

Article

Sustainability Perspectives of Urban Green Spaces from Their Carbon Stocks and Sequestration Potential in Two Cities of India

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Abstract

The assimilation capacity of the biosphere and the sustainability of the living resources are enhanced by the efficient and continued contribution of the vegetation from all ecoregions of the Earth. The urban greenery fulfills many regulatory ecosystem services (RES) as well. In this regard, the importance of urban green spaces (UGS) in helping to reduce the adverse impacts of overcrowding and changing climate is of pertinence. Lack of quantitative information from urban settings in different climatic regions seriously constrains the recognition of the important role UGS play in carbon storage and sequestration. To assess how the UGS is aiding the retention of carbon, which is photosynthetically assimilated into biomass and/or sequestered, relevant field parameters were collected from 4010 trees belonging to 34 different species, different hedge plants, and groundcover grasses spread in 24,991 m² area in three parks of Panaji city, India. Standard methods were followed to derive carbon stock and sequestration rates by trees, hedge plants, and groundcover. Notwithstanding wide differences between tree species, the weighted mean of CO₂ sequestered per tree averaged 55 kg y⁻¹ (ca. 78.82 tons ha⁻¹) in Panaji city. Accordingly, the CO₂ sequestration potential of trees, in the UGS of Panaji (by 76,751 trees) and Tumkur (with an estimated 38,152 trees) cities, respectively, was 4221.31 tons y⁻¹ ha⁻¹ and 2098 tons ha⁻¹ y⁻¹ @ 55 kg tree⁻¹ y⁻¹. It is apparent from this first-time study that calculated tree carbon biomass and species-wise yearly carbon sequestration rates (CSRs) of 78.82 tons ha⁻¹ y⁻¹ and that of carbon production rates of 31.77 tons ha⁻¹ y⁻¹ are far higher than the previously reported CSR estimates variously from 1 to 8 tons ha⁻¹ y⁻¹ and carbon production rates 3.23 to 6.55 tons ha⁻¹ y⁻¹. The hedge row carbon biomass averaged 13.18 tons ha⁻¹ and sequestration of 48.38 tons ha⁻¹ y⁻¹ CO₂. Similarly, occupying over 42% of the UGS, the groundcover carbon biomass averaged 14.69 tons ha⁻¹ with sequestration of 53.92 tons CO₂ ha⁻¹ y⁻¹. Combined CSP of existing trees, groundcover, and hedge plants in Panaji and Tumkur city UGS apparently neutralize carbon footprint of over 4550 and 2200 Indians at an annual per capita emission of 1.94-ton. It is thus undeniable that in our global fight against climate change, the addition of inputs and data from studies like these can aid in planning mitigation measure as well as in fulfilling local/regional sustainability plans and needs.



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Keywords: carbon sequestration; urban green spaces (UGS); carbon foot-print reduction; sustainable development goals (SDGs); west coast of India

1. Introduction

The quality of urban living is enhanced by landscaped urban green spaces (UGS). Through their basic, natural process of photosynthesis, all species of plants offer many benefits [1] and make many densely populated urban areas livable. In expanding cities [2–4] where air pollution levels can be tremendous, the UGS help purify air and serve as microclimate-regulating, urban heat island (UHI)-controlling [2,3] units. They help reduce noise pollution, soil erosion, and energy consumption, and through evapotranspiration, regulate the surface temperature [4,5]. Mcpherson et al. [6] highlighted that researchers, planners, and the public are concerned about how rapid urbanization could affect sustainability and quality of life in the future. Therefore, continued efforts are on for developing models that can quantify the role of urban vegetation in removing pollutants from the atmosphere [7–10]. Much more global data is essential to have useful models, considering the recent expansion of urban areas.

Major lack of quantitative information from urban settings in different climatic regions seriously constrain the recognition of the formidable role UGS play in carbon storage and sequestration. A key and substantial role in reducing atmospheric concentration of CO₂ can be ascribed to UGS, as they do store carbon in above and below ground biomass identical to trees in a forest or in any agroforest.

By attaching similar importance as for agroforestry practices, the great potential of UGS to add to carbon stocks must be recognized and their potential fully realized. For instance, green cover in New York City is reported to annually sequester 22.8 million tons and store a staggering 700 million tons of carbon [11]. However, estimates of carbon sequestration potential (CSP) even for the widely investigated agroforestry vary substantially [12–14]. Although many factors affect its reliable estimation, any reasonable derivation of CSP in urban settings would prove handy for urban planners and developers, to, among other needs, (a) make allowances for controlling pollution, (b) to reduce UHIs, (c) to look after and sustain existing UGS, and (d) to create new ones, as can be expected in rapidly expanding urban developments, including to gear up to meet smart city guidelines. This study focuses on addressing some of these aspects.

Importance of UGS in Carbon Sequestration and Storage

The urban greenery fulfils many regulatory ecosystem services (RES) [15–17]. The UGS help reduce LST and regulate many parameters of microclimate via sequestering and storing substantial quantities of carbon. As for cultural services, the UGS are inspirational, therapeutic, recreational, and tourism spots, biodiversity conservation motifs, and of interest for science and educational purposes. The UGS as a component that can meet a few of the Sustainable Development Goals (SDGs) of the United Nations were recently provided in detail by Ramaiah et al. [18]. In addition to these SDGs, the research outcome of this study falls well within the ambit of the 2015 Paris Agreement [2] covering the establishment of carbon neutrality targets, zero-carbon solutions by which the UGS sector can be expected to contribute substantial carbon capture and storage.

Many factors are understood to affect reliable estimation of CSP in urban settings [11]. Any derivation of carbon sequestration potential (CSP), including broad estimations based on field measurements carried out in this study, would prove handy and reasonable for urban planners and developers, among other needs. This analysis can enable them to (a) make allowances for controlling pollution, (b) reduce UHIs, (c) look after and sustain existing UGS, and (d) create new UGS, as can be expected in rapidly expanding urban developments.

In deciphering the complex processes of climate change, carbon is the currency in use to unravel and adapt to the adverse impacts this phenomenon is understood to cause [3].

While there is burgeoning literature from around the world portraying how agroforestry offers to increase carbon stocks/sequestration in the terrestrial biosphere [4,5,19], the role of UGS with analogous plant-growing practices is hardly recognized. Lack of quantitative information from urban settings in different climatic regions, in particular from many Asian cities, can constrain the need for and important roles that UGS play in carbon storage and sequestration. The primary aim of this work was to arrive at a realistic estimation of the annual carbon sequestration rates of a variety of trees, hedge plants, and groundcover (lawn) in city parks by collecting relevant data. While there are reports of certain trees growing in the tropical Indian climate, a comprehensive account—for instance, from the UGS—is lacking. Estimates such as those arrived at by this effort would be useful not only in recognizing the value of UGS in ushering relief for microclimate deviations in urban settings, but also in drawing down the atmospheric CO₂, facilitating the governance mechanisms targeting climate mitigation endeavors.

2. Materials and Methods

2.1. Brief Details of the Study Sites

Panaji and Tumkur cities were chosen for this study by considering several factors, such as their geographic location, population, and green space cover [7]. Apart from the disparate geographical locations of Panaji (a coastal city) and Tumkur (an interior city), various other factors such as population size, gross domestic product (GDP), and climatic factors were considered.

The coastal city of Panaji (Lat 15°29′48.3972″ N; Long. 73°49′40.1772″ E) is vulnerable to sea-level rise issues via climate change impacts. Due to rapid urbanization, the city's environmental resources are noted to be adversely impacted, potentially lowering the city's resilience to various natural disasters. Notably, there are serious concerns of heavy losses, as well as unsustainable and chaotic situations due to many parameters (impending sea level rise, severe traffic congestion, troubled pedestrian mobility, increased population and vehicles, citizens' health and livability, and resulting air/noise pollution). The average annual rainfall of Panaji is 2774 mm, with over 85% rainfall during June to September. With 17 parks in the city limits maintained by the Corporation of the City of Panaji (CCP) and the Forest Department, Panaji city (excluding the areas under the CCP) has about 0.80 km² under green cover [8]. The Bhagwan Mahaveer Park maintained by the Forest Department is the largest green patch in the city. The other 16 mostly small-sized parks plus public gardens, including the forest nursery and roadside plants, add up to about 5% of the green cover.

Located in the interior part of India, Tumkur city (Lat 13°20′17.7468″ N; Long. 77°6′5.0760″ E) is rapidly industrializing and recognized as an important National Investment and Manufacturing Zone (NIMZ). The predominant climate is a local steppe climate, with very little rainfall throughout the year; the average annual rainfall is 630 mm. A comparative account of the major features of these cities is given in Table 1.

In Tumkur city, under the Smart City Initiative, there are plans to increase the number (area) of green spaces. There are four large-sized parks (≥ 5 hectares (≥ 0.05 km²)) in the city maintained by Tumkur Urban Development Authority (TUDA). A 10 hectare (ha) (0.1 km²) newly developed Amanikere Park is on the area recovered by landfilling the Amanikere irrigation tank. Further, new roads being laid under the Smart City Development Initiative have walk paths and divider lanes. Suitable plantations on both sides of, and on, the divider in the middle are being made. The rainfall being low and sparse, the existing UGS need watering at least once every week in sufficient quantities to make up losses, including those occurring through dispersals into the soil.

Table 1. Details of different demographic, meteorological, and other parameters from Panaji and Tumkur cities proposed to be developed as smart cities (Ministry of Urban Development, Government of India, 2016).

Parameters	Panaji	Tumkur
City area (km ²)	21.60	48.60
Geographic location	Coastal	Interior
Land scape	Heterogenous	Majorly plain
Population (2018 estimate)	255,381	512,000
City GDP (Billion US\$)	9.22 (2016)	1.14 (2014)
Domestic water supply (MLD)	26	32
Domestic sewage generated (treated) MLD	14–16 (14–16)	26 (0)

Various climatological details of Panaji and Tumkur cities are available in Ramaiah et al. [7]. In addition to these metadata, seven different parks/gardens (social forests) within Panaji city were also covered for this study. Many essential details from these parks were collected through on-site guidance from garden staff and interactions with them. The details for the total area of the parks/gardens, species and numbers of trees, and ornamental/edge plants were noted (Table 2).

Table 2. Important details of the seven different parks surveyed for this study.

Park	Area (m ²)	No of Species		Grass Cover (m ²)	Source of Water	Daily Water Used (L)	Annual Litter Fall (Tons)	# of Staff
		Trees (Total Number)	Ornamental (Hedge Length; m)					
Kala Academy	10,630	21 (300)	6 (400)	2675	Borewell	10,000	15	6
North Goa Range Forest Park	5000	18 (390)	6 (200)	2250	Borewell	4800	10	3
South Goa Range Forest Park	6500	9 (200)	52 medicinal	1625	Borewell	8400	6 *	5
Mahavir Park	18,312	27 (3128)	17 (3000)	6410	Borewell	15,000	60	22
Art Park	18,999		0	0	Not watered	0	30	
Garcia da Orta Garden	4000	12 (180)	6 (450)	1500	Corporation water + Borewell	4000	6	5
Ambedkar Park	10,000	15 (478)	17 (1800)	6500	Treated wastewater	16,000	25	12
Joggers Park	11,500	8 (404)	12 (2600)	6900	Borewell	36,000	12	22

* Total number of trees in Mahavir Park and Art Park are per lists provided by the Park Offices; # numbers of staff employed. Daily water requirements of these plant species are published elsewhere (Ramaiah and Avtar [10]).

2.2. Data

2.2.1. Data Collection from Urban Green Spaces

Pertinent data were collected by visiting the sites on different days from January to February 2019 and again from August to October 2020. The questionnaires were prepared for obtaining information from parks, gardens, and STP (vide Ramaiah [9]). In addition to collecting the on-site data, details obtained through interactive discussions with the garden

staff and officers in charge were collated. Main details of these parks (sometimes referred to as Panaji city UGS) are compiled in Table 2.

Calculations of carbon sequestration potential (CSP) in this study were performed only for the UGS of Panaji. These calculations were based on (a) the number of trees of individual species in the parks and (b) per-hectare area of groundcover and hedge plants. The highest number of trees in Ambedkar Park, Joggers Park, Municipal Garden (Garcia da Orta), and in the premises of Kala Academy, are on the edges of the park/on both sides of the road. Carbon stocks of trees in these seven parks derived in this analysis were used for calculating the same from all other 10 parks in Panaji city [9] using the minimum of 108 tons biomass ha^{-1} reported in Lahoti et al. [20]. Since such measurements were not feasible from Tumkur city, such calculations were not performed.

Many different species of shrubs (<3 m tall) and trees (>3 m tall) in the parks were covered for this study. In addition to the approximate ranges of height and canopy diameter for each species of tree, the measured mean girth circumferences of randomly fetched individual trees of 25 of 27 tree species in Mahavir Park, all 13 species in Ambedkar Park, and all 9 species in Joggers' Park were noted. The girth circumference was measured from as many as 494 randomly selected accessible trees (without creepers or other fetch/accessibility issues). Ages of all three parks (Mahavir 57 years, Ambedkar 28 years, and Joggers 15 years) were used to derive the annual amounts of CO_2 sequestered per tree and in each park. Also, the species total carbon sequestration rate (CSR) was noted.

2.2.2. Estimation of Carbon Sequestration Potential Based on Wood Density Data

Unequivocally, the carbon sequestration rate is regulated by several factors, including trees' growth characteristics, wood density, and local conditions affecting trees' growth and age [12]. The carbon sequestration potential was estimated by following Ravindranath & Ostwald [13] for all tree species recorded from Mahavir Park, Ambedkar Park, and Joggers' Park. We employed cylindrical approximation for estimating the biomass of real trees. While this method is not necessarily species-specific, the measurement of girth at breast height (GBH) has been among the common procedures, as discussed by Ravindranath & Ostwald [13]. Indeed, the cylindrical approximation simplifies complex 3-D shapes into easy-to-calculate tubular/circular units. Care was taken to ensure that the measuring tape was pressed around the girth of the tree such that the tape hugged the girth as far as possible. As an exception, the DBH of the trees with larger girth diameter were measured with the help of the garden staff and also by taking the girth diameter in parts and summing the DBH for a few very large, older/aged trees. Therefore, the need to apply species-specific allometric equations was not considered for this study.

The main steps involving calculating the carbon stock and sequestration are shown in this flow chart (Chart 1) below.

Ravindranath & Ostwald [13] described a method for estimating dry weight of the tree as the product of volume (derived using tree DBH and height) and wood density. They recommend that the estimates of volume of the trees converted into weight-terms by using wood density yield the dry weight biomass of the tree species examined. One prerequisite is the collection of wood density value for each of the tree species, or of dominant species, or of the most closely related species from the literature. Using this method, both above ground dry biomass (AGDB) and below ground dry biomass (BGDB) were calculated. The procedure involved the following steps.

A: Measuring and tabulating the height and DBH of trees species-wise in the study site as explained above.

Calculation of Carbon Stocks and CSR

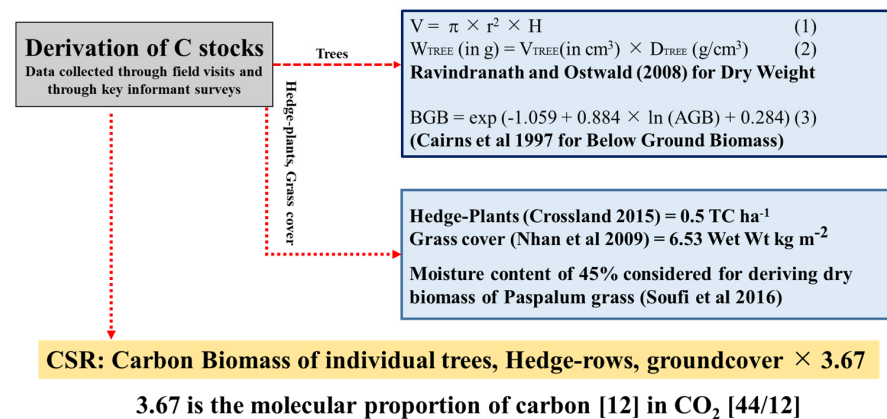


Chart 1. Schematic diagram showing steps for calculating carbon stocks and carbon sequestration rate (CSR) [13,14,21–23].

B: Estimating the volume of each tree in the sample plot using the formula of Ravindranath & Ostwald [13] for cylindrical shape.

$$V = \Pi \times R^2 \times H \quad (1)$$

where V is volume of the tree in cubic centimeters (or cubic meters); R the radius of the tree ~130 cm above the ground = DBH/2; and H, the tree height (in cm or m).

C: Multiplying the volume of the tree with the respective wood density to deduce the dry weight of that tree and then converting the weight from grams to kilograms or tons as follows:

$$T_w = T_v \times D \quad (2)$$

where T_w is weight of the tree (in g); T_v is volume of the tree (in cm³); and D is density (g/cm³).

D: Adding up of the weight of all individual trees in each species in the study site (in kilograms for each species).

E: Then the BGB (dry) was calculated following Cairns et al. [14] and using the dry biomass as:

$$B_{gdb} = \text{Exp}(-1.059 + 0.884 \times \ln(A_{gdb}) + 0.284) \quad (3)$$

F: Extrapolating the total dry weight of each species from the three parks in tons of biomass per hectare. Wood density data collected from literature, including those from Lahoti et al. [20], were used.

G: Derivation of C-stocks tons per tree or tons ha⁻¹ based on $W_c = 0.475 \times W_{dw}$ and sequestration potential in tons per tree per year based on $W_{CO_2} = W_c \times 3.67$.

Further, the dry carbon biomass/stocks of a total of 4010 trees in three parks (3128 in Mahavir, 478 in Ambedkar, and 404 in Joggers' parks) derived by following Ravindranath & Ostwald [13] and Lahoti et al. [20] were used for calculating the C-stocks from all 17 parks in Panaji city. Based on the estimated tree numbers (described in Section 4), the C-stocks and possible sequestration potential were calculated for the estimated 33,438 trees from 400 parks in Tumkur city UGS. For calculation of carbon sequestered, the biomass value of 108 tons ha⁻¹ estimated by Waran and Patwardhan [24], as reported in Lahoti et al. [20], was adapted. These were used for deriving an estimate of CO₂ sequestration rates of trees in the UGS areas of both Panaji and Tumkur cities.

The carbon biomass production ($\text{t ha}^{-1} \text{y}^{-1}$) was also calculated following Kumar et al. [25] using the relationship:

$$P_{cb} = W_c/T \quad (4)$$

where P_{cb} is carbon biomass production ($\text{t ha}^{-1} \text{y}^{-1}$); W_c the total tree carbon weight in tons; and T the age of trees in years.

2.2.3. Estimation of Carbon Sequestration Potential of Hedge Rows and Grass Cover

There have been no studies that definitively provide for an assessment of CSP of hedge plants growing in tropical cities. A weighted mean of 0.5 t C ha^{-1} hedge rows involving at least 12 species of hedge plants was provided by Crossland [21]. This relationship was used to arrive at the dry weight and total green weight (i.e., above and below ground biomass) by applying the universally accepted formula of Tooichi [12]. This totals to a wet biomass of 3.6 kg m^{-2} , which was used for calculating the total wet/green weight, dry weight, carbon weight, and CO_2 sequestration rates from the surveyed parks and extrapolated to all parks in Panaji and Tumkur.

As noted earlier, *Paspalum vaginatum* is the predominant grass in all 7 parks in Panaji surveyed for this study. For the groundcover wet biomass calculations, the estimates of $3.56 \text{ tons ha}^{-1}$ provided by Nhan et al. [22] were considered. The moisture content of this turf grass is 50 to 55% of wet weight [23]. Using this information, the total wet biomass at $6.53 \text{ kg wet/green biomass m}^{-2}$ was used for calculating its dry weight ($=2.94 \text{ kg}$) and carbon content (1.47 kg). The CSP of the grass covers/lawns in all parks was calculated following Tooichi [12] using the factor 3.67 as performed for trees to obtain an approximate estimate of CO_2 sequestered in the parks/UGS of Panaji and Tumkur cities.

In all, we took the DBH of over 494 trees of the then-existing 4014 trees and measured the hedge length, nearly 3 km long, and our sampling effort also covered several 1000 s of square meters of groundcover in three of the seven parks of Panaji city. Together in these parks, the hedge plant diversity was less than 12 species, with lawn cover of just 3 species. With the help of the records available in the park offices, we took into account all 34 species that were present at the time of sampling. It may also be noted that even two chinch trees and 2 and 4 sandalwood trees were included for estimating their possible biomass and carbon sequestration potential.

3. Results

3.1. Carbon Stocks and Sequestration Rates

3.1.1. Mahavir Park

The total dry biomass of 3128 trees existing in Mahavir Park was calculated using the formula of Ravindranath & Ostwald [13] and equaled $4,379,676 \text{ kg}$ ($=4379.68 \text{ tons}$). The corresponding carbon weight is $2,080,346 \text{ kg}$ (or 2080.35 tons). In Mahavir Park, the total CO_2 sequestered in the last 57 years is $7,634,870 \text{ kg}$ ($=7634.87 \text{ tons}$). This amounts to annual CO_2 sequestration of $133,945 \text{ kg}$ ($=133.95 \text{ tons}$) by 3128 trees. This plantation of mixed tree species is spread in an area of $22,101 \text{ m}^2$ of the total $37,199 \text{ m}^2$. Thus, their number ha^{-1} is 1416, and their CO_2 sequestration works out to $60,608 \text{ kg}$ (or 60.61 tons) $\text{ha}^{-1} \text{y}^{-1}$.

The CO_2 sequestration $\text{tree}^{-1} \text{y}^{-1}$ (Table 3) by nine large tree species in Mahavir Park (Figure 1a) are: *Samanea saman* (385.60 kg), *Delonix regia* (161.61 kg), *Tamarindus indica* (76.79 kg), *Spatodea companulata* (58.88 kg), *Millettia pinnata* (56.31 kg), *Casuarina equisetifolia* (53.89 kg), *Bauhinia purpurea* (49.25 kg), *Acacia auriculiformis* (45.39 kg), *Lagerstroemia speciosa* (44.40 kg), and *Cassia fistula* (39.51 kg). The eight medium trees with moderate CO_2 fixation rates ($<40 \text{ kg}$ per tree per year) were *Mimusops elengi* (37.95 kg), *Dyopsis lutescence* (37.60 kg), *Ceasalpenia pulcherima* (27.94 kg), *Peltophorum pterrocarpum* (27.83 kg), *Inga dulcis* (25.47),

Tecoma capensis (21.15), *Butea monosperma* (20.46), and *Syzygium cumini* (19.66 kg). The other seven species with lower CO₂ fixation rates (carbon sequestration) per year ranged from ca 2.9 kg tree⁻¹ y⁻¹ (*Mussaenda erythrophila*) to 19.14 kg tree⁻¹ y⁻¹ by *Alstonia scholaris*. The larger the girth circumference, the higher the sequestration rate, regardless of the tree age (~50 years) or species.

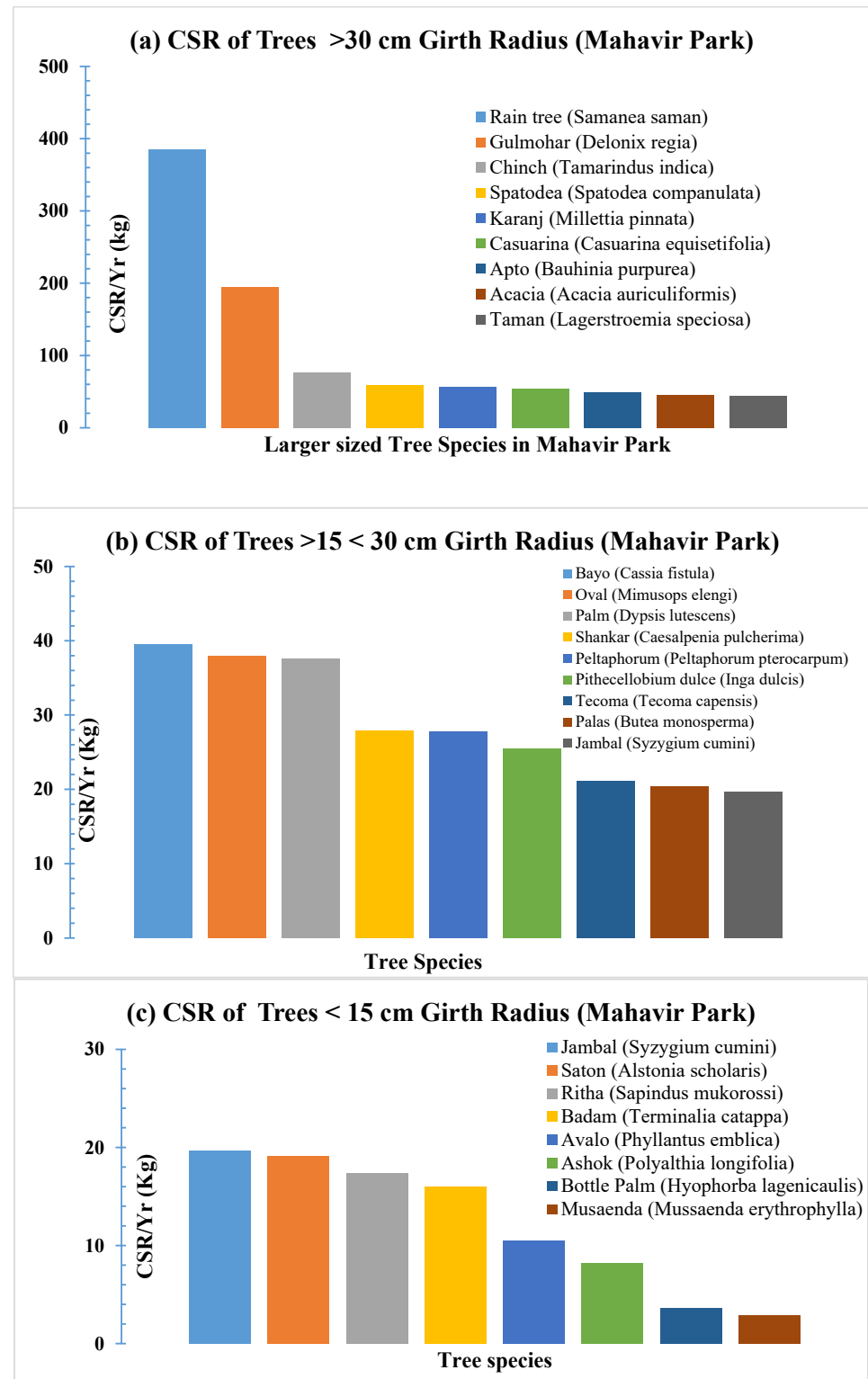


Figure 1. Carbon sequestration rates (CSR; kg tree⁻¹ yr⁻¹) of different trees with (a) larger ((a): >30 cm), (b) medium ((b): <30 to >15 cm), and (c) small ((c): <15 cm) girth radius.

Table 3. Details of total dry weight, carbon content, and sequestration rates of different species of trees (50 years old) in Mahavir Park.

Tree (Scientific Name)	Number	Mean ht (m)	Specific Gravity (g) *	Girth Circumference (cm)			Dry Weight, C-Stock and CO ₂ Sequestration/Tree (Weight in kg)			CO ₂ Sequestered/ Species/kg/yr
				Sample Size	Mean	±SD	Dry wt	Carbon	CO ₂ Seq/yr	
Casuarina (<i>Casuarina equisetifolia</i>)	1485	24.5	0.63	23	102.35	19.24	1545.80	734.25	53.89	80,032.87
Acacia (<i>Acacia auriculiformis</i>)	510	10.5	0.77	18	129.56	13.81	1301.91	618.41	45.39	23,149.38
Karanj (<i>Millettia pinnata</i>)	294	19.5	0.54	15	126.73	21.3	1615.40	767.32	56.32	16,558.34
Shankar (<i>Caesalpinia pulcherima</i>)	147	12.5	0.64	12	101.67	10.47	801.27	380.60	27.94	4106.64
Badam (<i>Terminalia catappa</i>)	129	8.5	0.52	12	102.92	8.908	459.17	218.11	16.01	2065.17
Ashok (<i>Polyalthia longifolia</i>)	89	7.5	0.54	10	76.40	6.168	235.44	111.84	8.21	730.58
Apto (<i>Bauhinia purpurea</i>)	87	15.5	0.67	11	119.18	17.14	1412.73	671.05	49.25	4285.18
Jambal (<i>Syzygium cumini</i>)	74	12.5	0.30	11	124.09	21.61	563.76	267.78	19.66	1454.50
Tecoma (<i>Tecoma capensis</i>)	53	8.5	0.58	11	112.36	14.42	606.68	288.17	21.15	1121.06
Gulmohar (<i>Delonix regia</i>)	44	19.0	0.80	10	198.1	15.99	5568.74	2645.15	194.15	8542.78
Saton (<i>Alstonia scholaris</i>)	27	9.0	0.49	10	112.9	17.77	549.11	260.83	19.15	516.91
Taman (<i>Lagerstroemia speciosa</i>)	26	13.0	0.53	9	138.78	9.935	1273.57	604.95	44.41	1154.48
Peltophorum (<i>Peltaphorum pterocarpum</i>)	25	20.5	0.62	16	80.5	8.422	798.14	379.12	27.85	695.68
Spatodea (<i>Spatodea complanata</i>)	24	17.0	0.71	13	121.08	10.28	1688.75	802.16	58.88	1413.08
Oval (<i>Mimusops elengi</i>)	23	9.0	0.72	11	132.09	8.608	1088.56	517.06	37.95	872.91
Palm (<i>Dyopsis lutescens</i>)	16	11.5	0.63	6	124.33	11.91	1078.47	512.27	37.60	601.62
Musaenda (<i>Mussaenda erythrophylla</i>)	15	5.0	0.60	13	52.154	4.947	83.41	39.62	2.91	43.63
Bottle Palm (<i>Hyophorba lagenicaulis</i>)	13	11.0	0.55	8	41.25	2.55	104.61	49.69	3.65	47.42
Bayo (<i>Cassia fistula</i>)	13	13.5	0.71	7	110.86	7.625	1133.24	538.29	39.51	513.63
Rain tree (<i>Samanea saman</i>)	11	25.0	0.71	6	259.83	23.56	11,059.22	5253.13	385.58	4241.38
Ritha (<i>Sapindus mukorossi</i>)	9	7.0	0.58	6	111.83	24.76	497.09	236.12	17.33	155.98
Pithecellobium dulce (<i>Inga dulcis</i>)	5	13.5	0.55	3	100.67	11.72	730.55	347.01	25.47	127.35
Palas (<i>Butea monosperma</i>)	4	9.5	0.74	3	92.5	4.95	586.74	278.70	20.46	81.83

Table 3. Cont.

Tree (Scientific Name)	Number	Mean ht (m)	Specific Gravity (g) *	Girth Circumference (cm)			Dry Weight, C-Stock and CO ₂ Sequestration/Tree (Weight in kg)			CO ₂ Sequestered/ Species/kg/yr
				Sample Size	Mean	±SD	Dry wt	Carbon	CO ₂ Seq/yr	
Avalo (<i>Phyllanthus emblica</i>)	3	9.5	0.78	2	64	0	300.50	142.77	10.48	31.44
Chinch (<i>Tamarindus indica</i>)	2	11.5	0.75	2	164	11.31	2202.57	1046.22	76.79	153.58
Total number of species	25	12.96	Average		116.00		1491.20	708.42	52.00	6107.90
Total number of individual trees in 22,101 m ² area (=1416 trees ha ⁻¹)	3128	5.31	Std deviation		44.53		2264.97	1075.86	78.97	16,358.72

* Specific gravity data from Lahoti et al. [20] (in bold) and from Brown [15]; Carsan et al. [16]; Harja et al. [17].

3.1.2. Ambedkar Park

In Ambedkar Park, the total dry biomass of highly-closely-spaced 478 trees (all along the roadside border) belonging to 13 species in an area of 1130 m² was 312.97 tons, with a carbon biomass of 148.65 tons. Their numbers per ha correspond to a very dense 4230 trees with a dry biomass of 2770 and probable carbon biomass of 1316 tons. The individual species of trees with the highest rate of CO₂ sequestration (Figure 2) per year were Rain tree (630 kg tree⁻¹ y⁻¹), Gulmohar (162 kg tree⁻¹ y⁻¹), and Acacia (71.34 kg tree⁻¹ y⁻¹). The CSRs of other species were: Mango (34.50 kg tree⁻¹ y⁻¹), Casuarina (33.00 kg tree⁻¹ y⁻¹), Peltophorum (31.50 kg tree⁻¹ y⁻¹), Coconut tree (29 kg tree⁻¹ y⁻¹), and Badam (28.50 kg tree⁻¹ y⁻¹), followed by the Ashoka (24.00 kg tree⁻¹ y⁻¹) and Veni trees (21.00 kg tree⁻¹ y⁻¹). The annual CO₂ sequestration rates by all 478 trees aged 28 years amounts to 19.48 tons at an average of 82.54 (±169.71) kg tree⁻¹. Apparently, the probable ha⁻¹ annual of 349 tons from an estimate of 4230 trees must be highly skewed. This is because just 23 large trees (9 Rain trees, 6 Gulmohar, and 8 Acacia; Table 4) in a total of 478 trees account for over 37% of the annual sequestration amounts. By excluding the higher CSRs of the rain tree and Gulmohar and the lowest CSR of the two-years-old sandalwood trees, the mean CSR for the remaining 453 trees belonging to 10 different species works out to 28.65 kg tree⁻¹ y⁻¹.

Table 4. Details of total dry weight, carbon content, and sequestration rates of different species of trees (28 years old) in Ambedkar Park.

Tree (Scientific Name)	Number (n)	Mean Height (m)	Tree Specific Gravity	Girth Circumference (cm)			Dry wt kg/tree	Carbon wt kg/tree	CO ₂ Seq kg/tree/yr	CO ₂ Sequestered/ Species kg/yr
				n	Mean	± SD				
Peltophorum, <i>P. pterocarpum</i>	184	12.5	0.62	22	81.67	6.64	505.88	240.29	31.50	5795.20
Casuarina, <i>Casuarina equisetifolia</i>	92	9.5	0.63	13	95.25	14.69	530.83	252.14	33.05	3040.5
Ashoka tree, <i>Polyalthia longifolia</i>	52	11	0.54	8	81.57	3.69	389.06	184.81	24.22	1259.6
Bottle palm, <i>Hyophorba lagenicaulis</i>	48	6.5	0.55	10	42.4	2.99	66.105	31.4	4.12	197.55
Coconut palm, <i>Cocos nucifera</i>	26	8.5	0.58	12	98.17	5.97	465.82	221.27	29.00	754.04

Table 4. Cont.

Tree (Scientific Name)	Number (n)	Mean Height (m)	Tree Specific Gravity	Girth Circumference (cm)			Dry wt kg/tree	Carbon wt kg/tree	CO ₂ Seq kg/tree/yr	CO ₂ Sequestered/ Species kg/yr
				n	Mean	± SD				
Badam, <i>Terminalia catappa</i>	26	8.5	0.52	10	102.8	8.4	458.13	217.61	28.52	741.58
Veni tree, <i>Acacia ferruginium</i>	12	13	0.86	6	55.33	1.75	338.01	160.56	21.04	252.53
Rain tree, <i>Samanea saman</i>	9	21	0.71	4	271	35.35	10,120	4807.1	630.07	5670.7
Acacia, <i>Acacia auriculiformis</i>	8	11	0.77	5	118.6	0.89	1145.9	544.29	71.34	570.72
Bamboo, <i>Phyllostachys pubescens</i>	7	9	0.40	18	38.22	3.04	54.38	25.83	3.39	23.698
Mango, <i>Mangifera indica</i>	6	14.5	0.74	6	72.67	3.56	553.44	262.88	34.46	206.74
Gulmohar, <i>Delonix regia</i>	6	18	0.80	4	138	18.2	2595.7	1233	161.6	969.63
Sandalwood, <i>Santalum album</i> (2 yr old)	2	3	0.54	2	24.5	2.12	10.56	5.01	0.66	1.31
Number of species	9	11.23	Average		93.86		1325.69	629.70	82.54	1498.75
No of individual trees in 1130 m ² area (=4230 trees ha ⁻¹)	478	4.74	Std deviation		62.47		2725.90	1294.80	169.71	2039.22

Specific gravity data from Lahoti et al. [20] (in bold) and from many wood databases, mentioned in Table 3.

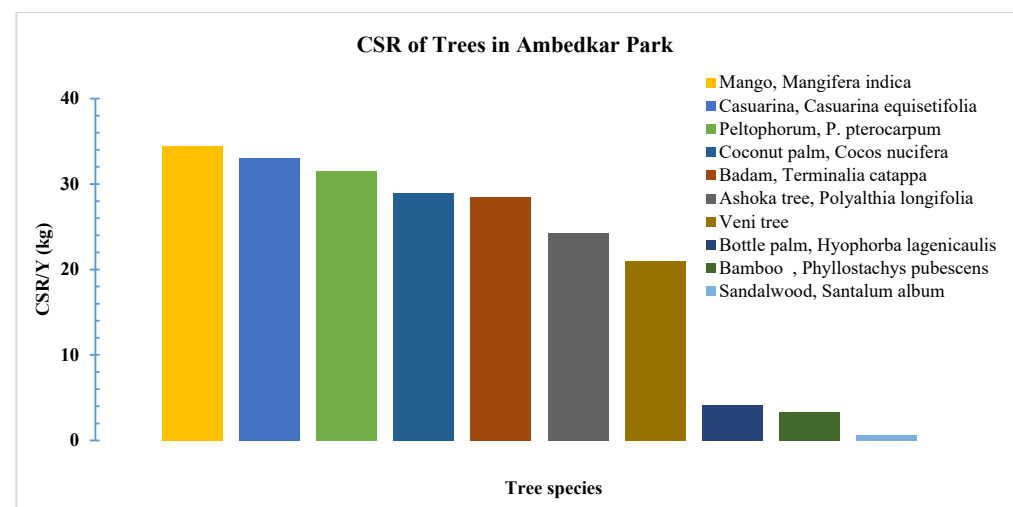


Figure 2. Carbon sequestration rates of 10 medium to small-sized trees in Ambedkar Park. In addition, the CSRs of Rain tree, Gulmohar, and Acacia, respectively, were 630, 160, and 71 kg CO₂ sequestered y⁻¹. These higher values are not fitted into the figure.

3.1.3. Joggers' Park

In Joggers' Park, the dry biomass of 404 trees was 164.11 tons, with a carbon weight of 77.95 tons. In the last 15 years, the total CO₂ sequestered worked out to 286.1 tons (equivalent to 19.1 tons y⁻¹). The top five CO₂ sequestration trees (Figure 3) were Peltophorum (64.60 kg tree⁻¹ y⁻¹), Palm (53.2 kg tree⁻¹ y⁻¹), Coconut (48.6 kg tree⁻¹ y⁻¹), Casuarina (36.9 kg tree⁻¹ y⁻¹), and Ashoka (35 kg tree⁻¹ y⁻¹). The per ha⁻¹ conversion of 404 trees in 1760 m² works out to 2296 trees, and, at a mean of 29.97 kgs per individual tree, the annual carbon sequestration would be a moderate 68.81 tons ha⁻¹ (Table 5).

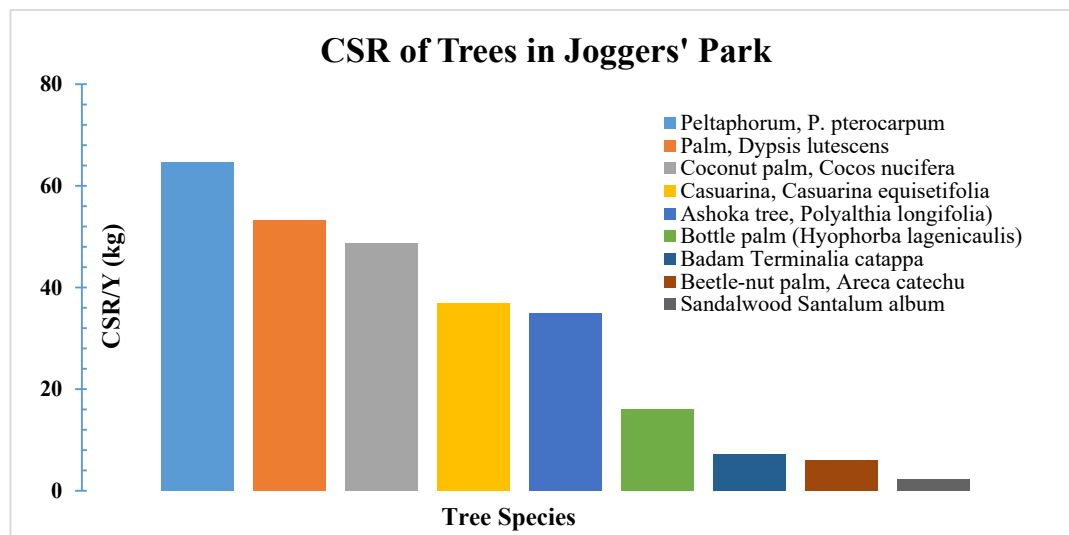


Figure 3. Carbon sequestration rates of nine medium to small-sized trees in Joggers' Park.

Table 5. Details of total dry weight, carbon weight, and sequestration rates of different species of trees (~15 years old) in Joggers' Park.

Tree (Scientific Name)	Number	Mean Height (m)	Tree Spec Gravity	Girth Circumference (cm)			Dry Weight kg/tree	Carbon Wt kg/tree	CO ₂ seq/tree/yr	CO ₂ Seq/Species (kg/y)
				n	Mean	±SD				
Peltaphorum, <i>P. pterocarpum</i>	213	13.5	0.62	11	82.46	8.99	555.82	264.02	64.60	13,758.81
Coconut palm, <i>Cocos nucifera</i>	48	8.00	0.58	14	95.79	7.88	418.43	198.75	48.63	2334.14
Beetlenut palm, <i>Areca catechu</i>	42	8.00	0.52	10	34.67	3.74	51.77	24.59	6.02	252.72
Bottle palm, <i>Hyophorba lagenicaulis</i>	33	5.50	0.55	6	67.33	5.79	138.37	65.73	16.08	530.66
Ashoka tree, <i>Polyalthia longifolia</i>	32	11.00	0.54	8	71.5	7.09	300.71	142.84	34.95	1118.31
Palm, <i>Dypsis lutescens</i>	12	6.50	0.55	8	114.25	9.47	457.69	217.40	53.19	638.30
Casuarina, <i>Casuarina equisetifolia</i>	10	8.50	0.63	10	77.4	7.71	317.28	150.71	36.87	368.73
Badam, <i>Terminalia catappa</i>	8	7.00	0.52	5	40.6	2.07	61.83	29.37	7.19	57.48
Sandalwood, <i>Santalum album</i> (2y old)	6	4.00	0.54	6	29	2.83	19.35	9.19	2.25	13.49
Total number of species	9	8.00	Average		68.11		257.92	122.51	29.97	577.43
Total number of trees in 1760 m ² (=2295 trees ha ⁻¹)	404	2.85	±SD>>		28.73		197.46	93.79	22.95	1205.08

Specific gravity data from Lahoti et al. [20] (in bold) and from different wood databases, mentioned in Table 3.

An overall comparison of the mean height (m), diameter at breast height (DBH (cm)), and dry and carbon weights, along with the per-tree and per-species carbon sequestration rates (Figure 4), is presented. It is useful to note from this comparison that irrespective of tree species composition, both mean height and DBH are the largest in the older trees, which are taller and bulkier than the ones ~15 years old in Joggers' park. As mentioned earlier, the mean sequestration rate per tree is the highest in Ambedkar Park.

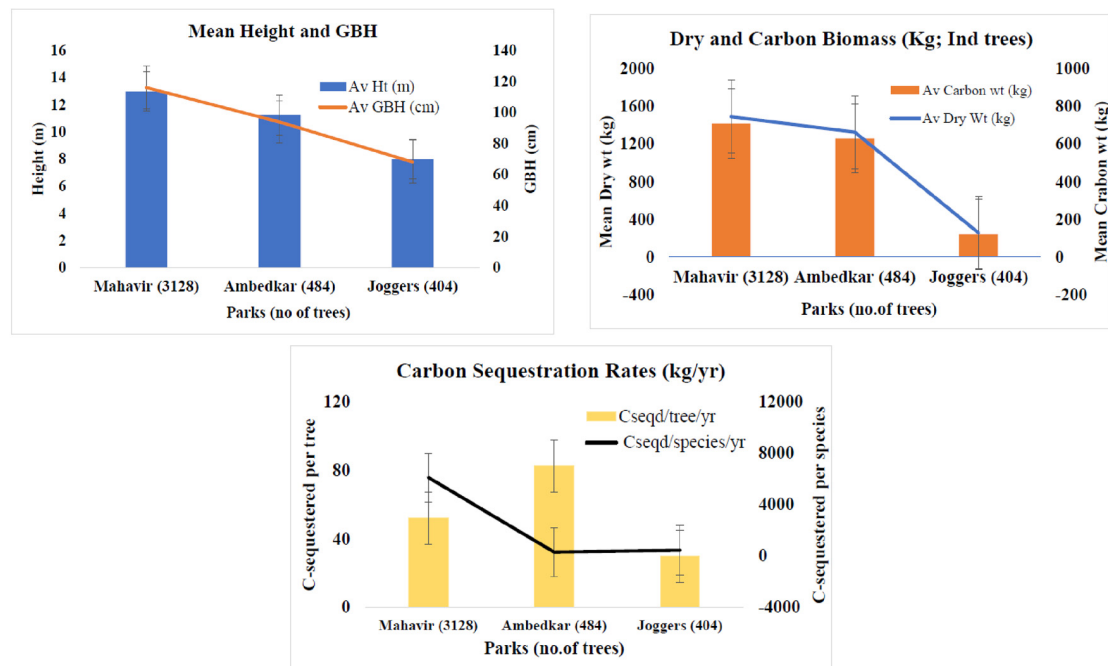


Figure 4. Mean values of height (m), GBH (girth at breast height), dry weights, and carbon weights (**top panels**) and carbon sequestration rates per tree and per species (**bottom**). Mean values are for the total number of trees in Mahavir, Ambedkar, and Joggers' parks in Panaji city.

3.2. Average Carbon Sequestration Rates of Trees in Surveyed Parks

The mean CSR tree⁻¹ is summarized at the end of each table above (Tables 3–5). Although the total number of trees and other details were noted from the seven parks surveyed, the list of trees with names were made available officially from only three parks. There are 4010 trees in a 24,991 m² area exclusively for trees (i.e., in Mahavir Park 3128 trees are in 22,101 m², in Ambedkar Park 478 in 1130 m², and in Joggers' Park 404 in 1760 m²). The number of trees in the other four parks in the summed-up area of 7855 sq m is 868. These 4878 (i.e., 4010 + 868) trees in 32,446 sq m average to 1433 trees ha⁻¹. Despite the wide differences between the tree species in each of the three parks, the weighted mean of CO₂ sequestered per tree averages to 55 kg y⁻¹ (i.e., 52 + 82.54 + 29.97 kg tree⁻¹ y⁻¹, respectively from Mahavir, Ambedkar, and Joggers' parks). With this average of 55 kg tree⁻¹ y⁻¹, the CSR ha⁻¹ y⁻¹ is 78.82 tons. This rate is used for estimating the per ha and per tree carbon sequestration potential of trees in the UGS of Panaji and Tumkur cities.

3.3. Carbon Biomass and Sequestration Rates of Hedge Plants and Grass Cover

The data pertaining to hedge rows (Table 6) and groundcover (lawn, Table 7) collected from each of the seven parks were analyzed. The total area of hedge plants and their wet and dry biomass values, as well as their carbon sequestration rates (Figure 5), were estimated. In the seven sampled/surveyed parks, the total hedge area is 8385 m², the carbon biomass is 10,943 kg, and carbon sequestered amounts to 40,159.7 kg. With a hedge row carbon biomass of 13.18 tons ha⁻¹, the fixation/sequestration of CO₂ is equivalent to 48.38 tons ha⁻¹ y⁻¹. Similarly, the grass cover area totaling 25,860 m² from these parks holds a carbon biomass of 37,995 kg and carbon sequestered of 139,940 kg y⁻¹ (equating 53.92 tons ha⁻¹ y⁻¹).

Table 6. Details of biomass (wet, dry, and carbon) in hedge rows and their carbon stocks and sequestration rates in different sampled parks in Panaji City (plus per ha conversions).

Park	Hedge-Area (m ²)	Wet Biomass (W _{tgw}); kg	Dry Biomass (W _{dw}); kg	Carbon Biomass (W _c); kg	Carbon Sequestered in Hedge Area kg
Kala Academy	360	1296	939.6	469.8	1724.17
NGRF Office Park	160	576	417.6	208.8	766.30
SGRF Office Park	800	2880	2088	1044	3831.48
Mahavir Park + Art Park	2700	9720	7047	3523.5	12,931.25
Garcia da Orta Garden	405	1458	1057.05	528.53	1939.71
Ambedkar Park	1620	5832	4228.2	2114.1	7758.75
Joggers Park	2340	8424	6107.4	3053.7	11,207.08
Total	8385	30,186	21,884.85	10,942.43	40,158.72
Biomass (Tons ha ⁻¹)		36.37	26.37	13.18	48.38 tons/ha

Table 7. Details of biomass (wet, dry, and carbon) in grass cover (lawns) and their carbon stocks and sequestration rates in different sampled parks in Panaji City (plus per ha conversions).

Park	Lawn Area (m ²)	Wet Biomass (W _{tgw}); kg	Dry Biomass (W _{dw}); kg	Carbon Biomass (W _c); kg	Carbon Sequestered in Lawn Area (kg)
Kala Academy	2675	17,467.75	7860.49	3930.24	14,423.00
NGRF Office Park	2250	14,692.5	6611.63	3305.81	12,132.33
SGRF Office Park	1625	10,611.25	4775.06	2387.53	8762.24
Mahavir Park + Art Park	6410	41,857.30	18,835.79	9417.89	34,563.67
Garcia da Orta Garden	1500	9795	4407.75	2203.88	8088.22
Ambedkar Park	6500	42,445	19,100.25	9550.13	35,048.96
Joggers Park	4900	31,997	14,398.65	7199.33	26,421.52
Total area (m); weight (kg)	25,860	168,865.80	75,989.61	37,994.81	139,440.93
Biomass Tons ha ⁻¹		65.30	29.39	14.69	53.92 tons ha ⁻¹

Another approach of using the mean leaf mass area of 12.1 mg cm⁻² derived by Gratani et al. [26] for four hedge plants was also applied to arrive at a reasonable estimate of above ground and below ground wet biomass, which worked out to 13.07 kg m⁻². The CSP of hedge plants was calculated using both these derivations to give a feel of possible CSP in the UGS considered in this study. The CO₂ sequestration was over 3–4 times higher than that of the one derived using Crossland [21].

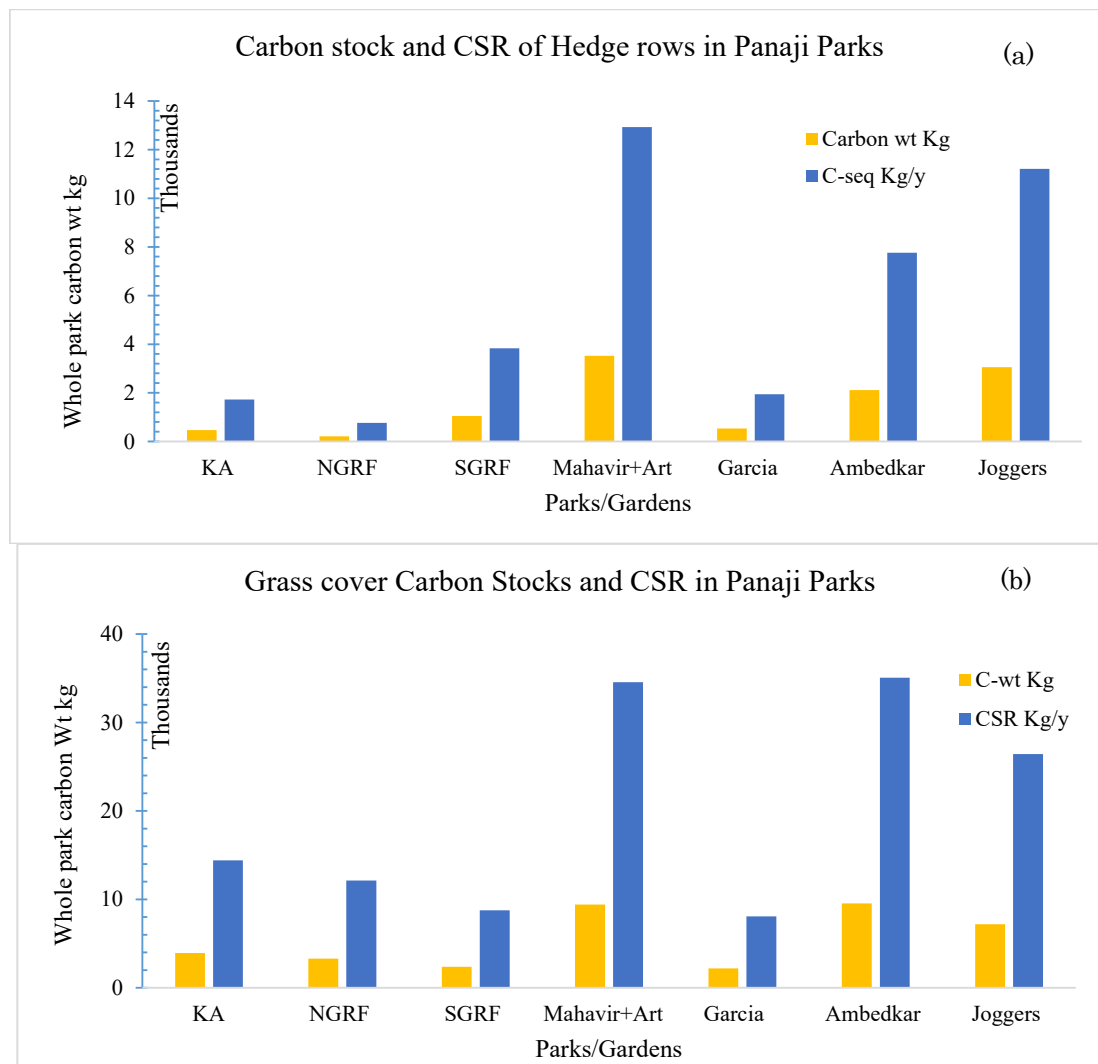


Figure 5. Carbon stocks (kg) and CO₂ sequestered (kg y⁻¹) by pruned plants in hedge rows (a) and grass cover (b) in different parks in Panaji city. Area and other details included in Tables 4 and 5.

3.4. Carbon Stocks, Production, and CSP in the UGS of Panaji and Tumkur Cities

The per-hectare carbon stocks of trees, grass cover, and hedge rows, respectively, are 697.69, 53.92, and 48.38 tons. Trees account for up to 12–14 times the stocks of grass cover or hedge rows in Panaji city parks. The average carbon biomass production in Mahavir Park, Ambedkar Park, and Joggers Park is 18.82-, 46.97-, and 29.52-tons ha⁻¹ yr⁻¹, respectively.

CSP rates for all of Panaji and Tumkur cities UGS was worked out using the information derived from the seven parks by making use of the derivatives of carbon stock (Figure 5a) and CSR of trees (55 kg tree⁻¹ y⁻¹ or 78.82-tons ha⁻¹ y⁻¹; calculated from the averages data in Tables 3–5), hedge plants (48.38 tons ha⁻¹ y⁻¹; Table 6), and grass cover (53.92 tons ha⁻¹ y⁻¹; Table 7). Trees hold large amounts of carbon and sequester far higher amounts (Figure 6). Though larger plot areas are allocated to grass cover (from easy maintenance and water-saving angles), the CO₂ sequestration contributions are meager. The volumes sequestered by trees per hectare are over six times either groundcover or hedge plants.

The carbon sequestration potential of trees in UGS of Panaji and Tumkur cities was calculated using the average annual production of 78.82 tons ha⁻¹ y⁻¹ obtained in this study rather than the rates of 108 tons ha⁻¹ CSR reported in Lahoti et al. [20]. This was performed to avoid overestimations and to use these carbon stocks and CSR for Panaji and

Tumkur city UGS. Since many basic details of the parks and roadside plantations were collected from Tumkur, an estimate of the probable CSR is provided.

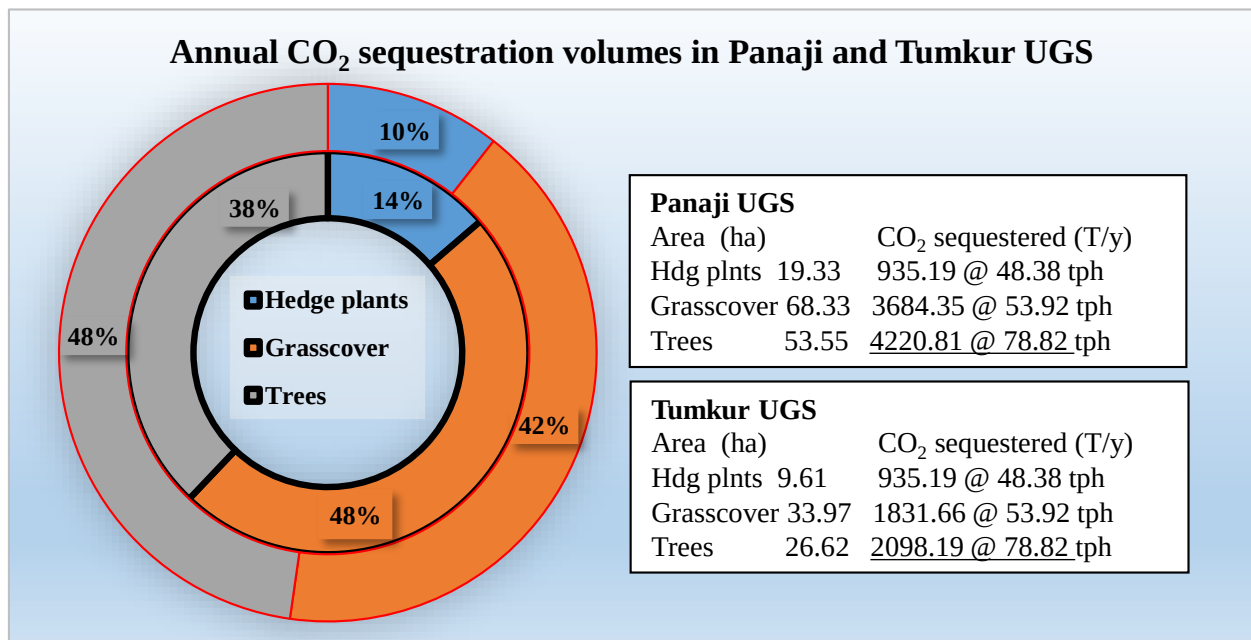


Figure 6. Area proportions (in percentage; inner circle) of hedge plants, grass cover, and trees (ha) and annual CO₂ sequestration volumes (tons ha⁻¹) derived in this study for UGS of Panaji and for Tumkur (estimated) cities.

Trees numbering 76,751 in Panaji UGS would sequester 4221.31 tons y⁻¹ at 55 kg tree⁻¹ y⁻¹, and those 38,152 trees in Tumkur would sequester 2098.36 tons y⁻¹. The CO₂ sequestered would be 4220.81 tons y⁻¹ in Panaji and 2098.19 tons y⁻¹ in Tumkur parks (Table 8). Further, as stated earlier, the weighted averages of sequestration potential of grass cover and hedges derived from all seven surveyed parks in Panaji were used to obtain an estimate of their carbon stock and sequestration rates in the UGS of these two cities. With over 36% of the UGS, the CO₂ sequestered by the lawn/grass cover/groundcover is quite substantial, though far lesser than the CSR by trees. The existing UGS neutralizes 4556 (Panaji) and 2265 (Tumkur) peoples' carbon footprint.

Table 8. Carbon stock (CST) sequestration rates (CSR) ha⁻¹ y⁻¹ of hedge plants, grass cover, and trees in the parks and gardens of Panaji and Tumkur cities.

Parameters	Panaji	Tumkur
City area km ²	21.6	48.6
UGS area km ²	1.858	0.924
UGS% in city area	8.6	1.9
UGS; m ²	1,857,600	923,400
Details of Hedge Plants		
Hedge plants area @ 10.40 (±6.42) % of UGS, ha	19.33	9.62
Hedge plants CS @ 13.18 tons ha ⁻¹ * (Tons)	254.71	126.61
Hedges CSP y ⁻¹ @ 48.39 tons ha ⁻¹ * (Tons)	935.15	464.85

Table 8. Cont.

Parameters	Panaji	Tumkur
Details of Grass cover		
Grass cover area @ 36.79 (± 16.09) % of UGS; ha	68.33	33.97
Grass cover C-stock @ 14.69 tons ha ⁻¹ * (Tons)	1003.81	4989.88
Grass cover CSP y ⁻¹ @ 53.90 tons ha ⁻¹ * (Tons)	3683.15	1830.87
Details of trees		
Trees' area 28.83 (± 16.27) % of UGS; ha	53.55	26.62
No of trees ha ⁻¹ @ 1433 trees ha ⁻¹	76,751	38,152
C-sequestered in the UGS @78.82 * tons y ⁻¹	4220.67	2098.06
Total seq (Trees + Hedge-rows + Grass cover; Tons)	8838.96	4393.78
C-sequestered by trees @ 55 kg tree ⁻¹ y ⁻¹ , Tons	4221.31	2098.36
CFPR ** @ 1.94 T per capita (no. of persons)	4556	2265

* Values Derived from This Study. ** CFPR—Carbon Footprint Reduction.

4. Discussion

4.1. Carbon Sequestration Potential of Main Plants Grown in Indian Cities

Unequivocally, the increasing atmospheric CO₂ levels are identified as the predominant cause of global change [27]. Though agricultural and forestry practices are believed to partially mitigate the increasing CO₂ concentration [28], the role of UGS in aiding sequestering carbon is yet to be fully acknowledged, and our understanding on this aspect is still frail. Ever since the Kyoto Protocol has become effective, there has been increased attention paid to strategies for carbon sequestration. More impetus is given to climate change mitigation and adaptation measures following The Paris Agreement. In essence, by planting trees in urban and/or suburban areas, and by improved management/maintenance of already existing green spaces, opportunities abound for reducing many ill effects.

While legislative frameworks do exist, depending on location, the plant species grown in major cities of India vary quite widely. The percentage of green space and main plants grown in major cities of India are listed in Table 9. In Panaji city, the approximate green space area is 80 hectares, accounting for 9.6% of the city area (Table 9). The city aims to be clean, environmentally friendly, and ecologically sustainable, with a focus on improving the urban infrastructure facilities and tourism infrastructure, along with conserving the natural elements and heritage structures by adopting eco-friendly alternatives and techniques.

In general, due to fast growth rate and adaptability to a range of environmental parameters, short-rotation plantations rapidly produce biomass for energy and contribute to reduced greenhouse gas emissions. This is in addition to carbon storage. Earlier studies in some species of trees from tropical regions suggest varying CSRs depending on the tree species considered. For instance, in the case study by Kaul et al. [29], it was found that long-term total carbon storage ranges from 101 to 156 Mg C ha⁻¹, with the largest carbon stock in the living biomass of long-rotation sal forests (82 Mg C ha⁻¹). From their study, the net annual carbon sequestration rates were found to have been achieved by fast-growing short-rotation poplar (8 Mg C ha⁻¹ yr⁻¹) and Eucalyptus (6 Mg C ha⁻¹ yr⁻¹) plantations, followed by moderate-growing teak forests (2 Mg C ha⁻¹ yr⁻¹) and slow-growing long-rotation sal forests (1 Mg C ha⁻¹ yr⁻¹). Native trees like *Azadirachta indica* (Neem), *Tamarindus indica* (Tamarind), *Ficus religiosa* (Peepal), and *Madhuca latifolia* are considered ecologically beneficial, as they have relatively high efficiency of carbon fixation; these species may be suitable for checking urban pollution and may provide a good

option for maximum carbon fixation [29–31]. While a variety of short-term and long-lived plants/trees are grown in different cities in India, the overall data are lacking on the carbon sequestration potential of different plant species. This first-time calculation/estimation of tree carbon biomass and species-wise yearly carbon sequestration in three of the seven different parks sampled from Panaji city is useful to recognize the importance of urban vegetation for improving living conditions. This is also apparent from the far higher carbon production rates of 31.77 tons ha^{−1} y^{−1} (see below) of the trees in Panaji city UGS than the previous estimates of 3.23 [30] to 6.55 [25] tons ha^{−1} y^{−1} reported in the literature.

Table 9. Green spaces and plant species grown in major cities of India.

City	Green Space (%)	Major Plant Species (Indicative)
New Delhi	11.90	Banyan tree, Peepal tree, Bael, Jamun, Ber, Arjun
Mumbai	6.20	Bhendi tree, Banyan trees, Tamarind tree, Coconut palm, Paral tree, Padauk trees, Mahogany tree, Cajuput tree, Baobab tree, Star Apple, Baobab tree, Peltophorum tree, Gulmohar tree
Chennai	7.50	Sansiveria, Dieffenbachia, Dracaena, Spider plant, Earth star, Money plant, Pothos, Syngonium
Hyderabad	1.66	Bougainvillea, Neerium, Adeneum, Lantana, Euphorbia russelia
Bengaluru	2.96	Australian wattle, Butterfly tree, Red silk-cotton tree, Popcorn bush cedar, Coconut palm, Gulmohur, Indian cork tree, Indian elm, Teak, Silver oak, Orange champak
Kolkata	7.30	Neem, Peepal, Banyan, Radhachura, Krishnachura, Tamarind, Coconut, Betelnut tree
Pune	1.40	Cadamb, Tetu, Awala, Chandan, Tamhan, Muchkund, Cadamb, Kanchan, Putranjiva, Semla Kanchan, Kapila, Murudsheng Ritha, Undi
Panaji	9.6	Casuarina, Peltophorum, Badam, Coconut, Bottle palm, Mango, Rain tree

4.2. Carbon Production and Sequestration Rates

A broad spectrum of carbon production ha^{−1} y^{−1} by in situ vegetation is available from agroforestry practices in India [31–33]. Depending on the region, where rainfall exceeds 2000 mm—similar to that in Panaji—the rate of biomass production is stated to be higher [25,32,33]. Indeed, Kaur et al. [34] reported that the carbon production from arid regions receiving less than 1000 mm rainfall annually was a meager 1.37 tons yr^{−1} ha^{−1}. In comparison to these reports [33,35,36], both the standing carbon biomass of 31.77 tons ha^{−1} y^{−1} and sequestration rates of 78.82 tons ha^{−1} y^{−1} in all three parks were higher, which might be due to consistently higher growth rates of all tree species in these parks. This could be attributed to the presence of a higher number of fast-growing tree species, such as Casuarina and Peltophorum, in all three parks. A few large trees in Ambedkar Park also skew the production rates to high values. Based on this production rate, the carbon sequestration rate would be 116.60 tons ha^{−1} y^{−1}. The rates of overall growth, carbon biomass production, and sequestration may vary widely in trees growing in the UGS of different cities. Although Goa is receiving higher than 2000 mm rainfall, unlike Tumkur, the CSR ha^{−1} in the UGS areas calculated on a per-tree and per-hectare basis in this study are useful to note wide species-wise differences within the three parks considered for this study. This result is thus implicit enough to suggest that the CSR is higher in taller, broader, and relatively younger trees.

These data, together with the CSR of hedge rows (48.38 tons ha^{−1} y^{−1}) and grass cover (53.92 tons ha^{−1} y^{−1}), are depicted in Figure 7.

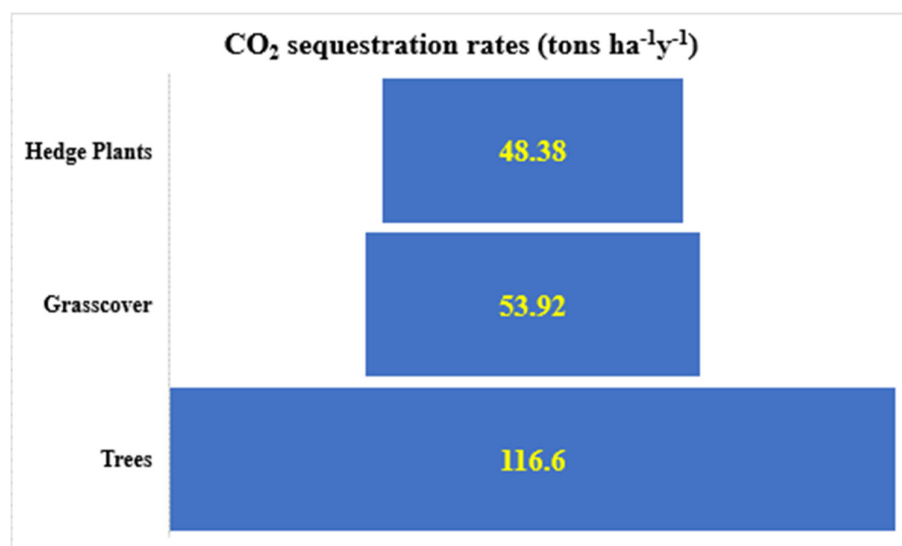


Figure 7. Carbon sequestration rates (CSRs) of hedge plants, grass cover, and trees in Panaji city parks. The CSR of trees is based on their average carbon production rates ha^{-1} derived from Mahavir, Ambedkar, and Joggers' parks.

4.3. Carbon Storage and Sequestration Potential of Trees

The Intergovernmental Panel on Climate Change [3] recognized agroforestry as a vital opportunity for both adaptation and mitigation actions. Together with the management of cropland, grazing land, and forests, agroforestry is projected to sequester over 1.2 billion tons of carbon annually [3,31,35,36]. The greatest sequestration stage is the younger ages, depending on rates and peak heights of individual species. The impact trees bear on CO₂ sequestration is undeniable in the global fight against climate change, as they are reported to sequester 22.8 million tons annually and store 700 million tons in US cities alone [11,37].

There are no previous studies on the possible CSP of the tree species in the parks of Panaji or Tumkur, or from most of the Indian city UGS. The carbon sequestration rates calculated in this study using standard methods are useful to note wide-ranging rates from under 2 kg yr^{-1} by ~2 yr old sandalwood trees to over 630 kg y^{-1} by 28-year-old rain trees. These results are suggestive of the possible wide ranges of sequestration rates within a given UGS. Nair [38] remarked that the non-linear growth of each tree results in widely differing CO₂ sequestration potentials, even within a given tree species. Numerous ecological factors, including ones that affect plant growth, affect CO₂ sequestration. Ultimately, as summed up earlier [39–42], the growth of each tree is very non-linear, and the greatest sequestration stage is in the younger stages of tree growth, depending on the rates and peaks of individual species.

In this regard, the choice of trees in urban forestry is crucial. As noted earlier, out of the 478 trees in Ambedkar Park, the superior rates of sequestration of only 23 of the trees in three species (Rain tree, Gulmohar, and Acacia) might substantiate such a need. Higher production rates in Ambedkar Park may also be due to these few individual species. In Mahavir Park with trees older than 50 years, the carbon stock was remarkably high, but sequestration rates were moderate to low. The per ha carbon stock, calculated following Ravindranath & Ostwald [13], equals 697.69 tons from an estimated 1433 trees ha^{-1} in the parks of Panaji city. With a CSR of $78.82 \text{ tons ha}^{-1} \text{ y}^{-1}$, the rate of tree carbon stock building in these parks with an average age of 31 (Mahavir: 50, Ambedkar: 28, Joggers: $15 [=93/3 = 31]$) years is $22.51 \text{ tons ha}^{-1} \text{ y}^{-1}$, equaling a CSR of $82.60 \text{ tons ha}^{-1} \text{ y}^{-1}$. This CSR value closely corroborates with the CSR of $78.82 \text{ tons ha}^{-1} \text{ y}^{-1}$, derived in this study based on the average CSR of $55 \text{ kg tree}^{-1} \text{ y}^{-1}$.

While the exact CO₂ sequestration rates may require more accurate measurements to pinpoint the impact trees can create, it is undeniable that in our global fight against climate change, the addition of data from studies like these can aid in mitigation measures as well as in fulfilling local/regional plans and needs.

4.4. Carbon Storage and Sequestration Potential of Hedge Plants and Grass Cover

Besides providing multiple benefits as border-fences and aesthesis-keepers, many diverse species of hedge plants, including innumerable medicinal herbs, also sequester carbon [43] in their above ground biomass and in roots, leaf litter, pruned discards, and other soil organic matter at and below ground level. Although the management of mixed hedge row systems certainly improves overall carbon sequestration [44], they are often overlooked in favor of larger carbon-capturing trees. The annual carbon sequestration rate of 48.38 tons ha⁻¹ hedge plants in the UGS of Panaji city, calculated by following Crossland [21], is apparently substantial. As per the IPCC [45] report, an increase in hedges “results in benefits to biodiversity through habitat creation” and regulates air and water quality through intercepting pollutants, maintaining essential diversity, besides being aesthetic landscape features [43,46,47]. With over 53.9 tons ha⁻¹ y⁻¹ of sequestration rate, their potential is similar to grass cover. These substantial rates, both by hedge plants and by grass cover, majorly of Paspalum grass, are possible through regular watering in the parks surveyed.

4.5. Sustainability Perspective of UGS

Several environmental and anthropogenic factors impact the UGS processes. The quality and quantity of material input (pollutants, pesticides, fossil fuel emissions, aerosols, etc.) and export (e.g., salts, minerals, and gases), including the removal rates (plant products from grass to fruits), affect the UGS soil, flora, and several other biological and chemical processes [9,48–50]. Investigations quantifying and identifying various factors influencing these processes in the UGS would help in comparing their performances with natural forests and agroforestry in the context of sustainable ecosystems and climate change mitigation measures.

As stated previously, urbanization offers several opportunities for growth in the economic, educational, societal, and technology sectors. Thus, during the past five decades, environmentally friendly and sustainable urbanization is highly sought after. Such seemingly desirable urban characteristics are dampened by the downsides of often unplanned and haphazard urbanization. The streaming migration into urban areas and the consequent overcrowding reduces the green cover and leads to environmental degradation. In any research endeavor aiming to recognize the importance/relevance of urban green spaces, a deeper understanding of the impact of land surface temperature (LST) on human thermal comfort is an important requirement. While the impact of urbanization on LST has been widely studied to monitor the UHI phenomenon, the sensitivity of various urban factors such as UGS, a built-up area, and extant water bodies to LST is not sufficiently resolved for many urban settlements.

Climate factors (rain and drought), geographic regions, and associated spatio-temporal variabilities of numerous ecological characteristics, like the availability of water, suitable land factors, age differences, and inter- and intra-specific differences, govern biomass production, carbon storage, and sequestration potential [41,51–53]. In this regard, as an outcome, this study can serve as an example in highlighting how well-managed UGS from very large metropolises can facilitate carbon footprint reduction due to urban/civilian activities. It can also be suggested from this study that there is a definite scope for increasing the UGS area and for efficient upkeep of existing UGS.

Results and inferences from this study would prove helpful in implementing sustainability practices in many townships/ settlements analogous to the ones considered for this analysis. Notably, even as a minor contributor, the combined CSP of existing trees, grass cover, and hedge rows in the UGS of Panaji is neutralizing the carbon footprint of over 4500 persons annually at a 1.94-ton per-capita emission. Even with its insufficient green cover, the UGSs in Tumkur city, which is much larger in area than Panaji city, neutralize the carbon footprint of over 2200 inhabitants. This aspect seems to have not received the attention it deserves. Nowak & Crane [11] provide an estimate that the UGS in New York City alone can sequester 22.8 million tons of CO₂, neutralizing the carbon footprint of nearly one million Americans.

5. Conclusions

It is undeniable that in our global fight against climate change, the addition of inputs and data from relevant studies such as the present one can aid in implementing mitigation measures as well as in fulfilling local/regional plans and needs, although exact CO₂ sequestration rates may require stringent estimation protocols and large data sets. In this study, the carbon stock and sequestration potential were worked out for 34 different tree species, hedge plants, and groundcover grasses.

Standard methods were used for deriving the carbon stock and sequestration rates. Notwithstanding the wide differences between the tree species in each of the three parks from where the data were collected, the weighted mean of CO₂ sequestered per tree averages 55 kg y⁻¹. With this rate, the CSR ha⁻¹ y⁻¹ is 78.82 tons. The volume of CO₂ sequestered by 76,751 trees in Panaji UGS is as much as 4221.31 tons y⁻¹ ha⁻¹ at 55 kg tree⁻¹ y⁻¹. In Tumkur city UGS, 38,152 trees sequester 2098 tons ha⁻¹ y⁻¹. Further, in the weighted averages of carbon biomass and sequestration potential of groundcover and hedges, the carbon biomass averages 13.18 tons ha⁻¹ and the fixation/sequestration of CO₂ is equivalent to 48.38 tons ha⁻¹ y⁻¹. Similarly, the groundcover, occupying over 42% of the UGS, with carbon biomass averaging 14.69 tons ha⁻¹, sequesters 53.92 tons of CO₂ ha⁻¹ y⁻¹. Annually, the combined CSP of existing trees, groundcover, and hedge rows in the UGS of Panaji and Tumkur apparently neutralize the carbon footprint, respectively, of over 4550 and 2200 Indians at a per-capita annual emission of 1.94-ton.

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Abbreviations

List of Acronyms Used: AGDB: Above Ground Dry Biomass; BGDB: Below Ground Dry Biomass; CCP: Corporation of the City of Panaji; CFPR: Carbon Footprint Reduction; CSP: Carbon Sequestration Potential; CSR: Carbon Sequestration Rates; DBH: Diameter at Breast Height; GBH: Girth

at Breast Height; IPCC: Intergovernmental Panel on Climate Change; LST: Land Surface Temperature; NIMZ: National Investment and Manufacturing Zone; RES: Regulatory Ecosystem Services; SD: Standard Deviation; SDGs: Sustainable Development Goals; STP: Sewage Treatment Plant; TUDA: Tumkur Urban Development Authority; UGS: Urban Green Spaces; UHI: Urban Heat Island.

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