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Carbon mitigation potential of banana crops biomass and biochar in tropical semi-arid region of India

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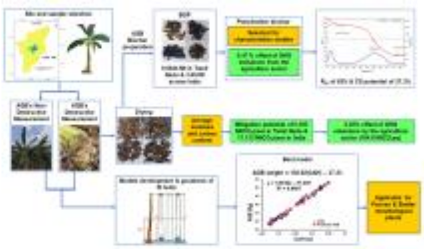
Graphical abstract



Abstract

The standing plant biomass that remains after harvesting bananas is the Above Ground Biomass (AGB); these residues have great carbon sequestration (CS) potential. This study quantifies the AGB yield of the Poovan (Musa acuminata) plant in semi-arid Tamil Nadu, India through novel modified non-destructive and destructive measurements. AGB's moisture and carbon content estimation quantifies the AGB carbon stock of 107.8 Gigagrams and CS potential of 0.395 $MtCO_2$/year. Improper management of AGB leads to greenhouse gas emissions, which can be remedied by biochar production as it is a negative emission technology. Leaves, pseudostem, peduncle and bud biochar are produced through slow pyrolysis method and their yield determines the Biochar Generation Potential (BGP) of the whole AGB. Among the four, the pseudostem biochar has a good yield of 37.1% and BGP of 0.084 Mt/year and its characteristics studies reveal the stability - Recalcitrance Index and CS potential as 62% and 27.3%. Quantifying biomass yield is essential for CS operations. The measurement of a plant's circumference and height form the basis of allometry to estimate biomass. Four linear estimation models are developed to estimate Poovan's AGB and morphologically similar crops. Model 4 most accurately predicts the AGB among the models developed.

Keywords: Agricultural residues; Allometric models; Carbon sequestration; Greenhouse gases; Non-destructive test; Pyrolysis

1. Introduction

Agriculture is vulnerable to the impacts of climate change, demanding urgent adaptation strategies to protect global food supplies; however, the agricultural sector is a significant source of greenhouse gas (GHG) emissions, necessitating focused mitigation strategies within the agricultural sector is a key component of many national climate response plans. In 2020, human activities resulted in 52 gigatonnes of CO_2 equivalent emissions across the globe, with agrifood systems contributing 16 gigatonnes. These emissions originated from three primary areas: farm operations, pre-and post-production activities, and land use change (FAO, 2022). Agricultural residue left in crop fields, residues from processing sectors and agro-industry contribute to environmental pollution. However, these residues are rich in lignin, cellulose, hemicellulose and fixed carbon (FC), which are valuable for applications such as effluent treatment, bioplastics production and CS (Devika and Saha, 2024).

Bananas are among the most extensively produced and consumed fruits worldwide, valued for their nutritional benefits, convenience, and versatility in cooking (FAO, 2024). Globally there are over 1,000 varieties of bananas, with production reaching 125 million metric tons in 2021 (Zaini *et al.* 2023). India is the leading producer and consumer of bananas, producing 33 million tons from 897,000 hectares in 2021 (FAO). Classified as perennial plants, banana crops maintain a consistent biomass throughout the year, containing significant carbon content (Ortiz-Ulloa *et al.* 2021). As substantial annual herbaceous plants, bananas excel in carbon fixation and CO_2 sequestration (Zhao *et al.* 2014). The banana plant can be utilized for a variety of applications which include paper manufacturing, biofuel production which includes biogas, biodiesel and biochar, wastewater treatment, bioplastics and organic fertilizers (Kanthavelkumaran *et al.* 2023; Alzate Acevedo *et al.* 2021).

Around 220 tons of fresh biomass waste is generated from a hectare annually. The higher content of cellulose delays the degradation process and releases GHG, but many farmers dispose of the residues by throwing them in landfills and water bodies, and some farmers burn them, leading to environmental pollution (Shah *et al.* 2005). Residual biomass utilization to make products like biochar and bioethanol contributes to the CS options; thus the quantification of these biomass becomes important (Ortiz-Ulloa *et al.* 2021). Allometric methods and remote sensing approaches are employed in the estimation of biomass. Allometric biomass estimation approaches include non-destructive and destructive field measurements, though the remote sensing approach is advanced it does need field measurements like allometric models and has limitations in estimating the carbon stock (Abdelmajeed AYA and Juszczak R, 2024). The study by Alcudia-Aguilar *et al.* (2019) compared six different models to estimate the AGB of M. balbisiana. Ortiz-Ulloa *et al.* (2021) developed three models to estimate the AGB of William banana plants. The study by Rathnayake and Mizunoya, (2023), adopted the best model provided by Ortiz-Ulloa *et al.* (2021) and estimated the CO_2 abatement potential as 13960.2 tCO_2/year across 1655 hectares of banana cultivation area in Mahaweli H agricultural region of Sri Lanka. The biomass and carbon stock of 43 banana plants is estimated by Danarto S. A. and Hapsari L. (2015) using a single allometric equation and it was found that 6 wild varieties have more carbon content than 37 edible varieties.

Established tree allometric models assumed the trunk as a cylinder and measured the circumference at 1.3 m (chest height) to estimate the AGB. The trees are much taller, and their trunk circumference is much bigger than banana plants. The allometric models proposed by other authors to estimate banana plant AGB adopted the same circumference measurement procedure followed in the trees' AGB estimation. The height of banana plant cultivars varies between 2 meters to 5 meters; correspondingly, the chest height circumference also varies for the cultivar under study. This led to either overestimation or underestimation of the AGB weight of the banana cultivar under study in a different location or region. The arrived AGB is used to estimate the carbon stock, CS potential, and climate change mitigation potential of the region under study, resulting in either overestimation or underestimation. This study assumes the banana plant as a conical frustum and proposes a novel measurement ratio for the Poovan (AAB) banana plant, which leads to identifying a new absolute height to measure the circumference. In this study, four allometric Models are developed based on the proposed conical frustum structure and newly arrived height, along with the conventional cylindrical structure and chest height (CH) adopted in allometric models. The AGB estimated by the best-predicted model can be used to estimate the carbon stock and CS potential of Poovan in Tamil Nadu. In India, Tamil Nadu is the fourth largest producer of bananas, contributing 3.89 million tons to the national output (MoAFW, 2022). All 38 districts in Tamil Nadu practice banana cultivation, Poovan is the top variety cultivated in 32 districts.

Selecting the best crop residue management practices to mitigate the impact of climate change is crucial. To manage corn, rice and sugarcane residues, Prateep Na Talang *et al.* (2024) adopted open burning, fertilizer production and biochar production practices. The biochar production shows the lowest global warming potential -1833.19 to -1473.21 kg CO_2eq/ton and the highest net cash flow than fertilizer production and open burning practices. Biochar production is a negative emission technology that affects climate change by sequestering carbon and enhancing soil health (Rani *et al.* 2024). Biochar improves soil nutrient retention and supports microbial activity, contributing to agricultural resilience against climate change impacts (Kundu and Kumar., 2024; Pandian *et al.* 2024). Biochar production through pyrolysis shows 43% of CH_4 and 42.2% of CO_2 emission reduction than natural decomposition of banana residues (Sial *et al.* 2019). The biochar production from AGB residues and their subsequent usage in agricultural practices proves to be a better carbon mitigation option. Good economic source among farmers beyond reducing the waste management costs (Waheed *et al.* 2025; Zou *et al.* 2024; Liqin *et al.* 2024; Xin J. *et al.* 2023; Xue L. *et al.* 2023).

The oxygen (O)-to-carbon (C) ratio determines biochar's stability, through which the biochar's CS potential can be estimated. Biochar with O/C < 0.2 is most stable, and its half-life is over 1000 years. The O/C ratio of 0.2 to 0.6 suggests biochar's half-lives between 100 and 1000 years and biochar with an O/C ratio > 0.6 has half-lives of over 100 years (Spokas, 2010). The biochar's resistance to oxidation also determines its stability. Thermal degradation (Recalcitrance index - R_{50}), proximate analysis, chemical accelerated ageing and enzymatic oxidation are the oxidation methodologies employed to find resistance. The volatile matter (VM) to FC ratio < 0.88 predicts the half-life of biochar as more than 1000 years and ratio between 0.88 to 3 predicts the half-life between 100 to 1000 years, (Leng *et al.* 2019). The feedstock and pyrolysis temperature play crucial roles in determining the CS potential of 21 biochar Adhikari *et al.* (2024). This study estimates the biochar potential of banana plants and characterizes the best biochar derived from the four AGB parts. The objectives of this study are: 1. To develop an error free novel non-destructive measurement technique to find the biomass of banana crops. 2. To provide the best allometric model to find the AGB of Poovan. 3. Estimation of carbon abatement potential of Poovan banana crops using the best allometric model across Tamil Nadu. 4. To estimate the biochar generation potential of banana crop's AGB and 5. To find the R_{50} and CS potential of biochar obtained from Poovan's pseudostem.

2. Materials and methods

2.1. Study sites and sampling:

Tamil Nadu has three banana cultivation zones: northwest, central, and south (Vadivel, 2018). The study was conducted from January 2023 to March 2024, focusing on two farms producing Poovan bananas: **Figure 1** shows Ariyamangalam farm (10°81'32.44''N 78°73'18.4''E) in the Tiruchirappalli district of central zone and the Nanagavarm farm (10°52'10.0''N 78°32'16.2''E) in the Karur district of the northwest zone. A tropical wet and dry climate with a temperature range of 23°C to 33°C is observed in Tiruchirappalli with an annual rainfall of 872 mm. Banana cultivation is practised in red loamy and sandy alluvial soils with canal irrigation. Karur has a hot semi-arid tropical climate with an annual average temperature range of 22.4°C to 32.2°C and an annual rainfall of 809.6 mm, with sandy loam and clay soil types and canal irrigation practised SHB (2022). Daphine *et al.* (2018) developed allometric models for biomass-carbon estimation in three East African Highland Banana cultivars using 84 samples (28 samples per cultivar). Yamaguchi and Araki (2004) developed biomass production models in northwest Tanzania using 14 banana plant samples. Ortiz-Ulloa *et al.* (2021) selected 36 samples, 12 samples from three provinces, to establish allometric models. In this study 24 mature Poovan plants are selected from each site.

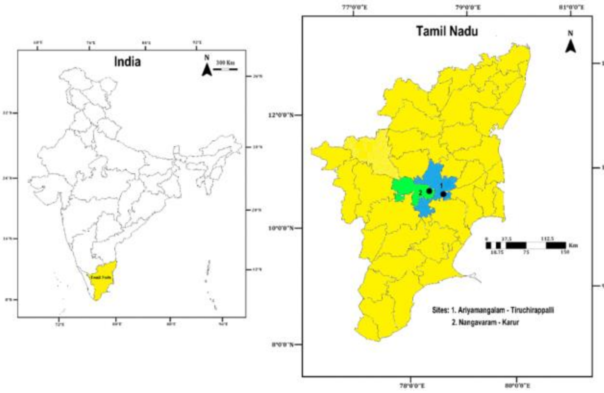


Figure 1. Study sites 1 and 2 in Tamil Nadu extrapolated from India map

The species density (SD) is the number of plants occupying space of 10,000 m^2 (1 hectare) at both sites found using equation 1 TNAU (2020). Banana production and cultivation area of each district are obtained from the MoAFW (2022) and SHB (2021). The Poovan species cultivation across Tamil Nadu is found through farm surveys and the data provided by TNAU (2020).

$$SD = \frac{10,000}{(spacing\ distance)^2} \quad (1)$$

2.2. Estimation of AGB and development of prediction models:

The pseudostem, leaves, peduncle and male bud are AGB of a plant as shown in **Figure 2(a)**. The pseudostem is tall and sturdy, composed of leaf bases, and the plant has large, elongated leaves that spiral around the pseudostem. The central core of the pseudostem extends as a peduncle from which a flower cluster producing both male (bud) and female flowers (banana bunch) arise. The mature banana fruit bunch is the product, not the residues, so it is not considered under AGB. **Figure 2(b)** shows the standing biomass of the banana plant, and **Figure 2(c)** shows the components of a conical frustum. A conical frustum has two circular bases: the large bottom base - Conical Frustum Base Circumference (CFBC) and the small top base - Conical Frustum Top Circumference (CFTC), the diameter of the bottom base and top base is denoted by D and d. The perpendicular distance between the CFBC and CFTC is the height of the frustum (H) whereas the slant height (h) is the distance measured along the curved surface from the edge of one base to the edge of the other. The volume of the conical frustum (V_f) can be found using the following equation 2.

$$V_f = \frac{H}{12\pi}\left[\mathrm{CFBC}^2 + \mathrm{CFTC}^2 + (\mathrm{CFBC})(\mathrm{CFTC})\right] \quad (2)$$

Figure 2(d) represents the cylindrical structure, which also resembles the pseudostem. Usually its circumference is measured at the CH, 1.3 meters from the ground level and its corresponding volume is V_c. The V_f and V_c comparison shows that the cylindrical structure has excess volume compared to the conical frustum structure, as shown in **Figure 2(e)**. The conical frustum assumption will support the water management operations. This assumption applies to all banana cultivars but is more evident in taller and larger varieties such as Monthan, Poovan, Red Dacca, and Karpooravalli compared to smaller ones like Nendran and Grand Naine. Larger plants yield approximately 62% fiber, whereas smaller plants produce around 58%, with the B genomic group potentially contributing to higher fiber content (Yamini D., *et al.* 2016). **Table 1** summarises both non-destructive and destructive measurements of Poovan AGB. For non-destructive measurements, sample plants are randomly selected and marked appropriately. The distance between the marked plants and their neighbouring plants is recorded. Metric tape measures the CCH and CFBC, and the number of leaves in the plants is noted. During the destructive measurements, the fruit bunch is cut down from the plant, followed by the cut at 10 cm from the ground level in the pseudostem. CFTC (where the third petiole starts), h, and H_{pp} (height between the third petiole and the peduncle base) are measured with a metric tape. The total height (TH) is the sum of the pseudostem height (H) and H_{pp}. The pseudostem and leaves with petioles, are cut separately and weighed using a weighing machine. The peduncle base portion section appears once all the petioles are removed. This base portion and its extension till the fruit bunch is sliced out forms the peduncle part and its weight is recorded. The recorded

parameters and their mean from the two study sites are presented in **Table 1**. The circumference at every 30 cm in pseudostem of all 48 plants shows that the reduction in circumference is consistent from bottom to top. One-way ANOVA is executed to check any significant differences in the parameters measured.

The major identification of this study is the establishment of measurement ratio circumference reduction to height of the pseudostem [(CFBC-CFTC)/H]. For example, the plant 38 from site 2 has a pseudostem height (H) of 3.20 m, its CFBC is 0.812 m, and CFTC is 0.464 m. The CCH (1.3 m height) is 0.671 m. The circumference at 2.5 m height above ground level is 0.546 m. When applied, (0.812-0.464)/(3.2) = 0.108. This formula is applicable to any two circumferences in a plant. i.e. (0.671-0.546)/(1.2) = 0.104. This 0.1 ratio is constant for plant 38. All 48 sample plants are studied under this concept, and the average value is 0.1, which is constant for Poovan. This ratio varies from species to species, Monthan and Karpooravalli have marginally higher values than Poovan.This value is used to find the Absolute Height (AH) for Poovan. The height at which the V_f and V_c are equal for a Poovan banana plant. The volumetric comparison of V_c and V_f for every plant reveals that the cylindrical structure has 3 to 10 % more excess volume than the cone frustum structure. The excess volume in the cylindrical structure starts reducing when the height at which the circumference is measured is moved beyond the CCH, which equals the volume of cone frustum at 2 meters in height. The circumference arrived at AH is CAH. The AH of Poovan is 2 m which is well above the usually measured CH 1.3 m from ground level. Four linear estimation models are developed using Minitab 18.1 software. These models take the form of the linear equation: Y = mX + C, where Y represents the AGB weight, X stands for volume in model 1 and model 2, and circumference in models 3 and 4. Whereas, 'C' is the intercept and 'm' is the coefficient of X.

Table 1. Non-destructive and destructive measurements of plant AGB and their weight distribution (mean±SD). The lower cases near the values indicate significant differences ($p<0.05$) (One-way ANOVA RESULTS).

Site	**Non-destructive sampling**				
	No. of samples	**CFBC (cm)**	**CCH (cm)**	**Plant spacing distance (m)**	**No. of leaves**
1	24	$77\pm0.05_a$	$63.8\pm0.055_a$	$1.88\pm0.08_a$	$10.8\pm2.6_a$
2	24	$73.1\pm0.06_b$	$60.34\pm0.058_b$	$1.82\pm0.06_a$	$10.3\pm2.9_b$
Site	Destructive sampling				
	TH (cm)	H_{pp} (cm)	H (cm)	h (cm)	CFTC (cm)
1	$336.8\pm0.23_a$	$33.6\pm0.02_a$	$303.1\pm0.2_a$	$303.2\pm0.21_a$	$46.3\pm0.035_a$
2	$327.8\pm0.14_a$	$32.7\pm0.01_a$	$295.05\pm0.1_a$	$295.08\pm0.13_a$	$44\pm5.0.04_b$
Site	Plant AGB parts weight distribution				
	Pseudostem (kg)	Leaves (kg)	Peduncle (kg)	Bud (kg)	AGB Total (kg)
1	$26\pm5.47_a$	$11.87\pm1.6_a$	$4.69\pm0.85_a$	$0.77\pm0.11_a$	$41.91\pm7.85_a$
2	$21.39\pm5.2_b$	$10.61\pm1.36_b$	$4.11\pm0.78_b$	$0.65\pm0.12_b$	$36.78\pm7.33_b$
Fresh Weight dispersal (%)	58.45	28.58	11.2	1.77	100

Table 2. Allometric models

Proposed linear model's AGB weight prediction capacity							
Model	**Allometric equation**	**MAE**	**R^2**	**MSE**	**MAD**	**Rank**	**Reference**
4	AGB weight = 138.92(CAH) – 37.23	0.91	0.98	1.19	7	1	current study
1	AGB weight = 399.84 (V_f) + 3.7	0.94	0.97	1.42	6.9	2	current study
3	AGB weight = 132.31(CCH) – 42.83	1.02	0.97	1.58	7	3	current study
2	AGB weight = 344.14(V_c) + 7.15	1.13	0.96	2.00	6.8	4	current study
The best model in comparison with the models of other authors							
Model	Allometric equation	MAE	R^2	MSE	MAD	Rank	Reference
4	AGB weight = 138.92(CAH) – 37.23	0.91	0.98	1.19	7	1	current study
5	ln(AGB) = -6.415+2.940*ln(DBH)	16.74	0.99	307.7	22.6	2	Daphine *et al.* (2018)
6	AGB = $0.0001CBH^3 + 35.62$	20.88	0.99	438.5	60.2	3	Ortiz-Ulloa *et al.* (2021)
7	AGB = $0.069e^{0.068CB}$	80.99	0.97	8336	120.3	4	Nyombi *et al.* (2009)

Model 1 $Y = m(V_f) + C$

Model 2 $Y = m(V_c) + C$

Model 3 $Y = m(\mathrm{CCH}) + C$

Model 4 $Y = m(\mathrm{CAH}) + C$

All four models are assessed through goodness-of-fit tests; coefficient of determination (R^2), mean absolute error (MAE), mean square error (MSE), and mean absolute deviation (MAD) (Ortiz-Ulloa *et al.* 2021; Alcudia-Aguilar *et al.* 2019). Daphine *et al.* (2018) developed an allometric power equation and linearised it. Ortiz-Ulloa *et al.* (2021) developed an exponential allometric equation; the dependent variable in their study is CCH. Nyombi *et al.* (2009) developed an exponential allometric equation, where the dependent variable is base circumference or base girth. The best model from this study is compared with above-mentioned models. Further, the destructive and non-destructive Poovan data are substituted in the allometric equation proposed by these authors.

2.3. Estimation of moisture content and carbon content:

Plants 1, 10 and 15 from site one and plants 27, 31 and 40 from site two are selected to estimate moisture content (MC) and carbon content (CC). Fresh samples weighing 400 gm are taken from the inner, middle and outer layers of the bottom, centre and top portions of pseudostem. Then 400 gm is taken from leaf lamina and petiole portions of the leaves. Further 400 gm of peduncle and 400 gm of male bud are collected and triplicated, a sum of 39 sub-samples per plant and a total of 234 sub-samples from 6 plants are collected. Sub-samples are sun-dried for 10 days (Alcudia-Aguilar *et al.* 2019) and oven-dried at 105°C for 24 hours (ISO 18134-2, 2017) then MC is found using equation 3. The dried samples are pulverised to pass through the 425-micron IS Sieve. A 5 gm sub-sample of each part is taken for CC estimation (BIS., 1972). AGB's average MC (AMC) and average CC (ACC) are found using Equation 4 and Equation 5 (Ortiz-Ulloa *et al.* 2021).

$$MC = \frac{(Fresh\ weight - Dry\ weight)}{(Fresh\ weight)} \times 100 \quad (3)$$

$$AMC = \frac{\sum_{i=1}^{4}\left[(MC)_i (fresh\ weight)_i\right]}{\sum_{i=1}^{4}(fresh\ weight)_i} \times 100 \quad (4)$$

$$ACC = \frac{\sum_{i=1}^{4}\left[(CC)_i (1-MC)_i (fresh\ weight)_i\right]}{\sum_{i=1}^{4}(1-MC)_i (fresh\ weight)_i} \times 100 \quad (5)$$

Where 'i' is the index that represents pseudostem (1), leaves (2), peduncle (3) and bud (4). AMC and ACC of all the six plants are taken for further studies. The average AGB fresh weight of the 48 sample plants is 39.34 kg, whereas the average AGB fresh weight of the six plants 39.83 kg, is used to find the AGB's carbon mass (CM) of the plant, represented in equation 6.

$$CMAGB = \left[AGB\ fresh\ weight(1-AMC)\right] \times \left[ACC\right] \quad (6)$$

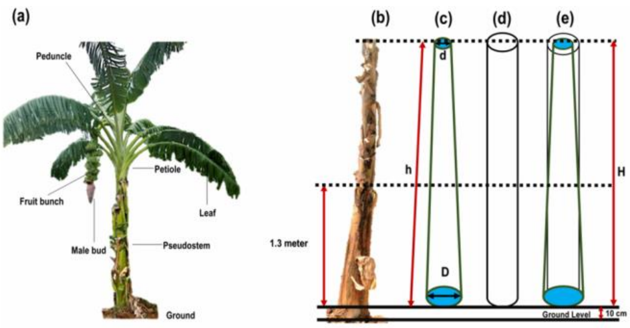


Figure 2. (a) Morphology of Poovan plant (b) Standing pseudostem (c) Conical frustum resembling pseudostem (d) cylindrical structure adopted by other authors and (e) Volumetric differences among conical frustum and cylinder.

2.4. Biochar generation potential

A total of 78 oven-dried sub-samples from the six plants are taken for biochar preparation. Each plant provides 3 gm of two leaf sub-samples, 3 gm of nine pseudostem sub-samples, 3 gm of peduncle and 3 gm of bud for biochar preparation. The samples are cut into small pieces of size 1 cm x 1 cm as shown in **Figure 3**. Biochar samples are prepared through slow pyrolysis in a muffle furnace with a nitrogen supply at a flow rate of 0.5 L/min. under the operating temperature of 500°C. The optimal operating temperature for leaves (Sellin *et al.* 2016), pseudostem (Abdullah N. *et al.* 2023), peduncle (Sugumarn P *et al.* 2012; Nanganoa *et al.* 2019). Half an hour holding time is observed and the samples are taken out after 2 hours. The biochar yield is obtained using equation 7 (Abdullah N. *et al.* 2023). The biochar samples are grounded to a dimension of less than 2 mm.

$$Biochar\ yield = \frac{(mass\ of\ biochar)}{(mass\ of\ dry\ AGB\ plant\ part)} \times 100 \quad (7)$$

This study proposes equation 8 to find the average biochar yield of a tree or plant.

$$\delta_E = (a^*\delta_L - h\delta_A - \varepsilon)/(1 - h + \varepsilon_k) \quad (8)$$

This study proposes Equation 9 to find the biochar generation potential (BGP) of a Poovan plant AGB parts.

$$\delta_E = (a^*\delta_L - h\delta_A - \varepsilon)/(1 - h + \varepsilon_k) \quad (9)$$

2.5. Carbon stock and CO_2 sequestration potential of AGB

Carbon stock at the site is found using equation 10.

$$\text{Carbon stock} = (\text{SD} \times \text{CMAGB}) \quad (10)$$

The molecular weight of CO_2 is 3.67 times higher than the molecular weight of carbon, the carbon stock obtained at the site is multiplied by 3.67 to provide the AGB's CO_2 sequestration potential, represented in Equation 11 (Ortiz-Ulloa *et al.* 2021).

$$\text{CO}_2\text{sequestration potentail} = \text{Carbon stock} \times 3.67 \quad (11)$$

2.6. Characteristics studies and CS potential of pseudostem biochar

All the AGB residues cannot be taken for biochar production, a part of the biomass has to be left in the ground for nutrient cycling and to minimise soil erosion. The maximum quantity of biomass that can be removed from the soil is unknown (Ortiz-Ulloa *et al.* 2021). Since pseudostem contributes a major part to the AGB residues and it is taken for characteristics analysis as other biomasses including the below-ground biomass can be considered for nutrient cycling. The pseudostem biochar sample is analysed under the magnification range of 2 µm - 200 µm in EVO 18 of CAREL ZEISS, (GERMANY) for scanning electron microscopy (SEM) analysis (Kaur *et al.* 2024). The chemical composition and structure of the outer and middle layers of biochar are found using the SEM with Energy Dispersive X-ray Spectroscopy (EDS) technique carried out in TESCAN Vega-3 (CZECH REPUBLIC) with an accelerating voltage of 30 kV. The biochar sample is sputter-coated with Au for better observation. The surface and pore volume are measured using the BET analyser AutosorbiQ, Quantachrome (USA). The ultimate analysis is performed using the Vario EL cube, Elementar, (GERMANY), and the difference between the sum of the carbon, hydrogen, nitrogen and sulphur provides the oxygen content (Song *et al.* 2023). The MC, VM and ash content of biochar are found through proximate analysis performed according to the ASTM 1762 standard (Abdullah N. *et al.* 2023).

The thermal gravimetric analysis (TGA) and differential thermogravimetric analysis (DTG) are performed using Hitachi STA (Japan) to study the decomposition of pseudostem biochar under oxygen atmosphere at the heating rate of 20°C/min. The recalcitrance index (R_{50}) is calculated using the equation 12

$$R_{50} = \frac{TB_{50}}{TG_{50}} \times 100 \quad (12)$$

TB_{50} and TG_{50} represent the temperatures at which 50% decomposition occurs in biochar and graphite, during TGA. The recalcitrance index of biochar is classified into three categories: Category A where $R_{50} \geq 70\%$, the biochar falls under this category is most recalcitrant, Category B where

50% ≤ R_{50} < 70% the biochar comes under this category shows minimal degradation and Category C where R_{50} < 50%, the biochar comes under this category is more degradable (Harvey *et al.* 2012).

The thermograph is corrected for water and ash content to obtain TB_{50}. The CS potential of biochar is found using Equation 13 (Adhikari *et al.* 2024).

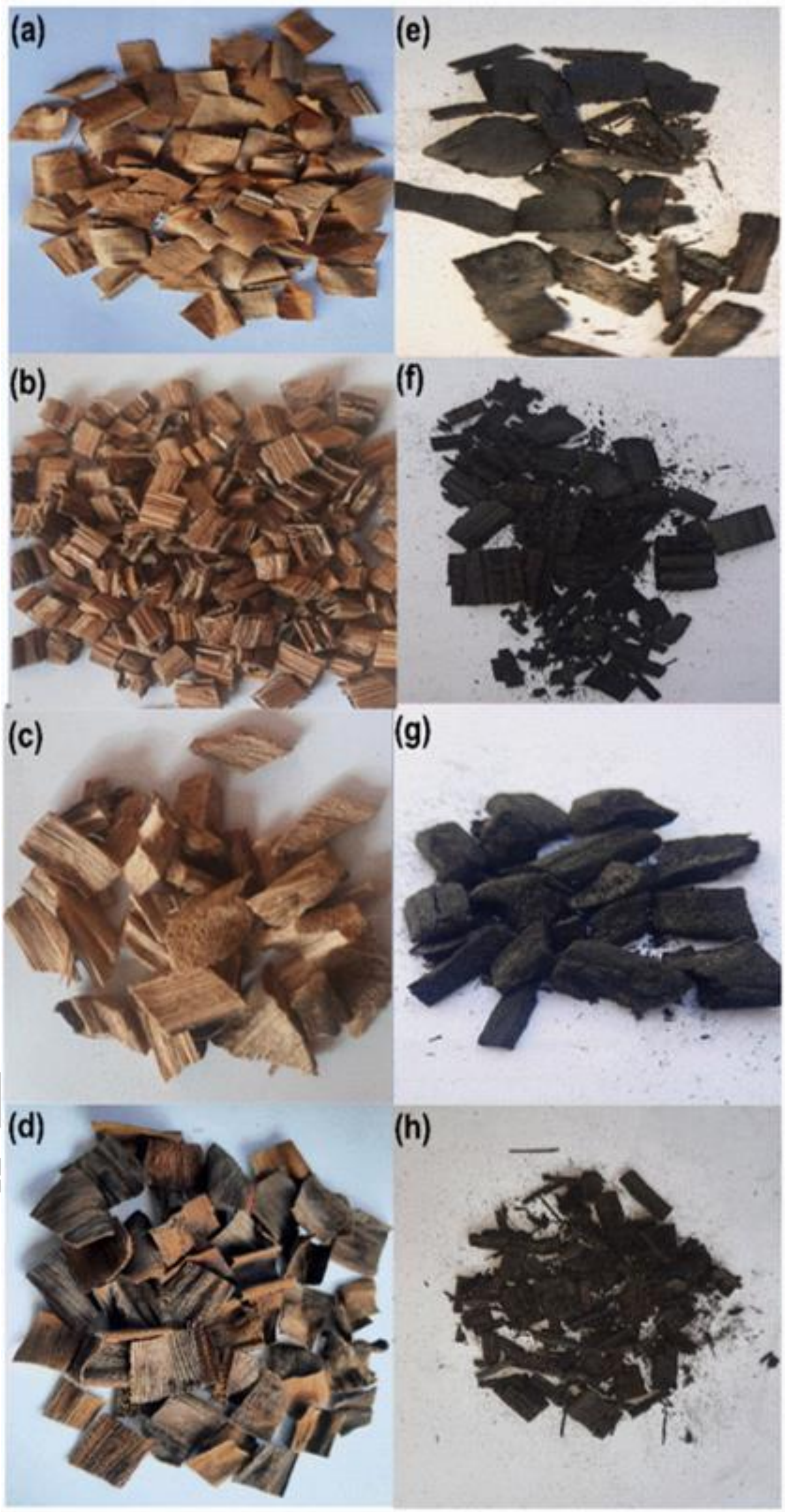


Figure 3. Plant parts and their corresponding biochar (a) leaves (b) pseudostem (c) peduncle (d) dud bract (e) leaves biochar (f) pseudostem biochar (g) peduncle biochar and (h) bud bract biochar

$$\text{CS potential of biochar} = \frac{M \times Y_B \times CC_B \times R_{50}}{M \times CC_1} \times 100 \quad (13)$$

Where M is the mass of the dry pseudostem, Y_B is biochar yield, CC_B is the biochar CC arrived from ultimate analysis, R_{50} is the recalcitrance index of biochar and CC_1 is the pseudostem CC on ash free basis.

3. Results and discussion

3.1. AGB weight and allometric prediction models

The Poovan plant cultivation area in Tamil Nadu is 20505.24 hectares. Tiruchirappalli and Karur districts contribute 2078.42 hectares and 884 hectares. The average spacing distance of plants in Tiruchirappalli and Karur districts are 1.88 meters and 1.82 meters and their corresponding SDs are 2829 and 3019 plants. The tallest and shortest plants recorded at Site 1 are 3.74 meters and 3.03 meters. Site 2, the height ranges between 3.05 meters and 3.58 meters. The ANOVA results reveal the existence of significant differences in the circumference of the pseudostem between the two sites ($p<0.05$). Specifically, the CFBC, CFTC, and CCH, are larger at Site 1 than at Site 2. CFBC at Site 1 ranges from 69 cm to 85 cm, while the range is 65 cm to 83.5 cm at Site 2. CFTC ranges from 41.2 cm to 51.2 cm in site 1 and 39.1 cm to 50.5 cm in site 2. Whereas the CCH ranges from 55.5 cm to 71.9 cm at site 1 and 53.4 to 69.3 cm at site 2. The pseudostem actual height (H) differed from the measured slant height (h) by an average of 0.1 mm at Site 1 and 0.3 mm at Site 2. Plant 1 from site 1 shows the maximum volumetric difference of 9.5% between V_c and V_f and at site 2 plant 16 shows the maximum volumetric difference of 6.1%. On average the V_c is 5% greater than the V_f in site 1 and 4% in site 2. The observed excess volume of the cylinder is rectified by the (CFBC-CFTC)/H ratio. The ANOVA results for the pseudostem and other AGB components are shown in **Table 1**. A significant difference in pseudostem weight is observed ($p<0.05$) between site 1 and site 2. At Site 1 AGB weight ranges from 16.8 kg to 32.1 kg, at Site 2, the range is 14.8 kg to 29.7 kg. Leaf weight at site 1 is higher than site 2, directly correlating the number of leaves per plant, at site 1 is more than at site 2. Similarly, the peduncle and bud weight are higher in site 1 than in site 2. The factor [AGB ×(1-AMC)] in equations 6 and 11 represents the average dry AGB and its value at site 1 is 4.37 kg and at site 2 is 3.93 kg and their mean value of 4.15 kg is taken as the average dry AGB across Tamil Nadu. The average CCH of Poovan is 62.11 cm, and the fresh weight of AGB is 39.34 kg. CCH, fresh and dry AGB of William banana cultivar is 67.53 cm, 103 kg and 11 kg and Nshansha cultivar is 72.47 cm, 62.33 kg and 5.85 kg (Ortiz-Ulloa *et al.* 2021; Yamaguchi and Araki, 2004). Poovan has less circumferential size and less fresh weight in comparisons. The fresh weight to dry weight conversion of Poovan is 10.54 % which is similar to the 10.67 % of William banana and greater than 9.38 % of Nshansha cultivar. This suggests that species-level AGB estimation is required for banana plants. The shape and structure of the pseudostem are crucial in determining the AGB.

Figure 4 shows the four proposed models and their residual plots. 4 (a) and (b) are volumetric models representing cone frustum and cylinder, whereas 4 (c) and (d) are circumference-based models representing CCH and CAH. The residual dispersion in the volumetric models is more than the circumference-based models, the CAH-based model 4 shows less residual dispersion than the CCH-based model 3. **Table 2** shows the AGB weight prediction capacity of the proposed models. Model 4 predicts the AGB weight better than every other model and is ranked first, with the MAE, R^2, MSE, and MSD values of 0.913, 0.98, 1.196, and 7. The less residual dispersion in **Figure 4 (d)** confirms that model 4 is the best. Although model 1 has better MAD than model 4, higher MAE and MSE values of 0.949 and 1.421 than model 4, along with the lower R^2 value of 0.97 results in its second ranking. Model 3 R^2 and MAD values are similar to model 1 and 4 but the higher MAE and MSE values make it be ranked at 3. Model 2 has the best MAD value but the higher MAE and MSE values and the lower R^2 value of 0.96 make model 2 to be ranked at 4. The average measured AGB weight in the field across the 48 samples of the Poovan plant is 39.347 kg. The average V_f, V_c, CCH and CAH across the 48 samples are 0.0891 m^3, 0.0935 m^3, 0.6211 m and 0.5513 m when these values are applied in their corresponding models, the estimated AGB weights are 39.325 kg, 39.327 kg, 39.339 kg and 39.347 kg. Notably, the Model 4 exactly predicted the AGB weight. To further assess the robustness of Model 4, its performance metrics were compared with Model 5, developed by Daphine *et al.* (2018) based on three banana cultivars, reported an R^2 of 0.825 and a standard error of 0.432. Model 6, proposed by Ortiz-Ulloa *et al.* (2021) for the William banana cultivar, achieved an R^2 of 0.86 and a MAE of 9.74. Meanwhile, Model 7, presented by Nyombi *et al.* (2009) for the Cv. Kisansa variety, demonstrated an R^2 of 0.96 and a standard error of 0.092. The Model 4 goodness of test metrics are better than these three models. The destructive and non-destructive data of 48 Poovan plants of this study is substituted in the allometric equations of model 5,6 and 7 and their corresponding goodness of test results are presented in **Table 2**.

Models 5 and 6 have better R^2 values than model 4 but the MAE values of 16.74 and 20.88 are 18-fold and 23-fold higher along with their higher MSE and MAD values than model 4 as these models are ranked 2 and 3. Model 7 AGB weight prediction capacity on Poovan is the least, a big gap exists between this model's and other models' goodness of test values. This is evident from **Figure 5**, which compares the field-measured AGB with the model-predicted AGB. The AGB measured in the field ranges from 27.6 kg to 53.2 kg. The average DBH (diameter at breast height), CBH (circumference at breast height) i.e., CCH of this study and CB (circumference at the base) i.e., CFBC of this study across the 48 samples are 19.77 cm, 62.11 cm and 75.08 cm and the AGB predicted by the model 5, model 6 and model 7 are 22.6 kg, 60.23 kg and 120.34 kg respectively. 12 matured Poovan plants CCH and CAH were measured before cutting down from a site (10°53'38.7636''N, 78°52'27.5772''E) Mettupatti, Tiruchirappalli. Average AGB arrived through model 3, model 4 and field weight measurements are 37.14 kg, 37.36 kg and 37.32 kg, this confirms the model 4 prediction efficiency.

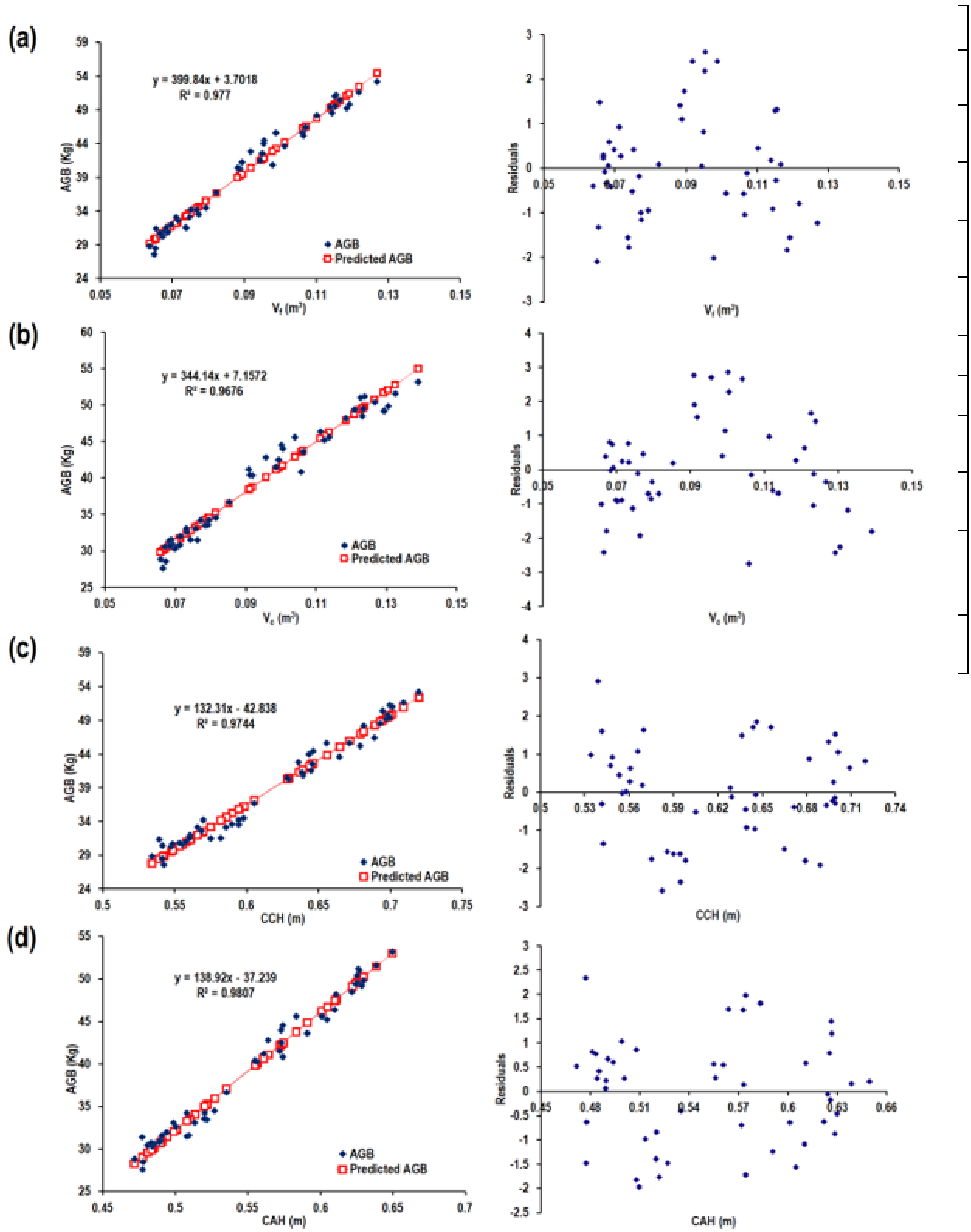


Figure 4. AGB weight prediction plots of the four proposed models and their residual plots (a) V_f (b) V_c (c) CCH and (d) CAH

3.2. MC, CC and biochar yield

MC of fresh AGB parts of six plants and their corresponding CC after drying are shown in **Table 3**. Among AGB parts pseudostem has a higher MC of 92.8% and leaves have a lower MC of 83.4 %, which suggests that more quantity of dry biomass can be obtained from leaves than pseudostem but, their corresponding fresh biomass contributions are 28.58% and 58.54%. The AMC at site 1 is 89.43% and at site 2 is 89.54% obtained using Equation 4. The dry biomass contribution by pseudostem, leaves, peduncle and bud among the 6 plants are 40.1%, 45.4%, 12.3% and 2.2%. The CC of peduncle 0.48 (kg/kg) on dry basis is higher than other AGB parts as shown in **Table 3**. The ACC of the plants from site 1 is 42.9% and site 2 is 43%, the ACC and CMAGB of the six individual plants are found using Equation 5 and Equation 6. In the CMAGB leaves' dry biomass contribution is higher followed by pseudostem, peduncle and bud. The CMAGB of site 1 is 1.87 kg and site 2 is 1.69 kg and their mean value of 1.78 kg is taken as CMAGB across Tamil Nadu. Poovan ABG's ACC is 42.95 %, which is higher than the William banana plant's 40% and lower than EAHB's (East African Highland Banana) 48.2% (Ortiz-Ulloa *et al.* 2021; Alcudia-Aguilar *et al.* 2019). **Table 3** shows the biochar yield obtained using Equation 7 and the dry AGB parts' contribution to biochar preparation from a plant. The biochar yield of the plant parts can be sorted as pseudostem > peduncle > bud > leaves while their contribution towards the biochar preparation is pseudostem> leaves > peduncle > bud. The average biochar yield at site 1 and site 2 is 32.6% and 32%, biochar yield of pseudostem at site 1 and site 2 is 37.4% and 36.8%. These factors make the pseudostem biochar the best among the biochar prepared and taken for physical, chemical and thermal characteristic studies.

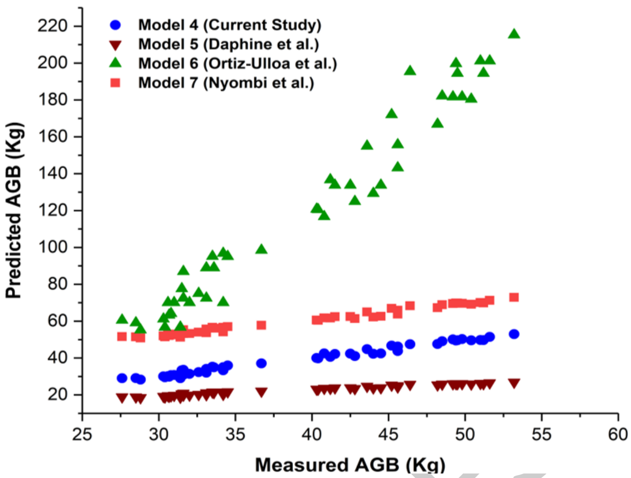


Figure 5. Comparison of AGB measured in the field with the AGB predicted by the models

Table 3. AGB parts MC, CC, biochar yield and contribution of a plant towards biochar production (mean±SD).

Plant parts	MC (%)	CC (kg/kg) dry basis	Biochar yield (%)	Contribution to biochar preparation from a plant (%)
Pseudostem	92.8±0.5	0.38±0.02	37.1±1.3	45.28±3.3
Leaves	83.4±0.4	0.46±0.03	27.48±1.6	38.9±3.9
Peduncle	88.7±0.5	0.48±0.02	35.35±1.1	13.28±0.8
Bud	86.5±0.6	0.45±0.01	33.12±1	2.5±0.7

Table 4. BGP, carbon stock and carbon abatement potential of Poovan's AGB at study sites, districts and Tamil Nadu

Location	Site 1	Tiruchirappalli	Site 2	Karur	Tamil Nadu
Area (ha)	1	2078.42	1	884	20505.24
SD (plant/ha)	2829.3	2829.3	3019	3019	2924.15
CMAGB (kg/plant)	1.894	1.894	1.704	1.704	1.798
BGP (kg/plant)	1.44	1.44	1.268	1.268	1.41
Total BGP (t/year)	4.0741	8467	3.828	3384	84454.416
Carbon stock of AGB (Gg)	0.0053586	11.1376	0.0051443	4.5476	107.808
Carbon abatement potential of AGB ($MtCO_2$/year)	1.966×10^{-5}	0.04088	1.8879×10^{-5}	0.01669	0.395655

Table 5. Elemental analysis, BET analysis, and proximate analysis of Poovan's pseudostem biochar compared with other studies.

	Banana Pseudostem Biochar (This study)	**Banana Pseudostem Biochar (Abdullah N. *et al.* 2023)**	**Banana Pseudostem Biochar (Song *et al.* 2023)**	**Banana leaves biochar (Sellin *et al.* 2016)**	**Banana stem and leaf biochar (Liu *et al.* 2022)**
Elemental analysis					
C (%)	58.8±0.2	43.23	47.61	48	58.19
H (%)	2.3±0.03	0	2	3.2	3.3
N (%)	1.61±0.02	19.96	0.41	1.2	1.3
S (%)	1.42±0.02	0	-	0.33	-
O (%)	35.86±0.4	36.81	19.39	47.27	19.78
O/C	0.60	0.85	0.4	0.98	0.34
H/C	0.04	0	0.04	0.06	0.05
C/H	25	-	25	16.67	20
BET					
Surface area (m^2/g)	21.74	1.078	56.92	-	15.73
Pore Volume (cm^3/g)	0.02	0.005	0.04	-	0.06
Pore size (nm)	5.3	-	2.71	-	17.04
Proximate analysis					
M (%)	5.8±0.4	6.1	-	1.68	-
VM (%)	30.6±0.3	33.2	-	53.2	-
Ash	20.3±0.2	34	-	23.5	-
FC	43.3±0.2	32.8	-	23.2	-

3.3. Carbon stock, CS potential and BGP of Poovan AGB

The BGP, carbon stock and carbon abatement potential of AGB at the sites, districts and across Tamil Nadu are shown in **Table 4**. The carbon stock of the two sites is similar, the CMAGB of site 2 is less than site 1 but the SD of site 2 is more than site 1 by 190 plants. BGP of a plant from site 1 and site 2 is 1.44 kg and 1.268 kg. The total BGP, total carbon abatement potential and total carbon stock of Poovan in the two districts are 11851 tons, 0.05757 MtCO_2/year and 15.6852 Gg/year and across Tamil Nadu is 0.084454 Mt/year, 0.395655 MtCO_2/year and 107.808 Gg/year.

Applying the Poovan AGB data to 897,000 hectares of banana cultivation area of India, yields 1.66 Mt of pseudostem biochar from 4.47 Mt of pseudostem dry biomass. This pseudostem dry biomass has a CS potential of 6.24 Mt CO_2/year. The AGB's total CS potential across India is 17.133 Mt CO_2/year contributing to a 2.25% reduction in the country's annual emission of 764.8 MtCO_2eq by the agricultural sector. AGB's total CS potential will reduce by 0.52 % in the Country's all sectoral emissions of 3262 MtCO_2e/year (G20 Reports, 2022).

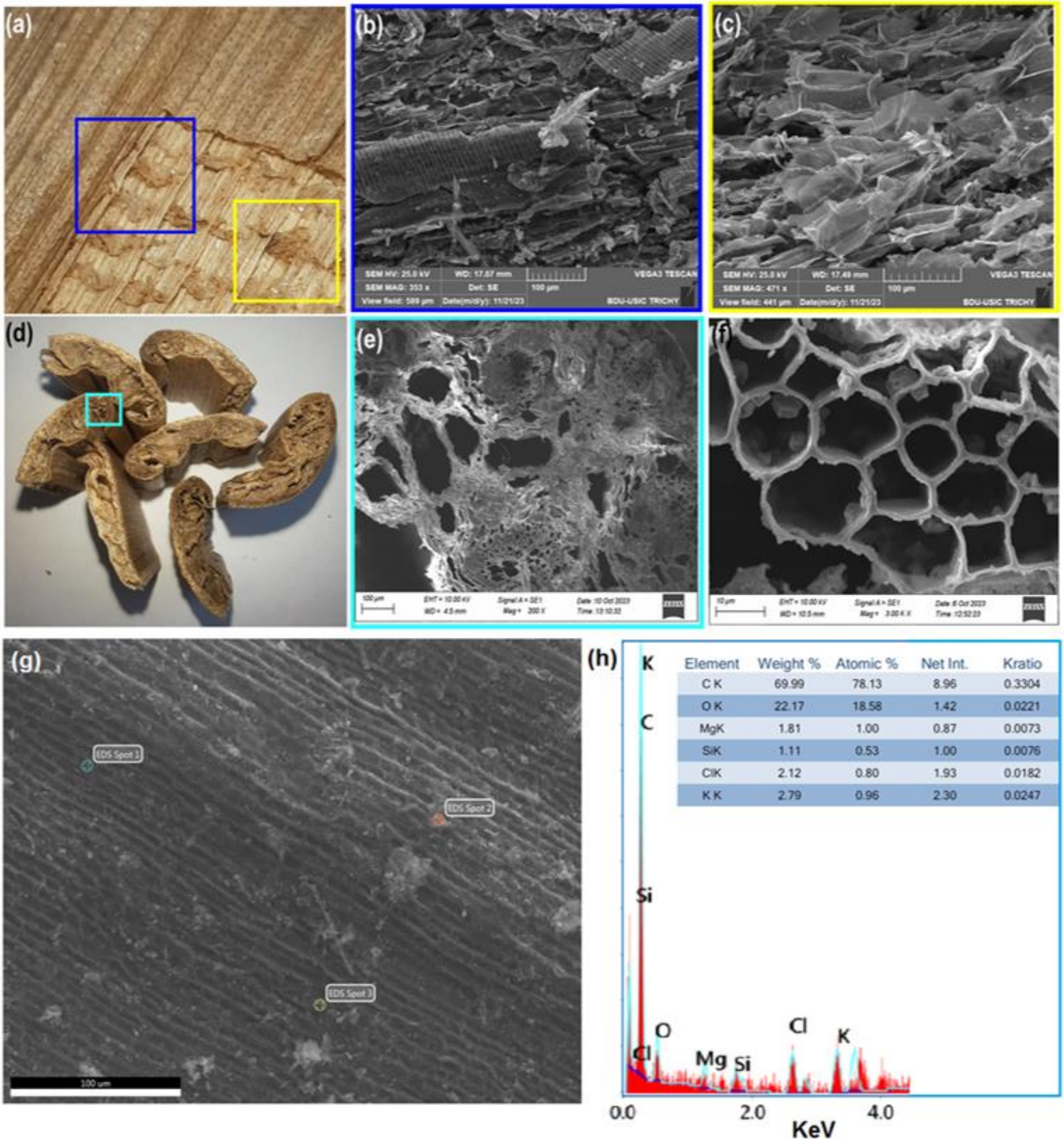


Figure 6. (a) pseudostem sheath (b) and (c) SEM image of pseudostem biochar outer layer and middle layer (d) Sheath's transverse section (e) SEM image of sheath's transverse section (f) SEM image of biochar's transverse section (g) EDSEM image of pseudostem biochar outer layer showing 3 spots and (h) EDS spectrum of spot 2

3.4. Pseudostem biochar characteristics

Figure 6 shows SEM and EDSEM images of pseudostem and biochar. **Figure 6(a)** displays the dried pseudostem sheath, where the slip from the outer to the middle layer is highlighted with a blue square, while the yellow square marks the middle layer. **Figure 6(b)** shows the SEM image of the biochar depicting the outer layer and some parts of the middle layer after pyrolysis, **Figure 6(c)** represents SEM image of the middle layer of biochar, **Figure 6(d)** depicts the transverse section of the dried sheath, **Figure 6(e)** captures the SEM image of the dried sheath where the tissues are visible, **Figure 6(f)** captures the SEM image of biochar where the tissues of the sheath are condensed to form stable porous structure after pyrolysis, the minimum pore size of 5 µm and maximum pore size of 40 µm can be observed, **Figure 6(g)** shows the marked spots on the biochar to analyses the chemical characteristics through EDSEM and the EDS spectrum of the spot 2 is shown in **Figure 6(h)**. Carbon dominates the spectrum with atomic weight of 69.9% followed by oxygen, potassium, chlorine, magnesium and silicon. The atomic weight of oxygen 22.17 % indicates the presence of the C-O stretching of alcohols, esters, phenols and esters in biochar and O-H bond in alcohols and phenols (Abdullah N. *et al.* 2023). The average atomic weight of carbon from the 3 spots is 63.72% and the average atomic weight of oxygen is 24.11. The EDSEM found O/C ratio is 0.37. The elemental, BET and proximate analysis of pseudostem biochar is shown in **Table 5**.

The elemental analysis reveals 58.8% of CC followed by 36.7% of oxygen. The Poovan pseudostem biochar has higher CC than other pseudostem and leaves studied by researchers are listed in **Table 5**. The C/H ratio of 25 highlights the potential application of pseudostem biochar in soil amendment and CS operations as this ratio suggests good biochar stability and significant aromatization during pyrolysis (Bednik *et al.* 2022; Hu *et al.* 2019). The O/C ratio of 0.6 by the Poovan pseudostem biochar has a half-life ranging from 100 to 1000 years Spokas, (2010). This O/C ratio is lesser than biochar studied by (Liu *et al.* 2022; Song *et al.* 2023) but better than the biochar studied by Abdullah N. *et al.* 2023. BET surface area of 21.74 m^2/g and pore size of 5.3 nm is the second best among the biochar compared. Suggesting its potential application in water treatment and heavy metals removal from contaminated water and soil. Proximate analysis provides insight into the FC, a higher Value enhances biochar's combustibilityand suitable for thermal applications. Poovan pseudostem biochar's FC is 43.3 % which is best among the biochar compared. Additionally, the VM/FC ratio of 0.7 suggests that the biochar has a half-life exceeding 1000 years, reinforcing its long-term stability and effectiveness in CS.

3.5. Pseudostem biochar CS potential

Figure 7 shows the TGA and DTG curves of pseudostem biochar. TGA curve is corrected for moisture and ash, the moisture correction accounts for both bounded and unbounded water up to 200°C, while ash is corrected from 820°C. The 50% degradation of biochar is observed at 550°C (TB_{50}), indicated by the dashed line in **Figure 7**. A peak in the DTG graph at 550°C indicates the mass reduction during thermal degradation. Harvey *et al.* (2012) mentioned TG_{50} as 886°C. The R_{50} of pseudostem biochar is 62% found using equation 12, which falls under the B category with a half-life range of 100 to 1000 years. The CS potential of pseudostem biochar is 27.6% obtained from equation 13. Adhikari *et al.* (2024) estimated the R_{50} and CS potential of biochar made from 21 feedstocks. Based on R_{50},13 biochar – including rice husk (RH) pyrolysed at 550°C and 700°C, 3 locally sourced hardwood (LHW) biochar, 2 locally sourced softwood (LSW) biochar, 4 locally sourced mixed feedstock (LMF) biochar, miscanthus straw and wheat straw pyrolysed at 700°C, among the 21 comes under the category B, the remaining 8 biochar comes under category C. Similarly, Windeatt *et al.* (2014) pyrolyzed 8 feedstocks at 600°C and estimated their R_{50} and CS potential. Based on R_{50}, the biochar derived from palm shell, sugarcane bagasse, rice husk, coconut shell, coconut stalk, and olive pomace fall under category B, whereas wheat straw and coconut fibre biochar are classified under category C. The Poovan pseudostem biochar R_{50} of 62% is the best among the 19-biochar compared under category B followed by palm shell biochar at 61%, coconut shell biochar at 59%. RH700, LHW2, and olive pomace biochar, each with an R_{50} of 58%. The CS potential of Poovan pseudostem biochar (27.6%) is lower than that of coconut shell (28.7%) and LMF4 biochar (28%). However, it is comparable to coconut fibre (26.8%), LHW2 (27%), and sugarcane bagasse (27.3%). The RH biochar studied by Adhikari *et al.* (2024) shows lower CS potentials of 20% (RH550) and 18% (RH700), while the RH biochar analyzed by Windeatt *et al.* (2014) at 600°C has a CS potential of 26%. These findings indicate that RH biochar generally exhibits lower CS potential across different pyrolysis temperatures compared to Poovan pseudostem biochar produced at 500°C. All biochar except coconut shell and LMF4 in comparison demonstrate lower CS potential than Poovan pseudostem biochar.

Land Use Impact is minimal as biochar production uses existing residues without additional land demand but in comparison, afforestation and BECCS (Bio energy with carbon capture and storage) compete for land with food production (Li H. *et al.* 2025) Mitigates emissions both by stabilizing carbon and by reducing methane emissions from natural residue decay but the methods like renewable avoids emission (Wu Y *et al.* 2025).

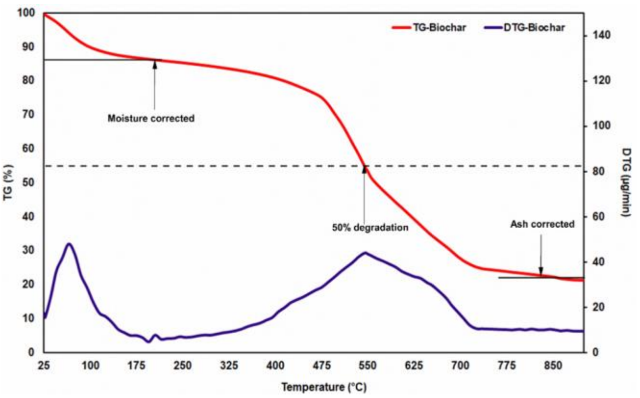


Figure 7. TGA and DTG curves of pseudostem biochar, TGA corrected for moisture and ash, the central dashed line indicates the 50% degradation of biochar in TGA curve

4. Conclusion

This study's novelty is the measurement of pseudostem's CFBC and CFTC. The (CFBC-CFTC)/H ratio is 0.1, which is uniform across all the 48 Poovan samples. This factor led to the consideration of pseudosterm as cone frustum structure and determination of V_f for all sample plants. The traditional consideration of pseudostem as a cylindrical structure and its corresponding CCH measurement provides the V_c data of plants. The volumetric comparison reveals that the V_c has 3 to 10 % of excess volume than the V_f. The (CFBC-CFTC)/H ratio is used to reduce the excess volume V_c and equals V_f at 2 meters height. This height is termed as absolute height (AH) of Poovan, and its circumference is termed as CAH. This CAH measurement provides the optimum AGB yield as evident from the development of four linear allometric models. The CAH-based model best predicts the AGB of Poovan with the MAE, R^2, MSE and MAD scores of 0.91, 0.98, 1.19 and 7. The conventional CCH model ranks 3rd with the MAE, R^2, MSE and MAD scores of 1.02, 0.97, 1.58 and 7. Thus, the conventional measurement of CCH (1.3 meters) to estimate AGB is not suitable for all the species of banana plants. The CAH measurement in Poovan is suitable for morphologically similar crops. The average fresh and dry AGB of Poovan is 39.347 kg and 4.15 kg. The ACC and CMAGB of the plant are 42.95 % and 1.78 kg. The CS potential of Poovan AGB across Tamil Nadu is 0.395655 $MtCO_2$/year. Applying the Poovan AGB data nationally results in 17.133 Mt CO_2/year sequestration contributes towards a 2.25 % reduction in annual emission of 764.8 $MtCO_2eq$ by the agriculture sector. Biochar production from dry AGB is a CS operation. The BPG of Poovan is 1.41 kg/plant and across Tamil Nadu is 0.0844 Mt/year. A part of biomass has to be left in the field for soil management operations, thus pseudostem dry biomass of 1.7 kg/plant with a biochar yield of 37.1% is considered for CS estimation. The potential annual pseudostem biochar production across Tamil Nadu and the country is 0.0378 Mt and 1.66 Mt and its CS potential is 27.6%, which is third best among the 19-biochar prepared from crop residue feedstock.

Poovan banana plants studied were ratoon crops (second cycle) under canal irrigation. To enhance the scope of biomass and carbon estimation for the Poovan variety, future research could include assessments of the first and third crop cycles under drip irrigation. Emission analysis of greenhouse gases arising from AGB and biochar decomposition in soils is required to determine the greenhouse gas inventory by banana cultivation and the benefits of residual AGB for carbon abatement operations in India.

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