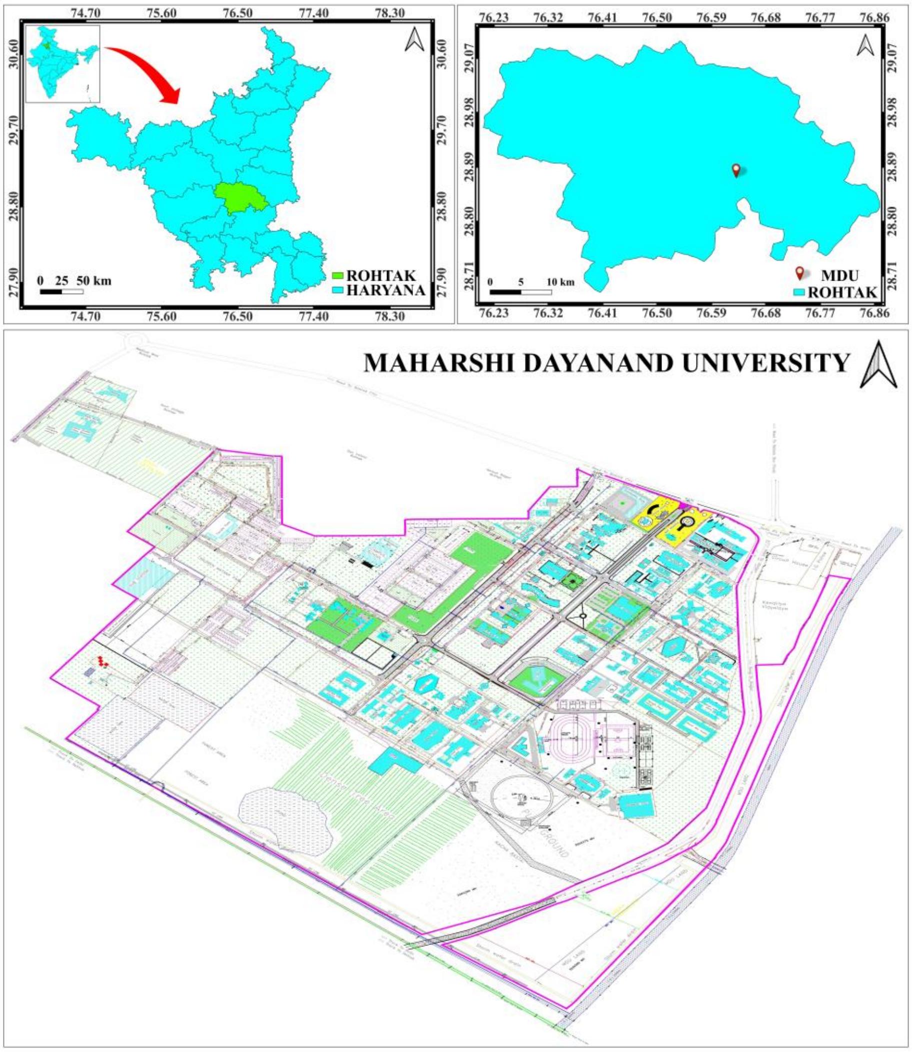


Figure 1. Study site (Maharshi Dayanand University)

DBH, which is given in meters, and BA, represented in $m^2\ ha^{-1}$, were used to calculate carbon stock. However, since the values in this unit were too small for clear representation, the results were expressed in m^2/tree for better clarity and interpretation. Different sources were used in the nativity classification [20, 21].

Tree biomass was calculated using direct biomass equations. All allometric equations were of a general nature. Table 1 contains four different allometric equations that were used for biomass calculation. Specific wood density (SWD) for each tree species was used to estimate tree biomass [22 - 27]. This obtained biomass was above-ground biomass (AGB). Below-ground biomass (BGB) was calculated by multiplying AGB by 0.26 [28]. The total biomass (TB) was calculated by adding the AGB and BGB. The amount of total carbon (TC) stored in a tree was calculated by multiplying the total biomass by 0.5, since the carbon stock in a tree is approximately half of the biomass [29]. The results in this study were not large enough to be presented in megagram values (Mg), so the results are presented in a more favourable and suitable unit, i.e., kilogram (kg).

Statistical analysis

The data were analysed using repeated measures one-way analysis of variance (ANOVA) to assess significant differences in TC values derived from various allometric equations. Pairwise comparisons were conducted to evaluate specific differences between equations. Statistical tests such as the two-sample t-test and the non-parametric Mann-Whitney U test were used to compare parameters of native and exotic tree species. All statistical analyses were performed at a significance level of $p < 0.05$ using Origin Pro software.

RESULTS AND DISCUSSION

A total of 5742 trees from 56 species were analysed. Out of these, 42.9 % species were exotic, and the rest were native. These trees belonged to 28 families, with Fabaceae and Moraceae being dominant. Fabaceae had 12 species, while Moraceae had 7 species. The dominance of Fabaceae and Moraceae is consistent with findings from the University of Lagos, where Fabaceae included 14 species and Moraceae 7 species [34]. This highlights their ecological adaptability in urban environments. The data in Figure 2 provides an overview of the key structural parameters of the studied tree species, showing the variability in parameters such as tree count, DBH, H, density, BA, and SWD. This highlights significant trends and outliers across the study area. A comprehensive dataset is provided for each species, detailing their specific measurements and characteristics (Table 2).

Tree count among species showed considerable variability, with a minimum of 2 trees recorded for *Ceiba pentandra* and a maximum of 392 trees for *Tamarix aphylla*.

Table 1. Different allometric equations used to estimate biomass in this study

Equation	Unit of SWD	Equation name	Reference
$AGB = \exp(-2.409 + 0.9522\ ln\ (D^2\ H\ \rho))$	g/cm³	Eq. A	[30]
$AGB = 0.0509 \times \rho \times DBH^2 \times H$	g/cm³	Eq. B	[31]
$AGB = 0.0673\ (\rho \times D^2 \times H)^{0.976}$	g/cm³	Eq. C	[32]
$AGB = 0.00015 \times \rho \times DBH^{1.82} \times H^{0.72}$	kg/m³	Eq. D	[33]

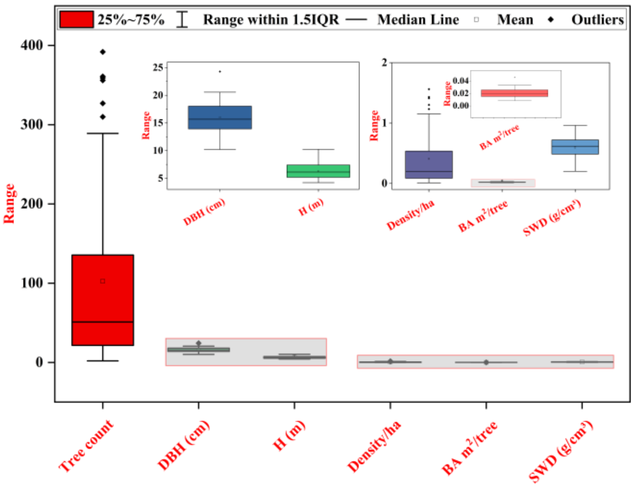


Figure 2. Description of structural parameters of trees in the form of box plots

Table 2. Details about the structural parameters of the trees

Scientific name	Family	Nativity	Tree count	DBH (cm)	H (m)	Density/ ha	BA m^2/tree	SWD (g/cm³)
Acacia auriculiformis Benth.	Fabaceae	Exotic	31	17.99	7.23	0.12	0.025	0.77
Acacia nilotica (L.) Delile	Fabaceae	Native	32	19.23	5.45	0.13	0.029	0.70
Aegle marmelos (L.) Correa	Rutaceae	Native	45	16.85	5.20	0.18	0.022	0.75
Albizia lebbeck (L.) Benth.	Fabaceae	Native	12	14.03	5.82	0.05	0.015	0.66
Alstonia scholaris (L.) R. Br.	Apocynaceae	Native	310	20.40	6.14	1.23	0.033	0.36
Artocarpus heterophyllus Lam.	Moraceae	Native	22	17.45	7.87	0.09	0.024	0.60
Bauhinia variegata L.	Fabaceae	Native	104	15.79	7.63	0.41	0.020	0.67
Bixa orellana L.	Bixaceae	Exotic	9	13.14	4.26	0.04	0.014	0.67
Bombax ceiba L.	Malvaceae	Native	51	18.91	8.52	0.20	0.028	0.33
Butea monosperma (Lam.) Taub.	Fabaceae	Native	38	14.18	7.13	0.15	0.016	0.48
Calliandra haematocephala Hassk.	Fabaceae	Exotic	78	15.00	7.63	0.31	0.018	0.72
Caryota urens L.	Arecaceae	Native	26	13.69	5.29	0.10	0.015	0.48
Cassia fistula L.	Fabaceae	Native	61	14.84	5.22	0.24	0.017	0.71
Casuarina equisetifolia L.	Casuarinaceae	Native	250	20.40	8.30	0.99	0.033	0.83
Ceiba pentandra (L.) Gaertn.	Malvaceae	Exotic	2	13.43	9.24	0.01	0.014	0.23
Cinnamomum tamala (Buch.-Ham.) T.Nees & Eberm.	Lauraceae	Native	3	13.82	5.17	0.01	0.015	0.43
Citrus limon (L.) Burm. f.	Rutaceae	Native	51	10.21	4.52	0.20	0.008	0.59
Citrus sinensis (L.) Osbeck	Rutaceae	Exotic	45	11.05	4.44	0.18	0.010	0.59
Cordia myxa L.	Boraginaceae	Native	16	14.64	5.92	0.06	0.017	0.53
Delonix regia (Hook.) Raf.	Fabaceae	Exotic	51	15.38	7.57	0.20	0.019	0.63
Elaeocarpus serratus L.	Elaeocarpaceae	Native	5	13.77	8.27	0.02	0.015	0.40
Ficus benghalensis L.	Moraceae	Native	124	24.29	7.65	0.49	0.046	0.20
Ficus racemosa L.	Moraceae	Native	23	20.56	7.96	0.09	0.033	0.55
Ficus religiosa L.	Moraceae	Native	361	19.63	6.28	1.43	0.030	0.51
Ficus retusa L.	Moraceae	Exotic	28	18.66	6.53	0.11	0.027	0.39
Ficus rumphii Blume	Moraceae	Native	234	19.91	6.45	0.93	0.031	0.39
Grevillea robusta A.Cunn. ex R.Br.	Proteacae	Exotic	254	14.66	6.17	1.01	0.017	0.30
Kigelia africana (Lam.) Benth.	Bignoniaceae	Exotic	71	12.90	5.82	0.28	0.013	0.72
Lagerstroemia speciosa (L.) Pers.	Lythraceae	Native	75	15.76	6.09	0.30	0.020	0.53

Table 2 (continued). Details on structural parameters of the trees

Scientific name	Family	Nativity	Tree count	DBH (cm)	H (m)	Density/ha	BA m^2/tree	SWD (g/cm^3)
Leucaena leucocephala (Lam.) de Wit	Fabaceae	Exotic	106	13.49	6.26	0.42	0.014	0.64
Madhuca longifolia (J.Koenig ex L.) J.F.Macbr.	Sapotaceae	Native	18	16.09	6.21	0.07	0.020	0.74
Mangifera indica L.	Anacardiaceae	Native	281	19.46	6.45	1.12	0.030	0.52
Manilkara zapota (L.) P.Royen	Sapotaceae	Exotic	21	14.71	5.19	0.08	0.017	0.79
Melia azedarach L.	Meliaceae	Native	189	18.74	5.39	0.75	0.028	0.57
Mimusops elengi L.	Sapotaceae	Native	327	16.68	4.22	1.30	0.022	0.72
Moringa oleifera Lam.	Moringaceae	Native	3	14.85	5.95	0.01	0.017	0.60
Morus alba L.	Moraceae	Exotic	192	17.01	5.63	0.76	0.023	0.49
Neolamarckia cadamba (Roxb.) Bosser	Rubiaceae	Native	289	18.07	9.99	1.15	0.026	0.40
Phyllanthus emblica L.	Phyllanthaceae	Native	58	16.20	5.13	0.23	0.021	0.80
Platycladus orientalis (L.) Franco	Cupressaceae	Exotic	15	14.63	5.62	0.06	0.017	0.49
Plumeria pudica Jacq.	Apocynaceae	Exotic	42	12.34	4.66	0.17	0.012	0.64
Plumeria rubra L.	Apocynaceae	Exotic	106	12.10	4.53	0.42	0.011	0.64
Populus deltoides Marshall	Salicaceae	Exotic	123	15.62	8.33	0.49	0.019	0.63
Prosopis juliflora (Sw.) DC.	Fabaceae	Exotic	12	14.64	6.13	0.05	0.017	0.84
Prunus persica (L.) Batsch	Rosaceae	Exotic	21	12.96	6.28	0.08	0.013	0.49
Psidium guajava L.	Myrtaceae	Exotic	105	11.40	5.09	0.42	0.010	0.74
Pterospermum acerifolium (L.) Willd.	Malvaceae	Native	27	12.40	4.66	0.11	0.012	0.38
Putranjiva roxburghii Wall.	Putranjivaceae	Native	356	14.21	4.50	1.41	0.016	0.67
Roystonea regia (Kunth) O.F.Cook	Arecaceae	Exotic	359	17.01	10.25	1.43	0.023	0.82
Senna siamea (Lam.) H.S.Irwin & Barneby	Fabaceae	Exotic	147	17.82	5.69	0.58	0.025	0.80
Sterculia foetida L.	Malvaceae	Native	29	15.54	7.26	0.12	0.019	0.55
Tamarindus indica L.	Fabaceae	Exotic	17	17.19	7.53	0.07	0.023	0.75
Tamarix aphylla (L.) H.Karst.	Tamaricaceae	Native	392	19.96	7.27	1.56	0.031	0.70
Terminalia chebula Retz.	Combretaceae	Native	53	17.41	6.43	0.21	0.024	0.96
Washingtonia robusta H.Wendl.	Arecaceae	Exotic	18	18.83	4.63	0.07	0.028	0.37
Ziziphus jujuba Mill.	Rhamnaceae	Exotic	24	16.07	5.17	0.10	0.020	0.76

It reflects the diverse representation of species across the campus. This variation highlights the adaptability of the species and differences in dominance within the study area. DBH ranged from 10.21 cm for *Citrus limon* to 24.29 cm for *Ficus benghalensis*, with an average of 16 cm. The large DBH of *Ficus benghalensis* highlights its role in contributing to biomass, a finding consistent with previous studies which identify large-diameter trees as key species in carbon storage [35]. The H measurements also showed wide variation, ranging from 4.22 m for *Mimusops elengi* to 10.25 m for *Roystonea regia*, with a mean H of 6.32 m. Species with greater H, such as *Roystonea regia*, play vital roles in providing habitat and shaping canopy structure, supporting various ecological processes [36]. Tree density ranged from ~ 0.01 trees/ha for sparsely distributed species like *Ceiba pentandra* to 1.56 trees/ha for *Tamarix aphylla*, with a total density of 22.81 trees/ha (for these 56 species), while considering all 66 species on campus, tree density was ~140 trees/ha. Higher densities of certain species reflect their ability to thrive in specific environmental conditions. The tree density observed in this study is lower than many urban environments, particularly well-managed parks or institutional campuses [4, 37]. BA values ranged from 0.008 m^2/tree for *Citrus limon* to 0.046 m^2/tree for *Ficus benghalensis*, with an average of 0.020 m^2/tree. This indicates that larger species, such as *Ficus benghalensis* contribute disproportionately to forest structure, but these values are relatively low compared to other campuses [38]. SWD ranged from 0.20 g/cm^3

for *Ficus benghalensis* to 0.96 g/cm³ for *Terminalia chebula*, with an average of 0.59 g/cm³. Variations in SWD highlight species-specific differences in wood properties, influencing their ecological roles and contributions to forest stability and resilience. The variability in structural attributes (parameters), such as DBH, H, and BA, highlights differences in species growth patterns and their contribution to forest biomass. Figure 3 and Table 3 show the biomass and carbon stock values for different tree species. AGB showed significant variation among species, with the lowest value recorded for *Pterospermum acerifolium* (16.05 kg/tree) and the highest for *Casuarina equisetifolia* (154.62 kg/tree), while the mean AGB was 55.83 kg/tree. Similarly, BGB ranged from 4.17 kg/tree for *Pterospermum acerifolium* to 40.20 kg/tree for *Casuarina equisetifolia*, with an average of 14.51 kg/tree. TB ranged from 20.22 kg/tree (*Pterospermum acerifolium*) to 194.82 kg/tree (*Casuarina equisetifolia*), with an average of 70.35 kg/tree which is equal to 403.95 Mg of total biomass. These values were relatively low compared to TB values in the North Maharashtra University Campus, Jalgaon [39]. Similarly, TB (1.60 Mg/ha) was lower than at Bogor Agricultural University, Darmaga campus, where TB was ~ 10 Mg/ha [40]. TC calculated using different equations (Eq. A to Eq. D) provided insights into the variability of estimation methods. Previously, researchers [4, 41] used different equations and compared them to estimate biomass and TC. The results obtained here were similar to a study conducted in the Philippines [41] (highest TC from Eq. A]). In contrast, a study in Chandigarh [4] obtained the highest carbon values from Eq. B. In this study, the values obtained from Eq. B were the lowest. This was attributed to the use of only the DBH equation in the former case and DBH and H in the latter case. The mean TC was 35.17 kg/tree, a total of 201.97 Mg (0.80 Mg/ha) of carbon stock in the study site. The species with the lowest mean TC was *Ceiba pentandra* (0.11 kg/ha), with individual values ranging from 0.10 kg/ha in equations B and D to 0.13 kg/ha in equation A. Other species with low mean TC values included *Cinnamomum tamala* (0.19 kg/ha), *Moringa oleifera* (0.34 kg/ha), *Elaeocarpus serratus* (0.45 kg/ha), and *Bixa orellana* (0.66 kg/ha), reflecting minimal carbon storage potential. On the other hand, *Roystonea regia* had the highest mean TC (117.27 kg/ha), with values ranging from 102.58 kg/ha (Eq. B) to 133.35 kg/ha (Eq. A). This was followed by *Tamarix aphylla* (109.22 kg/ha) and *Casuarina equisetifolia* (96.75 kg/ha), showing exceptional carbon storage capabilities. Other notable species were *Ficus religiosa* (62.20 kg/ha), *Neolamarckia cadamba* (51.15 kg/ha), and *Mangifera indica* (50.45 kg/ha), which also contributed significantly to carbon storage. These findings are similar to other studies [42 - 44]. These results highlight the wide interspecies variation in TC, which is influenced by species-specific traits and the equation used for estimation.

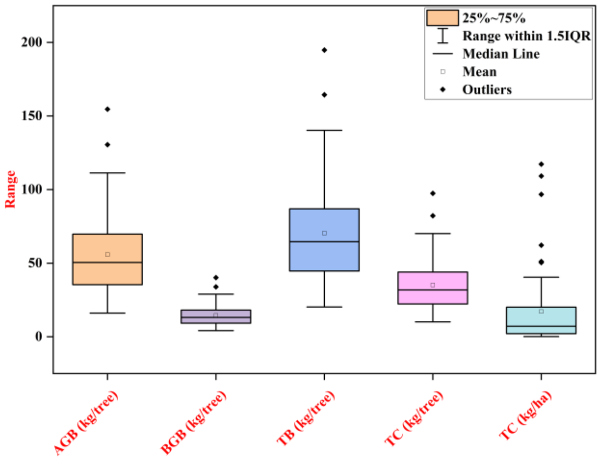


Figure 3. Overview of biomass and carbon stock values

TC storage capacity showed significant variation among families, as illustrated in Figure 4. The lowest mean TC was recorded for *Lauraceae* (0.19 kg/ha), followed by *Moringaceae* (0.34 kg/ha) and *Elaeocarpaceae* (0.45 kg/ha), indicating their minimal contribution to carbon storage. Similarly, families such as *Bixaceae* (0.66 kg/ha) and *Cupressaceae* (1.33 kg/ha) also showed low sequestration potential. In contrast, families with higher mean TC were *Fabaceae* (112.31 kg/ha), *Arecaceae* (120.70 kg/ha), and *Moraceae* (146.02 kg/ha), which were shown to be dominant contributors to carbon stocks. These families consistently outperformed others, highlighting their crucial role in storing carbon in the ecosystem. These results are similar to other recent findings where high carbon stocks were reported in *Fabaceae* and *Moraceae* and low in the *Moringaceae* family [4].

Table 3. Comprehensive details on tree biomass and carbon stock values

Scientific name	AGB (kg/tree)	BGB (kg/tree)	TB (kg/tree)	TC (kg/tree)	TC (kg/ha) [Eq. A]	TC (kg/ha) [Eq. B]	TC (kg/ha) [Eq. C]	TC (kg/ha) [Eq. D]	TC (kg/ha) [Mean]
Acacia auriculiformis Benth.	99.56	25.89	125.45	62.72	8.76	7.16	7.86	7.12	7.73
Acacia nilotica (L.) Delile	79.34	20.63	99.96	49.98	7.08	6.19	6.39	5.75	6.35
Aegle marmelos (L.) Correa	63.48	16.50	79.98	39.99	8.08	7.09	7.09	6.34	7.15
Albizia lebbeck (L.) Benth.	43.78	11.38	55.17	27.58	1.50	1.29	1.30	1.16	1.31
Alstonia scholaris (L.) R. Br.	51.76	13.46	65.22	32.61	46.25	37.40	40.73	36.29	40.17
Artocarpus heterophyllus Lam.	77.28	20.09	97.37	48.69	4.54	3.98	4.47	4.03	4.26
Bauhinia variegata L.	70.48	18.33	88.81	44.40	20.51	17.16	18.82	16.90	18.35
Bixa orellana L.	29.14	7.58	36.72	18.36	0.72	0.70	0.64	0.56	0.66
Bombax ceiba L.	55.22	14.36	69.58	34.79	8.12	6.23	7.32	6.53	7.05
Butea monosperma (Lam.) Taub.	39.19	10.19	49.37	24.69	4.30	3.51	3.76	3.33	3.73
Calliandra haematocephala Hassk.	68.99	17.94	86.92	43.46	15.33	12.58	13.69	12.28	13.47
Caryota urens L.	28.28	7.35	35.63	17.82	2.17	1.82	1.80	1.58	1.84
Cassia fistula L.	47.23	12.28	59.51	29.76	8.12	7.24	7.14	6.34	7.21
Casuarina equisetifolia L.	154.62	40.20	194.82	97.41	109.69	86.41	99.66	91.25	96.75
Ceiba pentandra (L.) Gaertn.	21.76	5.66	27.42	13.71	0.13	0.10	0.11	0.10	0.11
Cinnamomum tamala (Buch.-Ham.) T.Nees & Eberm.	24.91	6.48	31.39	15.70	0.21	0.19	0.19	0.16	0.19
Citrus limon (L.) Burm. f.	16.74	4.35	21.09	10.55	2.36	2.30	2.09	1.81	2.14
Citrus sinensis (L.) Osbeck	19.30	5.02	24.32	12.16	2.44	2.31	2.11	1.83	2.17
Cordia myxa L.	38.99	10.14	49.13	24.56	1.81	1.51	1.55	1.37	1.56
Delonix regia (Hook.) Raf.	63.00	16.38	79.38	39.69	9.15	7.50	8.19	7.33	8.04
Elaeocarpus serratus L.	35.47	9.22	44.69	22.35	0.52	0.41	0.45	0.40	0.45
Ficus benghalensis L.	49.76	12.94	62.69	31.35	18.09	13.39	16.02	14.27	15.44
Ficus racemosa L.	101.08	26.28	127.36	63.68	6.68	5.19	5.99	5.42	5.82
Ficus religiosa L.	68.83	17.90	86.73	43.36	70.21	58.53	63.27	56.77	62.20
Ficus retusa L.	49.57	12.89	62.46	31.23	3.92	3.26	3.55	3.16	3.47
Ficus rumphii Blume	55.72	14.49	70.21	35.10	37.13	30.35	33.32	29.74	32.64
Grevillea robusta A.Cunn. ex R.Br.	23.17	6.02	29.19	14.59	17.23	14.06	14.75	12.88	14.73
Kigelia africana (Lam.) Benth.	40.35	10.49	50.84	25.42	8.09	7.16	7.13	6.31	7.17
Lagerstroemia speciosa (L.) Pers.	45.97	11.95	57.93	28.96	9.93	8.29	8.63	7.67	8.63
Leucaena leucocephala (Lam.) de Wit	41.92	10.90	52.82	26.41	12.66	10.87	11.11	9.85	11.12
Madhuca longifolia (J.Koenig ex L.) J.F.Macbr.	67.11	17.45	84.55	42.28	3.39	2.93	3.05	2.73	3.03
Mangifera indica L.	71.73	18.65	90.38	45.19	59.01	46.62	50.68	45.50	50.45
Manilkara zapota (L.) P.Royen	51.24	13.32	64.57	32.28	3.02	2.72	2.67	2.37	2.70
Melia azedarach L.	61.41	15.97	77.38	38.69	33.02	28.18	29.04	25.97	29.05
Mimusops elengi L.	49.44	12.85	62.29	31.14	45.26	41.78	39.60	35.21	40.46
Moringa oleifera Lam.	45.14	11.74	56.87	28.44	0.38	0.33	0.34	0.30	0.34
Morus alba L.	46.17	12.00	58.18	29.09	26.00	21.28	21.97	19.51	22.19
Neolamarckia cadamba (Roxb.) Bosser	70.70	18.38	89.09	44.54	58.95	44.14	53.46	48.03	51.15
Phyllanthus emblica L.	61.94	16.11	78.05	39.02	10.15	8.98	8.89	7.95	8.99
Platycladus orientalis (L.) Franco	35.25	9.17	44.42	22.21	1.63	1.26	1.28	1.13	1.33
Plumeria pudica Jacq.	26.99	7.02	34.00	17.00	3.19	2.96	2.77	2.43	2.84
Plumeria rubra L.	25.47	6.62	32.09	16.05	7.67	7.07	6.56	5.74	6.76
Populus deltoides Marshall	70.99	18.46	89.45	44.73	25.09	19.92	22.35	20.07	21.86
Prosopis juliflora (Sw.) DC.	62.95	16.37	79.32	39.66	2.15	1.85	1.88	1.69	1.89
Prunus persica (L.) Batsch	30.04	7.81	37.85	18.92	1.82	1.54	1.57	1.38	1.58
Psidium guajava L.	28.93	7.52	36.45	18.22	8.54	7.88	7.45	6.54	7.60

Table 3 (continued). Comprehensive details on tree biomass and carbon stock values

Scientific name	AGB (kg/tree)	BGB (kg/tree)	TB (kg/tree)	TC (kg/tree)	TC (kg/ha) [Eq. A]	TC (kg/ha) [Eq. B]	TC (kg/ha) [Eq. C]	TC (kg/ha) [Eq. D]	TC (kg/ha) [Mean]
Pterospermum acerifolium (L.) Willd.	16.05	4.17	20.22	10.11	1.18	1.14	1.08	0.94	1.09
Putranjiva roxburghii Wall.	35.77	9.30	45.07	22.53	35.46	33.12	31.30	27.61	31.87
Roystonea regia (Kunth) O.F.Cook	130.51	33.93	164.44	82.22	133.35	102.58	121.95	111.21	117.27
Senna siamea (Lam.) H.S.Irwin & Barneby	79.31	20.62	99.93	49.97	30.43	29.18	30.05	27.06	29.18
Sterculia foetida L.	53.81	13.99	67.81	33.90	4.39	3.68	3.99	3.56	3.91
Tamarindus indica L.	92.38	24.02	116.39	58.20	4.48	3.63	4.00	3.61	3.93
Tamarix aphylla (L.) H.Karst.	111.32	28.94	140.26	70.13	124.41	99.84	111.45	101.19	109.22
Terminalia chebula Retz.	104.03	27.05	131.08	65.54	15.43	13.21	13.93	12.63	13.80
Washingtonia robusta H.Wendl.	35.19	9.15	44.34	22.17	1.80	1.57	1.58	1.39	1.59
Ziziphus jujuba Mill.	58.21	15.13	73.35	36.67	3.92	3.50	3.47	3.10	3.50

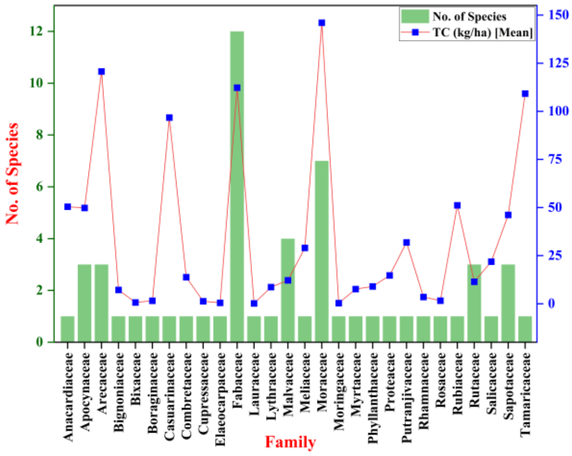


Figure 4. Carbon stock in different families in relation to the number of tree species

For the one-way repeated measures ANOVA, Mauchly's test of sphericity was violated ($p < 0.0001$). Therefore, Greenhouse-Geisser ($\varepsilon < 0.28533$) corrections were applied with a p-value < 0.0001. A comparative analysis of TC estimates derived from different equations and their mean values is shown. The range of TC (kg/ha) estimates for each equation (Eq. A, Eq. B, Eq. C, and Eq. D) and their mean are shown, with error bars representing variability and Tukey letters indicating statistical groupings based on post hoc tests (Figure 5a). Equations that share the same letter are not significantly different. Pairwise comparisons of mean differences in TC estimates among the equations show that Eq. A and Eq. D exhibit the most significant deviations from the mean (Figure 5b). Conversely, comparisons involving Eq. C show smaller deviations and insignificant differences in some pairs. The variability and direction of the deviations suggest that Eq. A and Eq. D may overestimate or underestimate TC relative to the mean, while Eq. C is much closer, highlighting its potential reliability. The results show that 1st hypothesis is accepted.

The heatmap shows the correlation matrix between different parameters related to tree characteristics and TC. Strong positive correlations were observed between DBH and BA, AGB, BGB, TB, and TC, with correlation coefficients above 0.6, indicating that DBH is a key predictor of carbon storage and biomass (Figure 6). Similarly, tree count shows a strong correlation with TC per hectare (kg/ha) (correlation coefficient is 0.85). Conversely, SWD shows weak or negative correlations with other parameters, suggesting that it has minimal influence on biomass or carbon storage in this dataset. Tree H shows moderate correlations with biomass and carbon metrics, but is less significant than DBH. These findings highlight DBH and tree density as critical drivers of carbon storage. These findings are similar to other findings where tree density [45], DBH, and BA [46] were strong predictors of carbon stock. Contrary to the strong positive correlation observed between tree count and TC in the present study, the association found in Bangladesh was also positive, but notably weaker, with an r-value of 0.2 [46].

A comparative analysis of exotic and native tree species, based on the parameters shown in Table 4, reveals both significant and insignificant differences. Statistical analyses were applied as follows: for normally distributed data, two-sample or independent t-tests with equal variance assumed were used, while for non-normally distributed data, the Mann-Whitney U test was used, giving U and Z scores. Native species have a higher total tree count (3865) than exotic species (1877), but this difference is not statistically significant. Among the parameters showing a normal distribution, DBH is significantly higher in native trees (16.81 cm) compared to exotic species (14.92 cm), with a t-statistic of -2.58 (DF = 54, p = 0.012). Similarly, BA (m^2/tree) is significantly higher in native species (0.023) than in exotic species (0.018), as shown by a t-statistic of -2.64 (DF = 54, p = 0.010). In contrast, no significant differences were observed in tree H, density per hectare, and TC. However, native trees generally had higher values for these parameters than exotic species. The results are consistent with other findings [47], where the structural and functional attributes were higher in native trees than in exotic trees, the percentage distribution, and contribution towards carbon stock of species between these classes was also similar. In contrast, a study [48] reported that in urban areas, native trees contribute more than 90 % to carbon stock. Based on the results, the 2nd hypothesis has been accepted, while the 3rd was rejected.

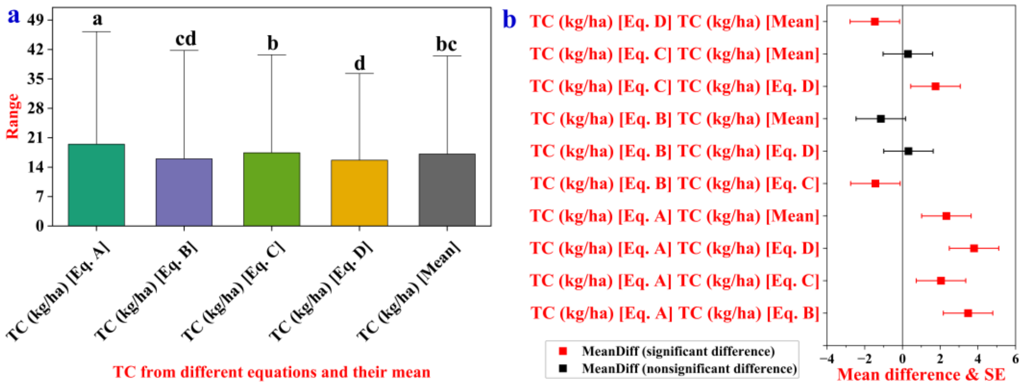
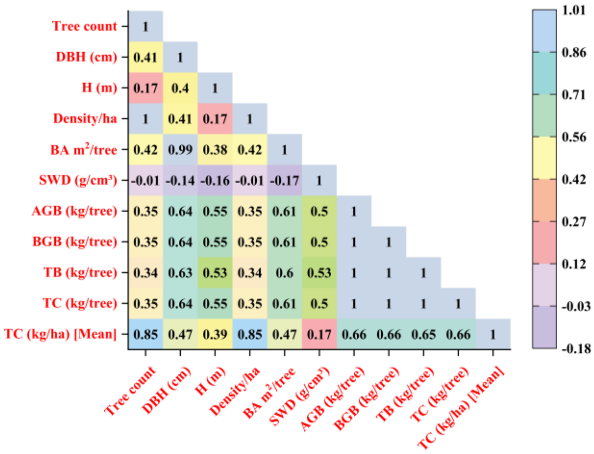


Figure 5. a) one-way repeated measures ANOVA, b) pairwise comparison between different equations used to estimate carbon stock



	Tree count	DBH (cm)	H (m)	Density/ha	BA m^2/tree	SWD (g/cm^3)	AGB (kg/tree)	BGB (kg/tree)	TB (kg/tree)	TC (kg/tree)	TC (kg/ha) [Mean]
Tree count	1										
DBH (cm)	0.41	1									
H (m)	0.17	0.4	1								
Density/ha	1	0.41	0.17	1							
BA m^2/tree	0.42	0.99	0.38	0.42	1						
SWD (g/cm^3)	-0.01	-0.14	-0.16	-0.01	-0.17	1					
AGB (kg/tree)	0.35	0.64	0.55	0.35	0.61	0.5	1				
BGB (kg/tree)	0.35	0.64	0.55	0.35	0.61	0.5	1	1			
TB (kg/tree)	0.34	0.63	0.53	0.34	0.6	0.53	1	1	1		
TC (kg/tree)	0.35	0.64	0.55	0.35	0.61	0.5	1	1	1	1	
TC (kg/ha) [Mean]	0.85	0.47	0.39	0.85	0.47	0.17	0.66	0.66	0.65	0.66	1

Figure 6. Correlations between structural attributes and biomass and carbon stock values

Table 4. Statistical comparison between exotic and native tree species

Parameter	Normal data distribution	Exotic (mean)	Native (mean)	U score/t statistic	Z score/DF	p-value
Tree count	No	1877*	3865*	326.50	- 0.94	0.345
DBH (cm)	Yes	14.92	16.81	- 2.58	54	0.012
H (m)	Yes	6.25	6.39	- 0.35	54	0.722
Density/ha	No	0.31	0.48	329	- 0.90	0.366
BA m^2/tree	Yes	0.018	0.023	- 2.64	54	0.010
TC (kg/ha)	No	12.20	20.83	318	- 1.08	0.278

* values are totals, not mean

CONCLUSION

Strategic management of urban green spaces is essential for enhancing carbon stocks and supporting sustainable ecosystems in the face of rapid urbanization and climate change. This study shows that native tree species outperform exotic species in their ability to store carbon, highlighting their critical role in urban ecosystems. By highlighting the greater carbon stock potential of native trees, the findings reinforce the need to prioritize native vegetation to increase carbon storage capacity. The study also highlights the importance of methodological rigor in estimating carbon stocks. The significant variability observed between the four applied allometric equations highlights the need for careful selection and calibration of equations based on local context and tree characteristics. Structural parameters, particularly DBH and BA, have been shown to be robust predictors of biomass and carbon stock, providing valuable metrics for monitoring contributions of urban trees to carbon storage. The disproportionate contribution of certain families and species to the total carbon stocks indicates the potential for optimizing species selection in urban planning. For example, families like Moraceae and Fabaceae made significant contributions, while others like Lauraceae and Moringaceae contributed minimally. This variation highlights the need for data-driven species selection that prioritizes ecological suitability and carbon stock potential, transcending aesthetic preferences. These findings provide a comprehensive framework for improving the management of urban carbon stock. This study is essential for integrating carbon stock dynamics into urban forestry practices, contributing to climate mitigation goals and sustainable urban development.

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