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Feasibility assessment of aboveground biomass and carbon stock estimation in heterogeneous tropical campus green spaces using unmanned aerial vehicle RGB photogrammetry

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ABSTRACT

Climate change is a global challenge, yet the contribution of higher education institutions to greenhouse gas (GHG) emissions remains insufficiently examined. Campus green open spaces may function as carbon sinks, but biomass and carbon stock estimates in heterogeneous tropical campus environments are still limited. Biomass estimation using unmanned aerial vehicles (UAVs) typically relies on expensive LiDAR sensors, while UAV RGB-based studies are mostly confined to homogeneous forest ecosystems. This study presents a feasibility assessment of using UAV RGB photogrammetry combined with an individual tree canopy (ITC) approach to estimate aboveground biomass (AGB) and carbon stocks in the green open spaces of Universitas Negeri Semarang (UNNES). The workflow includes UAV data acquisition, ground control point (GCP) and check point (CP) measurements, orthophoto and digital elevation model (DEM) generation, and canopy height model (CHM) development. Individual tree canopies were delineated through visual interpretation of orthophotos, while diameter at breast height (DBH) data from field surveys were used to calculate reference biomass. AGB models were developed using linear and power regression. The most feasible model was the power regression based on the total CHM values within each canopy, yielding an RMSE of 1770, an MAE of 1348, and a correlation coefficient of 0.41. Although the linear regression model showed slightly better statistical metrics, its raster-scale application produced unrealistic AGB estimates. Spatial aggregation at a 1 × 1 m resolution resulted in a total AGB of 36,962,888 kg for the UNNES campus, corresponding to a carbon stock of approximately 18,481,444 kg C and CO_2 sequestration of 67,822,300 kg CO_2. This study is not intended to replace high-precision LiDAR-based methods, but rather to demonstrate the feasibility of UAV RGB as an estimation approach that is acceptable, stable, and sufficiently replicable in heterogeneous tropical campus contexts, enabling spatially explicit assessments of campus-scale carbon storage.

Keywords: above ground biomass, campus green spaces, carbon stocks, heterogeneous tropical vegetation, individual tree canopy, spatially explicit biomass modeling, UAV RGB photogrammetry.

INTRODUCTION

Climate change has evolved into a major global threat within the triple planetary crisis, alongside biodiversity loss and escalating environmental pollution. Since the Industrial Revolution, greenhouse gas (GHG) concentrations have continuously increased and have now reached their highest levels in modern history, accelerating global warming (Graven et al., 2020; Alhadithie and Barwari, 2024; Soeder, 2025). This condition has prompted the international community to pursue a 45% reduction in emissions by 2030, in line with the Paris Agreement commitments and the Net Zero Emission 2060 agenda (Kementerian Lingkungan Hidup dan Kehutanan, 2024; Lee et al., 2023).

In this context, higher education institutions are increasingly recognized as overlooked sources of carbon emissions in urban studies. Campus activities such as building energy consumption, laboratory operations, and academic community mobility contribute to urban GHG emissions. At the same time, universities occupy a strategic position as living laboratories for climate change mitigation and adaptation through integrated management of environmental systems and campus green open spaces (Lozano et al., 2019; Ngabekti et al., 2025). This role is particularly relevant given that the building and construction sector accounts for approximately 21% of global GHG emissions, including educational infrastructure (Cabeza et al., 2021; Yang et al., 2025). Accordingly, biomass and carbon stock assessments in campus green spaces have become essential to support the transition toward sustainable campuses. Campus carbon inventories not only contribute to emission reduction efforts but also align with the University of Indonesia GreenMetric (UIGM) framework, particularly in the energy and climate change, setting and infrastructure, and environmental management categories. Quantitative measurement and management of campus carbon reserves indirectly support the achievement of the Sustainable Development Goals, especially Goal 13 (Climate Action) and Goal 15 (Life on Land).

Over the past decade, unmanned aerial vehicle (UAV) technology has transformed biomass and carbon stock mapping by providing high spatial resolution data at the centimeter scale (Puliti et al., 2020; Gong et al., 2023; Xu et al., 2025). The most reliable UAV-based biomass estimates generally rely on LiDAR sensors due to their ability to capture detailed three-dimensional vegetation structures, including tree height, canopy volume, and crown characteristics (Chen et al., 2025; Ma et al., 2023; Su et al., 2024). However, the high costs associated with LiDAR data acquisition, operation, and processing limit its practicality for routine monitoring in campus environments, particularly in developing countries such as Indonesia.

In this regard, UAVs equipped with RGB sensors provide a more economical and flexible alternative. The application of UAV RGB photogrammetry for biomass and carbon stock estimation has been widely reported, particularly in mangrove ecosystems (Basyuni et al., 2025; Duan et al., 2025; Budiarto and Dewanto, 2025). These studies demonstrate that UAV RGB data can generate digital surface models (DSM) and digital elevation models (DEM) suitable for biomass estimation in ecosystems with relatively homogeneous vegetation structures. Nevertheless, mangrove canopies tend to be uniform, and the transferability of these approaches to more complex landscapes remains uncertain.

The challenge becomes more pronounced when UAV RGB approaches are applied to heterogeneous tropical campus green spaces. Campuses such as Universitas Negeri Semarang (UNNES) are characterized by woody vegetation with high species diversity, varied canopy morphology, heterogeneous tree spacing, and substantial height variability (Ngabekti et al., 2025; Setyowati et al., 2024). Previous UAV RGB studies in campus environments, including Upadhyaya et al., (2023), have primarily relied on horizontal canopy cover parameters, which may inadequately represent three-dimensional vegetation complexity. Garcia et al., (2017) demonstrated that parameters incorporating vertical vegetation dimensions are more sensitive in capturing carbon sequestration capacity, particularly in heterogeneous and multilayered landscapes.

In this context, the individual tree canopy (ITC) approach offers a key advantage by enabling biomass estimation at the individual tree level while accounting for structural attributes such as tree height and canopy area (Sun et al., 2023). Although ITC is commonly integrated with LiDAR data, cost constraints motivate the exploration of UAV RGB-based ITC as a more practical and realistic alternative for campus environments. Building on this background, the present study introduces novelty by positioning itself as a feasibility assesment that applies UAV RGB photogrammetry combined with a canopy height model (CHM) and an ITC approach to estimate biomass and carbon stock in heterogeneous tropical campus green spaces, as a representation of vertical vegetation structure. This approach is expected to bridge the gap between the demonstrated success of UAV RGB methods in homogeneous ecosystems and the need for carbon modeling in complex campus landscapes, while reinforcing the role of universities as key actors in advancing Net Zero Campus initiatives aligned with the Sustainable Development Goals and Indonesia's Net Zero Emission 2060 policy.

METHODOLOGY

Study area and site characteristics

This study was conducted at the Universitas Negeri Semarang (UNNES) campus, located in Sekaran, Gunungpati District, Semarang City, Central Java Province (Figure 1). The campus covers approximately ±1.83 km², the majority of which consists of green spaces characterized by land cover dominated by woody vegetation from various species, with irregular spatial distribution and relatively dense planting patterns. These vegetated areas are interspersed with open spaces, shrubs, and built elements such as roads and campus buildings.

Spatially, UNNES is situated in a peri-urban zone that represents a transitional urban–rural landscape experiencing increasing urbanization pressure. According to spatial planning documents, Gunungpati District functions as an ecological buffer and the "green lung" of Semarang City, particularly in supporting groundwater recharge, microclimate regulation, and the provision of urban ecosystem services (Fariz et al., 2025; Saratri et al., 2024).

From a hydrological perspective, the UNNES campus is located in the upper part of the Garang Watershed, one of the priority watersheds in Central Java Province, giving it a strategic role in regulating downstream hydrological processes. Geomorphologically, the campus lies on the northern flank of Mount Ungaran and is developed on volcanic footplain landforms composed of pyroclastic materials, which influence soil properties,

Figure 1. Study location at Universitas Negeri Semarang (UNNES)

drainage conditions, and vegetation growth (Saputra et al., 2022).

These characteristics represent a heterogeneous tropical urban green space, where canopy height, canopy area, and vertical vegetation structure vary considerably among individual trees. Such conditions resemble tropical urban forests and arboretums reported to have high structural complexity, thus requiring an ITC based approach for biomass estimation (Ferreira et al., 2024).

UAV data acquisition and GNSS survey

Aerial image acquisition was conducted on July 26, 2025, during the dry season. Aerial image acquisition was conducted using a DJI Mavic 2 Pro multirotor UAV equipped with an RGB camera with a resolution of 5472 × 3648 pixels. Flights were performed at an average altitude of 154 m above ground level, with forward and side overlaps of 80%. This configuration produced 1.088 aerial images with a ground sampling distance (GSD) of approximately 3.56 cm per pixel, covering an area of ±1.83 km². These flight parameters were selected to ensure robust three-dimensional reconstruction using a structure-from-motion (SfM) approach and sufficient spatial resolution for identifying individual tree canopies in heterogeneous vegetation (Iryanthony et al., 2025).

To correct and validate geometric accuracy, eight ground control points (GCPs) and eight independent control points (ICPs) were collected and strategically distributed across the study area. Point coordinates were measured using an EFIX F7+ geodetic GNSS receiver with the network real-time kinematic (NRTK) method. Observation duration was 900 seconds for each GCP and approximately 60 seconds for each ICP. Measurements were conducted using a bipod and controlled through the eField application to ensure positional stability and precision. Accuracy was expressed as root mean square error (RMS) values for the X and Y axes (horizontal) and the Z axis (vertical).

Following image acquisition and control point collection, photogrammetric processing was carried out using Agisoft Metashape. The workflow included image alignment, camera parameter optimization, dense point cloud generation, and the production of a DSM and geometrically corrected orthophotos (Basyuni et al., 2025; Iryanthony et al., 2025). The resulting orthophoto and DSM were calibrated using the eight GCPs and subsequently assessed for accuracy using the ICP data. Horizontal accuracy was evaluated using CE90, while vertical accuracy was assessed using LE90 (Fariz et al., 2020; Saputra et al., 2024).

Canopy height model (CHM)

The CHM was developed to represent vegetation height by calculating the difference between the upper surface elevation and ground surface elevation using the following equation:

$$CHM = DSM - DTM \tag{1}$$

The digital terrain model (DTM) was generated through manual interpolation of ground points selected from the dense point cloud in non-vegetated areas such as roads and open land. This manual approach is commonly applied in UAV RGB-based studies in areas with complex vegetation structures, where automated ground point filtering is often suboptimal (Basyuni et al., 2025; Iryanthony et al., 2025). In heterogeneous campus green spaces, the CHM serves as a key structural proxy for capturing inter- and intra-species canopy height variability. Previous studies indicate that CHM metrics, including maximum, mean, and cumulative values, are strongly correlated with aboveground biomass (Chirici et al., 2016; Ferreira et al., 2024).

Individual tree canopy (ITC) delineation

ITC refers to the identification and mapping of individual tree crowns, enabling tree-by-tree analysis, which is particularly useful in heterogeneous forests and agroforestry systems for detailed assessment of structure and species composition (Guerra-Hernández et al., 2018). ITCs were generated through visual interpretation and manual digitization based on high-resolution orthophotos, using ArcMap software. Visual interpretation relies on image interpretation keys such as tone, texture, shape, size, shadow, pattern, site, and association (Fariz et al., 2023).

This approach was selected due to its high accuracy in delineating individual canopy boundaries in heterogeneous vegetation, despite requiring longer processing time. It has been shown to be effective in mapping individual canopies in tropical urban forests and arboretums with complex crown structures (Ferreira et al., 2024) and is more reliable than simple automated segmentation applied to UAV RGB data. A total of 130 ITCs were delineated, focusing on canopies that were clearly identifiable. These ITCs were subsequently divided into training and validation samples.

Field-based aboveground biomass (AGB) analysis

AGB is defined as the total mass of living organic material above the ground, expressed as oven-dry weight (Franco, 2021; Kassa et al., 2022). Living biomass includes aerial plant components such as stems, branches, and leaves. Field-based AGB estimation was conducted using primary data consisting of diameter at breast height (DBH) and wood density. DBH was obtained through direct field measurements, while wood density was determined by identifying tree species in the field and matching them with species-specific wood density values obtained from global databases. Individual tree biomass was calculated using the allometric equation proposed by Chave et al., (2005):

$$AGB = \rho \times exp(-1.499 + 2.148\ \ln(\text{DBH}) + \\ + 0.207\ (ln(DBH))^2 - 0.0281\ (ln(DBH))^3) \quad (2)$$

This approach is widely applied in tropical biomass studies, particularly when field measurement of tree height is difficult. DBH-only models have been shown to provide reliable AGB estimates in heterogeneous forests (Basuki et al., 2009; Tetemke et al., 2019). Carbon stock was subsequently calculated by assuming that 50% of dry biomass consists of carbon, in accordance with IPCC guidelines (Chaturvedi et al., 2012; Eggleston et al., 2006; Yadav et al., 2023):

$$C = 0.5 \times AGB \quad (3)$$

Development and validation of CHM-based AGB estimation models

The development of the AGB estimation models was conducted using CHM metrics and ITC characteristics. This approach builds on previous findings that canopy height and canopy area are key structural predictors of biomass (Ferreira et al., 2024). The models were subsequently subjected to validation, in line with the principle that the technical feasibility of UAV RGB-based approaches should be demonstrated through model validation, as commonly applied in studies estimating agricultural phenomena (Zhang et al., 2023). Four models were developed, as follows:

- Model 1: power regression between AGB, maximum CHM value within ITC, and ITC area
- Model 2: power regression between AGB and the sum of CHM values within ITC
- Model 3: linear regression between AGB, maximum CHM value within ITC, and ITC area
- Model 4: linear regression between AGB and the sum of CHM values within ITC

A total of 100 samples were used as the training dataset for model development. The resulting equations were then applied to the testing data and validated using 30 independent validation samples. Model performance was evaluated using root mean square error (RMSE), mean absolute error (MAE), and correlation coefficients, as commonly applied in UAV and CHM-based biomass estimation studies (Basyuni et al., 2025; Ferreira et al., 2024; Maesano et al., 2022; Sidiq et al., 2025).

The best-performing model based on validation results was subsequently applied to the spatial dataset to generate a campus-wide AGB map. Carbon stock was then calculated using the same 50% biomass assumption applied in field-based estimation. Finally, carbon dioxide sequestration was estimated using the carbon stock of each tree as follows:

$$CO_2 = 3.67 \times C \quad (4)$$

where: CO_2 is carbon dioxide sequestration (kg CO_2 eq), C is carbon stock (kg), 3.67 is the conversion factor from carbon (C) to carbon dioxide (CO_2).

RESULTS AND DISCUSSION

UAV RGB photogrammetry results

Ground control points (GCPs) were measured and distributed across the campus area (Figure 2). The measurement results indicate that most points exhibit horizontal errors below 3 cm and average vertical errors below 2.5 cm, reflecting a high level of positional precision. The highest RMS value was recorded at GCP2, yet it remained within acceptable tolerance limits for medium- to large-scale mapping. These results demonstrate that the NRTK method with a 900-second observation duration provides sufficiently accurate and reliable measurements for topographic and photogrammetric mapping purposes. For the independent control points (ICPs), most points also

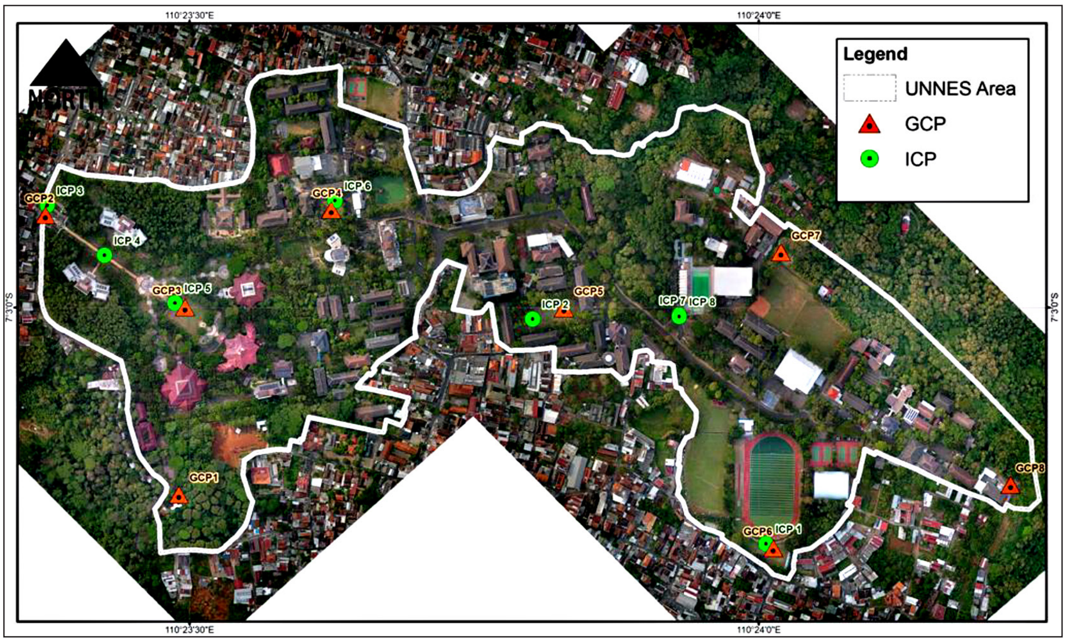

Figure 2. Distribution of GCPs and ICPs

showed horizontal errors below 3 cm and average vertical errors below 2.5 cm, indicating good measurement accuracy. ICP2 recorded the highest RMS value, but it remained within acceptable tolerance limits. Overall, ICP measurements with an observation duration of approximately 60 seconds produced results that were adequately accurate and reasonably reliable for topographic and photogrammetric applications.

Horizontal accuracy assessment of the UAV-derived orthophotos was conducted to evaluate the spatial precision of the mapping results calibrated using eight evenly distributed GCPs across the UNNES campus. The GCP coordinates were obtained through GNSS RTK measurements using an EFIX F7+ receiver, which provides high positional precision. Field-measured coordinates were compared with corresponding point locations on the orthophotos.

The results indicate an average positional error ($\Delta X^2 + \Delta Y^2$) of 0.0481, with a root mean square error (RMSE) of 0.04 m and a horizontal accuracy based on the CE90 standard of 0.0666 m. The CE90 coefficient applied was 1.5175, following established spatial data processing standards. These values indicate excellent horizontal accuracy, supported by a GSD of 0.06 m, which provides highly detailed spatial resolution suitable for vegetation mapping and environmental monitoring.

Vertical accuracy assessment using the LE90 standard was also conducted at the UNNES Sekaran campus using the same eight GCPs measured with the EFIX F7+ GNSS receiver and the NRTK method. The test aimed to evaluate the consistency between UAV-derived elevation data and GNSS-measured elevations. Elevation differences between the mapped Z values and GNSS reference values were calculated, squared, and aggregated. The results show an average elevation difference of −0.0646 m, with a mean squared difference of 0.2478. Based on the standard deviation multiplied by the CE90 coefficient of 1.5175, an RMSE of 0.0996 m was obtained. Accordingly, the vertical accuracy of the UAV orthophoto reached 0.15 m. This accuracy meets the standards for large-scale mapping, where horizontal accuracy below 0.3 m is required. Therefore, the UAV imagery is considered reliable for detailed mapping, campus spatial planning, spatial analysis, and other applications requiring high precision.

Characteristics of the canopy height model (CHM)

The canopy height model (CHM) was generated at a spatial resolution of 1 m, enabling detailed representation of canopy structure at the individual tree scale. The CHM results show a maximum canopy height of 34.82 m, a minimum of 3.69 m, a mean value of 13.33 m, and a standard deviation of 5.61 m. This distribution reflects the heterogeneous vegetation structure of the UNNES campus, which includes large shade trees, landscape vegetation, and fruit trees with substantial height variability (Figure 3).

A major challenge in CHM development was the presence of non-vegetation objects, particularly building roofs, which were still detected in the DSM–DTM difference model. Although ground surfaces were effectively removed, separating tree canopies from rooftops required manual masking. While this approach was relatively effective, it remains susceptible to errors due to limitations in visual interpretation and spectral similarity between objects.

Overall, UAVs equipped with RGB sensors offer advantages in terms of relatively low cost

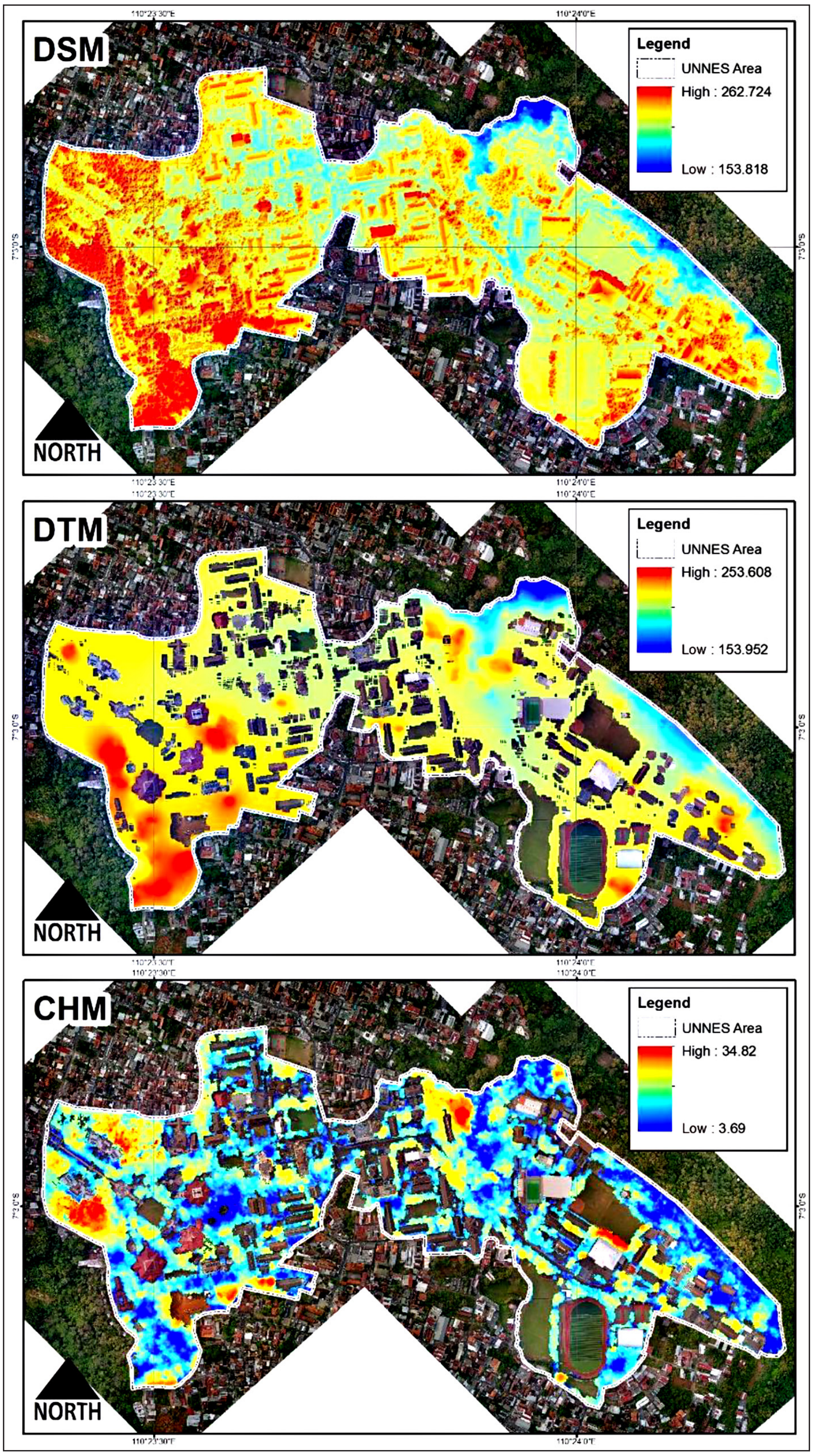

Figure 3. DSM, DTM and CHM in the study area

and extensive spatial coverage, making them suitable for repeated surveys and cost-efficient ecosystem monitoring (Li et al., 2020; Ullah et al., 2025). However, CHM generation from UAV RGB data is highly dependent on lighting conditions, image overlap, and vegetation structural complexity. Dense or multilayered vegetation can result in incomplete 3D reconstruction and reduced height accuracy (Storch et al., 2025).

Identification of individual tree canopy (ITC)

ITCs were identified through visual interpretation of high-resolution UAV orthophotos (Figure 4). This approach was selected because it captures individual tree spatial details more effectively than automated methods based on machine learning or deep learning, particularly in heterogeneous environments (Fariz and Lutfiananda, 2025; Waite et al., 2019). Nevertheless, the process faced notable challenges due to the uniform green coloration of canopies and the presence of vertically layered vegetation, where a single ITC may visually represent more than one individual tree.

The main strength of visual interpretation lies in its ability to precisely delineate individual tree crowns in areas with moderate canopy cover, while facilitating the extraction of spatial attributes such as canopy area and tree height (Chadwick et al., 2020; Guerra-Hernández et al., 2018; Han et al., 2022). However, this method is also prone to segmentation errors caused by overlapping canopies, lighting variability, and interpreter subjectivity, potentially resulting in under-segmentation or over-segmentation (Gu et al., 2020).

The results show that the largest ITC area belonged to *Samanea saman* (rain tree), with a canopy area of 716.62 m², while the smallest ITC was observed for *Polyalthia longifolia* (the false ashoka tree), with a canopy area of 3.4 m². This variation highlights interspecific differences in canopy architecture and their implications for biomass estimation.

Variability of field-measured AGB

The vegetation of the UNNES campus exhibits high species diversity. Previous studies by Setyowati et al., (2020) reported that campus green spaces host a large number of tree species, predominantly *Tectona grandis* (teak), *Albizia chinensis* (albizia), *Swietenia macrophylla* (mahogany), *Acacia mangium* (acacia), *Terminalia catappa* (indian almond / ketapang), and Samanea saman (rain tree), along with various fruit trees. More recent study by Ngabekti et al., (2025) showed that one faculty area within UNNES, namely the Faculty of Mathematics and Natural Sciences, also contains dense and diverse tree stands, with *Swietenia macrophylla* (mahogany) as the dominant species.

Field-based AGB data reveal a wide range of biomass values among individual trees. The five highest AGB values were recorded for *Ficus benjamina* (22,677.32 kg), *Leucaena leucocephala* (16,486.20 kg), and *Samanea saman* (up to 11,928.62 kg), indicating the substantial contribution of large trees to total biomass stocks. In contrast, the lowest AGB values were observed

Figure 4. Example of individual tree canopy (ITC) delineation using visual interpretation, showing the comparison between orthophoto-based canopy delineation and field conditions for *Samanea saman* (rain tree)

in smaller trees and fruit species, such as *Ficus callosa* (24.38 kg) and *Averrhoa carambola* (49.73 kg).

Performance and evaluation of CHM-based AGB prediction models

Four AGB prediction models were developed using combinations of CHM metrics and canopy area through power and linear regression approaches. The regression equations are presented in Table 1. Among the models, Model 2, which applies power regression using the total CHM values within an ITC, exhibited the strongest correlation coefficient of 0.818.

Following model development, validation was performed. In general, the model based on power regression on total CHM values in ITC demonstrated more stable performance than the model relying on maximum height and canopy area as separate predictors. Model 2 yielded an RMSE of 1770, an MAE of 1348, and a correlation coefficient of 0.41 (Table 2). Notably, Model 2 produced the best MAE among all models, indicating superior average error performance, while its RMSE ranked second best and its correlation coefficient was also the second highest.

Although Model 4 exhibited slightly better statistical metrics, with an RMSE of 1672 and a correlation of 0.46, its application at the raster scale produced unrealistic AGB estimates. This contrast highlights that models with marginally better validation statistics do not necessarily yield feasible or ecologically plausible results when applied to continuous CHM surfaces. This finding emphasizes that superior statistical performance during validation does not necessarily guarantee spatial stability or ecological plausibility when models are applied across continuous surfaces.

Conceptually, the accumulation of CHM values within a single canopy represents a proxy for three-dimensional canopy volume, which is directly associated with tree biomass (Li et al., 2024; Shu et al., 2023). However, this relationship is influenced by species heterogeneity, variations in wood density, and canopy segmentation uncertainty, and therefore reflects a structural association rather than direct causality (Fu et al., 2024). For this reason, Model 2 was selected as the most feasible model, as it offers the best balance between simplicity, spatial stability, and ecological plausibility, rather than merely maximizing statistical indicators.

Applying Model 2 to the CHM raster produced pixel-level AGB values at a 1 × 1 m resolution ranging from 41.66 to 191.63 kg, which are ecologically reasonable. When applied spatially, Model 2 generated AGB distributions that were consistent with expected vegetation structure and avoided extreme or implausible biomass values observed in other models. Based on spatial aggregation, the total AGB of the UNNES campus was estimated at 36,962,888 kg, corresponding to a carbon stock of approximately 18,481,444 kg C and an equivalent CO_2 sequestration of about 67,822,300 kg CO_2 (Figure 5).

Compared with other campuses in Indonesia, the estimated carbon stock of UNNES falls within a realistic range. The campus forest of Universitas Indonesia, covering 73.63 ha, has been reported to store up to 468.02 tons of carbon per hectare (Febiriyanti et al., 2021), which is higher than UNNES due to its closed-canopy forest structure. A Landsat 8-based study at IPB University in Darmaga reported biomass of 14,960.79 Mg and carbon of 5,530.59 Mg over an area of 256.97 ha (Lavista et al., 2016), while green spaces at the Faculty of Forestry, Universitas Tanjungpura, were reported to store 77.52 tons of carbon per hectare (Ng et al., 2021). These comparisons

Table 2. Model validation results

Model	RMSE	MAE	Correlation
Model 1	1710.66	1374.76	0.49
Model 2	1687.87	1348.12	0.52
Model 3	1720.92	1456.73	0.45
Model 4	1657.64	1384.65	0.55

Table 1. Regression model equations

Model	Regression equation	Correlation (R)
Model 1	12.46 · (CHM_max)^0.81 · (ITC area)^0.64	0.814
Model 2	17.14 · (CHM_sum)^0.68	0.818
Model 3	−943.25 + 120.87 · CHM_max + 15.37 · ITC area	0.800
Model 4	0.9813 · CHM_sum + 951.23	0.790

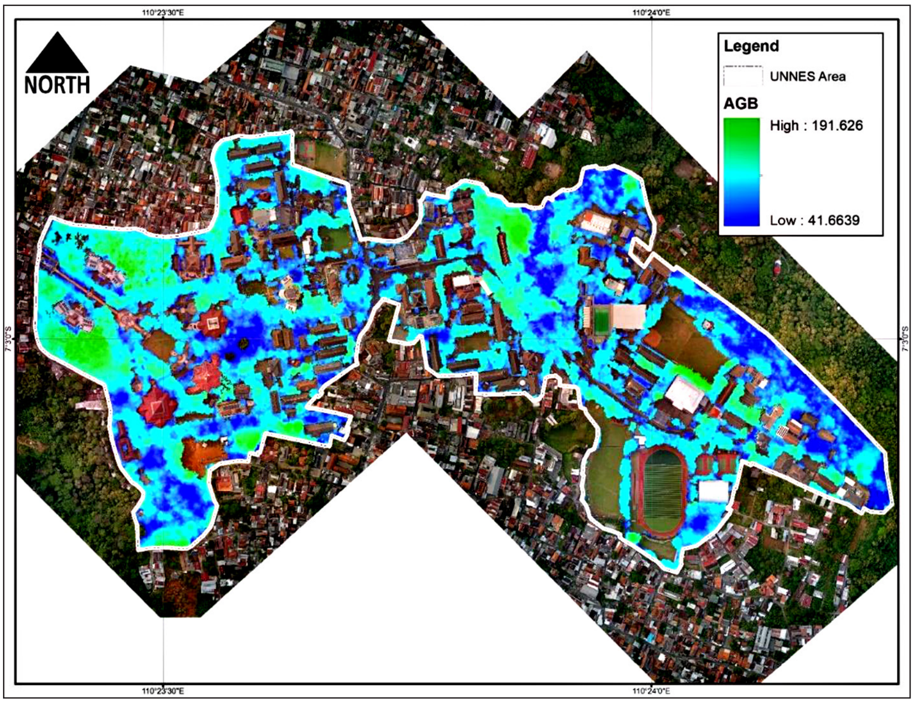

Figure 5. Spatial distribution of AGB

confirm that the AGB and carbon stock estimates for the UNNES campus are ecologically and methodologically reasonable, positioned between campuses with limited green spaces and those characterized by well-developed urban forests.

DISCUSSION

Based on the evaluation of the four prediction models developed in this study, Model 2 exhibits the highest level of feasibility for estimating aboveground biomass (AGB) and carbon stock in heterogeneous tropical campus green spaces. Conceptually, Model 2 utilizes the accumulation of CHM values within individual tree canopies as a representation of three-dimensional canopy volume, rather than relying solely on maximum height parameters. This approach is more robust in heterogeneous landscapes characterized by diverse canopy architectures, overlapping crowns, and pronounced vertical stratification among individual trees. Consequently, Model 2 provides a favorable balance between model simplicity, spatial stability, and ecological interpretability, making it particularly suitable for feasibility-oriented studies of biomass and carbon stock estimation in complex tropical campus environments. Although the results of this study demonstrate strong potential for the use of UAV-based RGB photogrammetry in biomass estimation, several methodological limitations require critical consideration. First, the UAV data acquisition design employed a single-grid flight pattern, which may limit the quality of three-dimensional canopy reconstruction, particularly in areas with multilayered vegetation and overlapping canopies. Previous studies have shown that dual-grid or cross-grid flight patterns can increase point cloud density, reduce shadowing effects, and improve canopy height model accuracy in ecosystems with high structural complexity (Swayze et al., 2021).

Second, ITC identification remains a major challenge in tropical campus green spaces. Although visual interpretation of high-resolution orthophotos offers greater spatial flexibility and accuracy than automated methods under certain conditions, this approach is highly dependent on the interpreter's local knowledge. In this study, understanding of tree species composition and planting patterns at the UNNES campus played an important role in canopy delineation. Nevertheless, this approach is inherently subjective and may lead to inconsistencies across areas or among different interpreters. Therefore, the development of standardized and systematic ITC interpretation keys is necessary to ensure consistent replicability, as demonstrated by So et al., (2025) and Fariz et al., (2023).

Third, uncertainty in the estimation results is influenced by limited validation of tree height. This study did not explicitly compare UAV-derived CHM values with direct field measurements of actual tree height, except indirectly through correlations with AGB data. However, the integration of field-based measurements, even with a limited number of samples, is essential for calibrating and validating canopy height models, as recommended in numerous remote sensing-based biomass estimation studies. Future study is therefore encouraged to incorporate direct tree height measurements for selected samples to reduce sources of structural uncertainty.

Fourth, the field sampling design in this study did not fully account for balanced species representation. Variations in wood density, canopy architecture, and growth patterns among tropical species are known to strongly influence the relationship between CHM and AGB. As a result, more stratified sampling based on species or functional tree groups would improve model robustness and reduce potential bias in biomass estimation.

In a broader context, the limitations identified in this study reflect common challenges in remote sensing-based AGB estimation. Passive optical data, including UAV RGB imagery, despite offering high spatial resolution and flexible coverage, still face issues of biomass saturation and limited capability in capturing complex vertical canopy structures. Nevertheless, numerous studies have shown that UAV RGB technology utilizing DEM or CHM can produce AGB and AGC estimates that are acceptable, stable, and sufficiently replicable, although generally less accurate than LiDAR-based approaches (González-Jaramillo et al., 2019; d'Oliveira et al., 2021).

In contrast, UAV LiDAR directly captures three-dimensional forest structure and offers higher precision for biomass and carbon stock estimation, particularly in dense and structurally complex forests. However, this advantage is accompanied by substantially higher data acquisition and processing costs (d'Oliveira et al., 2020; So et al., 2025). While integrating UAV LiDAR with RGB or multispectral data can further improve accuracy, such approaches also increase operational complexity and cost, which often constrain routine monitoring in tropical developing regions (Chen et al., 2025; Khan, 2025). In this context, UAV RGB-based approaches using DEM or CHM can be regarded as practical and efficient solutions that balance accuracy, cost, and operational feasibility, whereas UAV LiDAR remains the preferred option when high precision and detailed structural information clearly justify greater investment (Víctor González-Jaramillo et al., 2019; d'Oliveira et al., 2021; Bazrafkan et al., 2023).

Looking forward, future studies should be directed toward the development of multi-sensor approaches through the integration of UAV RGB data with SAR or satellite imagery to obtain more comprehensive representations of three-dimensional canopy structure and to reduce structural uncertainty (Mai et al., 2025; Melitha et al., 2025; Xu et al., 2025). In addition, the application of non-parametric or machine learning methods that combine structural, spectral, and textural variables has the potential to further enhance model performance, particularly for regional-scale or cross-campus assessments. Comparative studies across campus green spaces in Indonesia also represent a strategic direction for understanding carbon stock variability and its management in higher education environments. Overall, the approach developed in this study is not intended to replace high-precision LiDAR-based methods, but rather to demonstrate the feasibility of UAV RGB as an estimation approach that is acceptable, stable, and sufficiently replicable in tropical campus contexts, while supporting Net Zero Campus initiatives aligned with SDG 13 (Climate Action), SDG 15 (Life on Land), and Indonesia's Net Zero Emission 2060 policy.

CONCLUSIONS

This study demonstrates that the use of UAV RGB photogrammetrycombined with an ITC approach can produce reasonable estimates of AGB and carbon stocks in heterogeneous tropical campus green spaces. Among the evaluated models, Model 2, which applies power regression using the total (sum) of CHM values within individual tree canopies, emerged as the most feasible approach. Although this model did not consistently yield the highest statistical metrics, it provided the most balanced performance in terms of error magnitude, spatial stability, and ecological plausibility when applied across the CHM raster. These findings emphasize that biomass model selection should not rely solely on statistical indicators, but must also consider ecological realism and spatial consistency.

The estimated total AGB, carbon stock, and CO_2 sequestration at the Universitas Negeri Semarang campus indicate that campus green open spaces play a meaningful role as carbon sinks within urban environments. By adopting a relatively cost-effective and flexible approach, the UAV RGB-based method developed in this study demonstrates strong potential for broader application, particularly in educational institutions in developing countries where access to LiDAR technology remains limited. Importantly, this study is not intended to replace high-precision LiDAR-based methods for biomass and carbon stock estimation. Rather, it aims to demonstrate the feasibility of UAV RGB as an estimation approach that is acceptable, stable, and sufficiently replicable in tropical campus contexts, especially for routine monitoring and preliminary assessments. Conceptually and practically, this study reinforces the role of universities as key actors in advancing Net Zero Campus initiatives and provides a tangible contribution to achieving SDG 13 (Climate Action) and SDG 15 (Life on Land), in line with Indonesia's Net Zero Emission 2060 policy. The proposed approach also shows high potential for replication across tropical campuses as part of science-based climate change mitigation and campus environmental governance strategies.

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