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# Derivation of allometric equations and carbon content estimation in mangrove forests of Malaysia

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ABSTRACT

Mangrove forests play a vital role in carbon sequestration and climate change mitigation, yet comprehensive data on their carbon storage capacity in Malaysia remain limited. This study investigated allometric relationships and carbon content in Malaysian mangrove forests, aiming to develop site species-specific allometric equations, determine carbon content in tree components, and assess total carbon stock. Research was conducted in four compartments of the Sg. Pulai Permanent Reserved Forest, representing a mixed-species mangrove stand. We measured 1403 trees across ten species, with *Rhizophora apiculata* identified as the dominant species. Using diameter at breast height (DBH) and tree height, we developed site species-specific allometric equations to estimate aboveground biomass. The total aboveground biomass ranged from 183.30 t $ha^{-1}$ to 187.06 t $ha^{-1}$ across the study area. We calculated the total carbon stock at 91.01 t C $ha^{-1}$, incorporating measurements from trees below 5 cm in diameter, dead and downed wood, and litter. An economic valuation of carbon storage was conducted using two approaches: the social cost of carbon method estimated a value of USD 4054.76 per hectare. In contrast, the market price approach yielded USD 1064.34 per hectare. This study provides essential data for improving biomass and carbon stock estimation methods in Malaysian mangrove ecosystems. Our findings highlight these forests' economic and ecological importance, supporting their integration into climate change mitigation strategies and informing sustainable management and conservation policies for mangrove forests in Malaysia and similar regions.

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## 1. Introduction

Mangrove forests, integral to tropical and subtropical coastal ecosystems, are vital hubs for biodiversity, coastal defence, and carbon sequestration (Choudhary et al., 2024). These unique ecosystems are found at the interface of land and sea, adapting to saline conditions and tidal fluctuations that would be inhospitable to most terrestrial plant species. Their ability to sequester significant amounts of carbon highlights the need for accurate biomass estimation methods, such as site-specific allometric equations developed for local species and environmental conditions (Alongi, 2022; Anees et al., 2024a; Luo et al., 2024).

Mangroves are widely recognized for their exceptional capacity for carbon storage (Sunkur et al., 2023; Tahir et al., 2023). This high carbon storage capacity is due to their large biomass, both above and below ground, and their ability to accumulate organic matter in sediments over long periods (Lange et al., 2023). Research has shown that coastal mangrove forests can store up to four times more carbon per hectare than other tropical forests, making them crucial components in the global carbon cycle and climate change mitigation strategies (Bourgeois et al., 2024; Tahir et al., 2023).

Mangroves' exceptional carbon sequestration capacity underscores the need to accurately quantify their biomass and carbon content (Choudhary et al., 2024). Such measurements are essential for effective conservation and management strategies (Choudhary et al., 2024; Anees et al., 2024b, 2025; Anees et al., 2024b). Allometric relationships have emerged as a valuable tool in this context, where destructive sampling is often impractical or undesirable due to conservation concerns (Duncanson et al., 2021). They provide a non-destructive method for estimating tree biomass based on easily measurable parameters such as trunk diameter and height.

However, developing accurate allometric equations for mangroves presents several challenges that require careful consideration. The structural complexity and diversity of mangrove species often necessitate the development of species-specific or site-specific equations (Sanam et al., 2024). In the Malaysian context, limited studies have focused on deriving site-specific allometric equations for mixed-species mangrove forests. Existing equations, though valuable, often fail to capture the unique structural and environmental attributes of these ecosystems, leading to potential inaccuracies in biomass and carbon stock estimations. This specificity is crucial because mangrove growth forms can vary significantly depending on environmental conditions, species, and age. Furthermore, the unique growth forms of mangroves, including their complex root systems, make traditional forestry measurement techniques less applicable. Environmental variability across mangrove habitats can also lead to significant differences in tree form and biomass allocation, necessitating the development of equations that account for these variations (Sriram et al., 2023).

In addition to biomass estimation, determining the carbon content of different mangrove components (leaves, branches, stems, and roots) is crucial for a comprehensive understanding of carbon storage in these ecosystems (Islam et al., 2023; Anees et al., 2024d). Carbon content can vary among species and even within different parts of the same tree, affecting overall carbon stock estimates (Anees et al., 2024c). This variability highlights the importance of detailed, component-specific carbon content analysis. Accurate carbon content determination and reliable biomass estimates are essential for assessing mangrove forests' true carbon sequestration potential (Chaudhary and Aryal, 2024b).

The methodologies developed and insights gained from mangrove carbon research can be adapted and applied to other mangrove-rich regions, contributing to global efforts to protect and restore these critical coastal ecosystems (Roy et al., 2024). By bridging the gap between scientific research and practical management, such studies support the long-term sustainability of mangrove forests, thereby preserving their ecological, economic, and climate mitigation roles. In particular, research addressing significant gaps in our understanding of allometric relationships and carbon content in specific mangrove forests enhances biomass estimation techniques and carbon stock assessments, ultimately contributing to more effective mangrove conservation strategies and climate change mitigation efforts.

Malaysia is a crucial area for mangrove research within this global context. With its extensive and diverse mangrove ecosystems, Malaysia provides an ideal setting for studying various aspects of mangrove ecology. The country's mangroves represent an essential subset of Southeast Asian mangroves, offering a range of ecological conditions and management approaches (Islam et al., 2024). Malaysian mangroves are both ecologically significant and economically important, providing resources and ecosystem services to local communities (Khan et al., 2024). However, they face threats from coastal development, aquaculture expansion, and climate change impacts, making their conservation and sustainable management a priority (Chaudhary and Aryal, 2024b).

Despite the recognized importance of Malaysian mangroves, there remains a gap in our understanding of their specific allometric relationships and carbon storage potential. To address these issues and contribute to the broader mangrove ecology and carbon sequestration research, the present study focuses on the Sg. Pulai Permanent Reserved Forest, a representative mangrove ecosystem in Malaysia, with the following objectives: 1) to develop allometric relationships for estimating the aboveground biomass of mangrove trees, 2) to estimate the total aboveground carbon stock in the studied mangrove forests, and 3) to calculate the economic value of the carbon stock, providing a tangible metric for conservation efforts. This research aims to enhance our ability to accurately estimate carbon stocks and sequestration rates in this ecosystem by addressing these objectives.

## 2. Material and methods

### 2.1. Study area and plot designing

The Sg. Pulai Permanent Reserved Forest (SPRF) is a large mangrove ecosystem in Johor, southern Peninsular Malaysia (Fig. 1). This tropical mangrove forest experiences high humidity and temperatures (WAN JULIANA et al., 2020; Khan et al., 2024). The SPRF is characterized by a multi-layered canopy dominated by *Rhizophora apiculata* and *Avicennia alba*, typical of Malaysian mangroves (Jusoff, 2013). As a vital carbon sink, the SPRF plays a crucial role in climate change mitigation (Alongi, 2012). The forest also serves as a natural coastal defense, supports local fisheries, and maintains water quality (Lee et al., 2014). Despite its protected status as a Permanent Reserved Forest, the SPRF faces threats from urban development and climate change impacts (Hamdan et al., 2012; Wan Juliana et al., 2020). The unique characteristics of this ecosystem, including its high carbon storage capacity and rich biodiversity, make it an invaluable site for research into tropical coastal forest dynamics and carbon sequestration, underlining the importance of comprehensive studies in biomass density and carbon stock estimation in such environments (Adame et al., 2018).

This study focuses on four specific compartments of the SPRF: 16, 259A, 412B, and 453B (Fig. 1). These areas were selected using a judgment sampling technique to represent mixed mangrove species stands estimated to be over 20 years old (Rachmad et al., 2024). This sampling approach is consistent with methods used in similar mangrove studies, which often employ stratified or purposive sampling to capture the heterogeneity of mangrove ecosystems (Kauffman and Donato, 2012).

The sampling design randomly established two 50m × 50m plots (labeled A and B) within each of the four selected compartments. This resulted in a total study area of 2 ha across eight plots. In agreement with best practices in forest carbon assessment (Komiyama et al., 2008), the plot size falls within the range recommended for mangrove forest carbon assessments, as it balances practicality with the need to capture ecosystem variability. Also, GPS coordinates were recorded for each plot to ensure precise location data (Table 1), which is crucial for potential

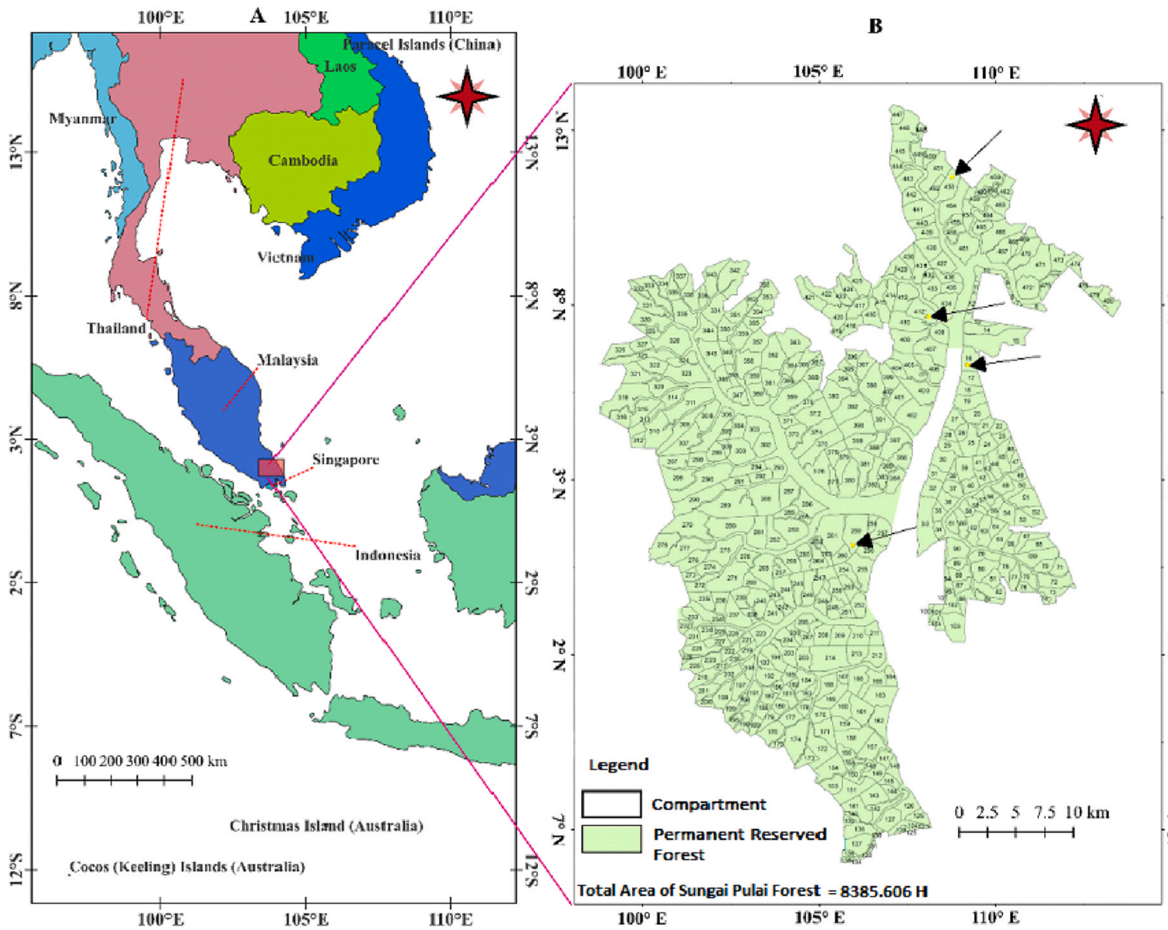


**Fig. 1.** Map of the study area and the investigated mangrove forest compartments.

**Table 1**
GPS coordinates for the four corners of each 50 m × 50 m plot within the selected compartments.

| COMPARTMENT | | | |
|---|---|---|---|
| 16 | 259A | 412B | 453B |
| **A** | | | |
| N 01°26′16.0″ | N 01°24′09.9″ | N 01°26′42.4″ | N 01°28′06.4″ |
| E 103°33′08.0″ | E 103°31′43.6″ | E 103°32′47.9″ | E 103°32′49.0″ |
| N 01°26′16.0″ | N 01°24′08.4″ | N 01°26′42.0″ | N 01°28′06.3″ |
| E 103°33′09.7″ | E 103°31′43.8″ | E 103°32′46.5″ | E 103°32′50.6″ |
| N 01°26′17.7″ | N 01°24′08.3″ | N 01°26′40.7″ | N 01°28′07.8″ |
| E 103°33′09.6″ | E 103°31′45.4″ | E 103°32′46.7″ | E 103°32′51.4″ |
| N 01°26′17.6″ | N 01°24′10.1″ | N 01°26′41.1″ | N 01°28′07.7″ |
| E 103°33′08.2″ | E 103°31′45.4″ | E 103°32′48.4″ | E 103°32′48.9″ |
| **B** | | | |
| N 01°26′16.0″ | N 01°24′11.8″ | N 01°26′40.1″ | N 01°28′07.6″ |
| E 103°33′10.0″ | E 103°31′43.5″ | E 103°32′46.1″ | E 103°32′51.4″ |
| N 01°26′16.0″ | N 01°24′10.1″ | N 01°26′38.8″ | N 01°28′07.6″ |
| E 103°33′11.8″ | E 103°31′43.5″ | E 103°32′46.5″ | E 103°32′53.0″ |
| N 01°26′18.2″ | N 01°24′10.5″ | N 01°26′38.9″ | N 01°28′09.2″ |
| E 103°33′11.5″ | E 103°31′45.4″ | E 103°32′48.0″ | E 103°32′52.8″ |
| N 01°26′17.8″ | N 01°24′11.9″ | N 01°26′40.6″ | N 01°28′09.4″ |
| E 103°33′10.0″ | E 103°31′45.3″ | E 103°32′48.0″ | E 103°32′51.5″ |

future studies or long-term monitoring efforts in the same area.

### 2.2. Forest inventory and biomass assessment

#### 2.2.1. Tree measurements

The diameter at breast height (DBH; 1.3 m above ground level or above the highest stilt root in *Rhizophora* species) and the height (H) of all trees with diameters exceeding 5 cm were recorded within the plots. To ensure the accuracy of tree height measurements, we employed a clinometer, a widely used instrument in forest measurements, which provides reliable height estimations when combined with careful field practices. Measurements were taken by trained personnel to minimize observer errors and cross-checks were performed using a subset of trees to validate the consistency of height estimates.

Regarding the use of more than just DBH data, incorporating height alongside DBH enhances the precision of biomass estimation, particularly in mixed-species forests like the studied mangrove ecosystem. The model used in this study integrates both diameter and height, yielded higher $R^2$ values, indicating better predictive power compared to using DBH alone. This reinforces the value of combining multiple parameters for accurate biomass estimation. These measurements were carried out to assess tree growth features and calculate the overall stand biomass, as smaller trees generally contribute only a small fraction to the ecosystem's total carbon stocks (Bhomia et al., 2016).

#### 2.2.2. Shrubs and dwarf mangroves

Small (5 cm< in diameter) specimens were assessed within four circular plots, each with a radius of 2 m, nested in larger circular plots of 20 m diameter located at the corners of the 50 m × 50 m plots (Fig. 2). This method optimized data collection for less than three individuals without compromising the overall survey quality. Importantly, the same technique was applied uniformly across living trees and standing dead wood, ensuring consistency in their assessment methodology. Detailed information on smaller trees was obtained by employing these nested subplots while maintaining the broader sampling strategy for larger specimens, thus balancing comprehensive data collection with practical

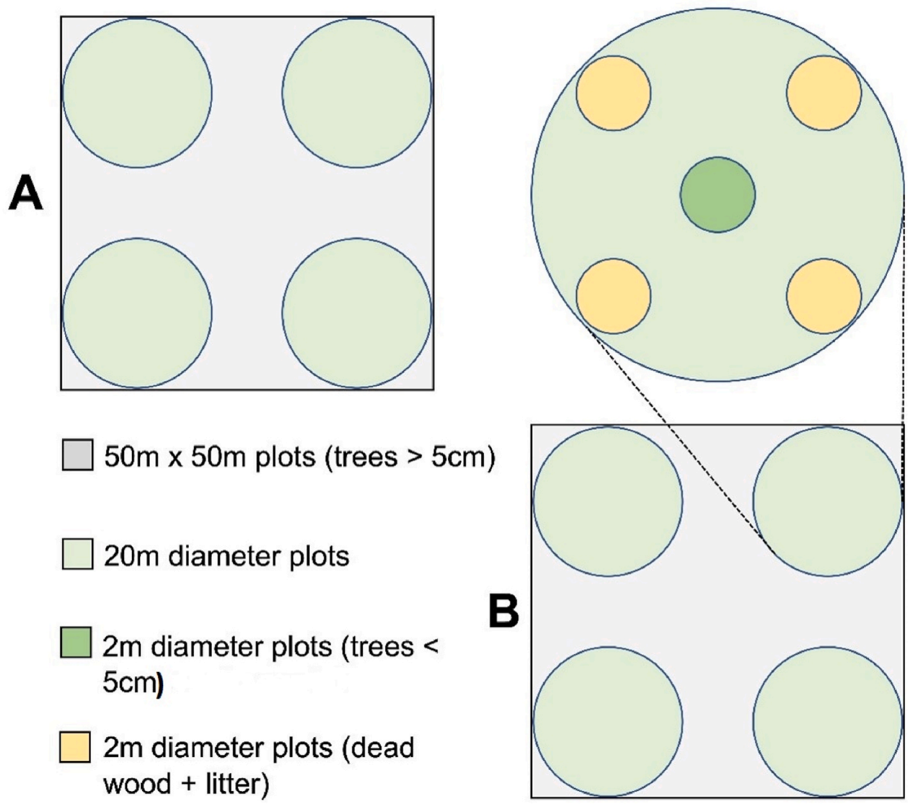


**Fig. 2.** Schematized sampling design. Two plots sized 50 m × 50 m (A and B) were randomly established (from the coast to the center of each compartment (4 compartments, total surface = 2 ha) to sample trees >5 cm. In each square plot, four 20-m diameter circular plots were identified, each of them including (i) one 2-m diameter circular plot for sampling trees <5 cm and (ii) four 2-m diameter circular plots for sampling dead wood and litter.

field constraints (Percel et al., 2018). Biomass estimations were calculated using a pre-existing allometric formula (Fourqurean et al., 2014).

### 2.2.3. Dead and downed wood

We assessed downed woody debris using a vertical transect method. At four points within each 20-m circular plot, we established 2-m diameter sampling plots (Fig. 2). Within these smaller circles, fallen woody materials that intersected the sampling plane were measured, including detached trunks, branches, prop roots, and shrub stems. This non-destructive line intersects technique enabled efficient quantification of woody debris without disturbing the forest floor (Decena et al., 2023).

### 2.2.4. Litter

Litter sampling was conducted using a destructive method within the four areas selected for sampling dead and downed wood (Fig. 2). At each sampling plot, we placed a square microplot measuring 0.5 m on each side, totaling 1 square meter. All litter within these microplots was collected and combined in a single bag, with its total wet weight measured on-site. A portion of this sample was then extracted as a subsample for further analysis. This subsample was dried in the laboratory until it reached a constant weight. We calculated a moisture ratio by comparing the wet and dry masses of the subsample. This ratio was then applied to the entire collected litter sample to estimate its total dry mass, providing an accurate measure of litter biomass across the study area (Leal et al., 2023).

## 2.3. Aboveground biomass allometry

The total aboveground biomass was calculated using a locally developed allometric equation. The destructive sampling was carried out based on the optimized sampling technique to reduce the number of trees to be felled or selected for biomass allometry, allowing the measurement of fewer trees if compared to the random selection plan (Biggs et al., 2023). The total aboveground biomass was calculated using locally developed allometric equations for compartment-specific variability in species composition and structural characteristics. This approach ensured precise estimation by incorporating the heterogeneity observed in the study area. These equations, based on diameter and height parameters, were utilized to calculate the biomass of individual tree components, which were subsequently summed to derive the total biomass for the compartments.

Thirty trees from various species and sizes were selected based on DBH distribution to formulate allometric equations for destructive measurements. Plots were chosen evenly from all classes of coverage. Following the felling of a sample tree, the stem's height and diameter were measured at 0 m, 0.3 m, 1.3 m (DBH), 3.3 m, and then at every 2 m. The diameter of the stem at the joint of the lowest living branch (Db) was also measured. Branches and twigs were separated from the stem, and the stem was cut into logs. Each log was numbered properly and weighed using platform balance. Samples from each component were taken as follows: logs from 0 to 0.3 m, 0.3–1.3 m, 1.3–3.3 m, 3.3–5.3 m, and then at every 2-m interval, along with living branches, twigs, dead branches, twigs, and leaves (Hazandy Abdul Hamid et al., 2015). After weighing and recording the required data in tally sheets, samples were put inside marked plastic bags (Khan et al., 2020; Abd-Majid et al., 2021).

The data obtained from both destructive sampling and laboratory analysis were consolidated into a single tally sheet for further calculations, specifically: 1) stem volume using Smalian's Formula in cubic meters ($m^3$), which calculates logs based on the parabolic frustum shape, 2) biomass calculation for sample disks from each destructively sampled tree, and 3) the total dry weight was calculated for all living branches, twigs, dead branches and twigs, and foliage (Baglat et al., 2023).

Tree aboveground biomass of each component (i.e., leaves, branches, and stems) was estimated by using the equations derived from the allometric relationship based either on diameter or on both diameter and height data as follows:

$$W = a(D)^b \quad (1)$$

or

$$W = a(D^2H)^b \quad (2)$$

where, $W$ is the aboveground biomass of the component, D is the diameter at breast height, H is the height, whereas a and b are constants.

The total aboveground biomass was then calculated as the sum of the biomass of the different components, as follows:

$$W_{total} = W_{leaves} + W_{branches} + W_{stems} \quad (3)$$

### 2.4. Carbon stock measurement

A LECO CR-412 Carbon Analyzer determined the total carbon content in dried samples. During the analysis, samples were combusted in an oxygen-rich atmosphere, converting any carbon present into $CO_2$. The sample gas flows into a non-dispersive infrared (NDIR) detection cell. The NDIR measures the mass of $CO_2$ present. The mass was then converted to percent carbon based on the dry sample weight. The total organic carbon content was subtracted from the total carbon content to determine a given sample's total inorganic carbon content. The carbon values were calibrated using the standard procedure, as Hazandy Abdul Hamid et al. (2015) stated. The total carbon stock was then estimated by aggregating all the aboveground carbon pools. The final total carbon content was calculated by multiplying the carbon percentages from each aboveground component by their respective biomass values. Finally, the values of all components were summed to obtain the total aboveground carbon stock (Pechanec et al., 2022).

### 2.5. Statistical analyses

Allometric equations were derived by fitting a power regression of tree growth parameters against biomass components separately and to the total biomass. The biomass of the components was derived using the two models, D (see equation (1)) and $D^2H$ (see equation (2)). The total biomass from the two models was obtained by summing the respective components (equation (3)). Diameters at breast height (D) and tree height (H) were tested as independent variables. Then, all regressions were fitted using SPSS ver. 12 (Srikiran et al., 2023), followed by SigmaPlot for plotting the graphs.

### 2.6. Economic valuation

This study employed two distinct approaches for carbon valuation to provide a comprehensive economic assessment of carbon stocks in the study area. This study's monetary valuation of carbon storage employed both the social cost of carbon and market-based approaches to capture complementary aspects of its economic value. The social cost of carbon reflects the long-term societal costs associated with carbon emissions, aligning with global policy initiatives for climate change mitigation. In contrast, the market-based approach represents the immediate tradable value of carbon stocks, providing a realistic perspective for carbon credit schemes. Together, these approaches offer a holistic understanding of the economic significance of carbon sequestration in mangrove ecosystems.

First, we utilized the social cost of carbon approach outlined by the United States Environmental Protection Agency (EPA). This method estimates the long-term economic impact of carbon emissions, valuing carbon at USD 12 (MYR 51.24) per metric ton of $CO_2$ (Barrage and Nordhaus, 2024). Second, we applied a market-based valuation using current carbon prices from the Carbon TradeXchange. Specifically, we used the Golden Standard CER prices, which were set at USD 3.15 (MYR 13.45) per metric ton of $CO_2$ equivalent at the time of the study.

To quantify the carbon stocks, we first measured aboveground carbon pools following established protocols (detailed in previous sections). We then applied both valuation methods to these quantified carbon stocks to calculate their economic value. For the social cost method, we multiplied the total carbon stock (in metric tons of $CO_2$) by the EPA's estimated social cost of USD 12 per metric ton. For the market-based method, we multiplied the same carbon stock by the current Carbon TradeXchange price of USD 3.15 per metric ton. This dual approach compares the estimated long-term societal costs of carbon emissions and the current market valuation, as shown in Table 8. It provides a more robust economic assessment of the carbon stocks in our study area, accounting for both potential future impacts and present market conditions (Mirici and Berberoglu, 2024). By employing these two valuation techniques, our study aims to provide a comprehensive economic perspective on the carbon stocks present in the examined ecosystem, contributing to a more informed understanding of their value in the context of climate change mitigation efforts.

## 3. Results

### 3.1. Tree inventory for individuals with a diameter greater than 5 cm

Table 2 presents the descriptive statistics of the tree inventory, focusing on trees with diameters greater than 5 cm found in the study area (2 ha). The total number of individuals was 1403 from ten species found in this study site (see Appendix 1 for details), and no multiple leader stems (branches or stems that compete to become the main trunk) were counted at 1.3 m height. The average number of stems per hectare is about 701.5, which indicates a lower density of trees in this mixed-species forest. *Rhizophora apiculata* species was found to dominate the area with a total number of individual trees equal to 870, followed by *Bruguiera cylindrica* (249), *B. sexangula* (138), *Xylocarpus granatum* (48), *R. mucronata* (46), *Ceriops tagal* (8), *B. gymnorrhiza* (3), *Avicennia* spp. (2) and *Lumnitzera littorea* (1).

The average DBH and height of the trees in this area were 18.43 cm and 18.09 m, respectively. The most giant tree was *X. gran*atum, with a DBH of 43.2 cm, and the tallest tree was *R. apiculata*, reaching 34 m in

**Table 2**
Summary of descriptive statistics for trees >5 cm diameter.

| Species | No. of tree | Diameter (cm) | | | Height (m) | | |
|---|---|---|---|---|---|---|---|
| | | Mean (±SE) | Min | Max | Mean (±SE) | Min | Max |
| *Avicennia* spp. | 2 | 30.45 ± 1.85 | 28.6 | 32.3 | 16.80 ± 0.80 | 16 | 17.6 |
| *Bruguiera cylindrica* | 249 | 15.49 ± 0.33 | 5 | 41 | 16.36 ± 0.28 | 5.2 | 30 |
| *Bruguiera gymnorrhiza* | 3 | 11.37 ± 2.94 | 5.6 | 15.2 | 11.13 ± 3.03 | 5.2 | 15.2 |
| *Bruguiera parviflora* | 38 | 18.25 ± 1.18 | 6.9 | 34 | 19.19 ± 0.75 | 6.5 | 28 |
| *Bruguiera sexangular* | 138 | 16.28 ± 0.38 | 6.1 | 34 | 17.10 ± 0.29 | 4.1 | 26 |
| *Ceriops tagal* | 8 | 19.45 ± 1.41 | 13 | 25.2 | 19.33 ± 1.27 | 15 | 26 |
| *Lumnitzera littorea* | 1 | 17.2 | 0 | 0 | 16 | 0 | 0 |
| *Rhizophora apiculate* | 870 | 19.57 ± 0.20 | 5.6 | 40.5 | 18.90 ± 0.13 | 6.9 | 34 |
| *Rhizophora mucronata* | 46 | 17.22 ± 0.64 | 10.3 | 27.8 | 18.16 ± 0.42 | 11 | 24 |
| *Xylocarpus granatum* | 48 | 20.35 ± 1.05 | 9 | 43.2 | 14.61 ± 0.62 | 5.2 | 24 |
| **TOTAL** | **1403** | **18.43 ± 0.16** | **5** | **43.2** | **18.09 ± 0.11** | **4.1** | **34** |

height.

The size distribution for DBH was quite skewed (Fig. 3), indicating that a higher number of DBH was distributed towards lower values from eight diameter classes, whereas a symmetric class distribution pattern was found for height (Fig. 4).

### 3.2. Tree inventory for individuals with diameter less than 5 cm

Data on shrubs, dwarf saplings and seedlings with diameters below five cm are summarized in Table 3. In parallel to trees observed for diameter above 5 cm, the majority of trees less than five cm were dominated by *R. apiculata* followed by *B. cylindrica, X. granatum, R. mucronata*, *B. sexangula* and *B. parviflora* with a total of 216 individuals (see Appendix 2 for details). From this finding, an estimated 10,748 individuals were found in the study area, comprising the majority of saplings and seedlings.

### 3.3. Stand biomass production

#### 3.3.1. Biomass proportion

Table 4 displays the biomass values for each aboveground component measured destructively in sampling plots. The total aboveground biomass for the sampled trees (N = 30) ranged from 40.46 kg to 956.41 kg, while stem volumes ranged from 0.04 $m^3$ to 0.99 $m^3$. Fig. 5 depicts the distribution of biomass among different tree components within the mixed mangrove species, as determined through destructive sampling. The distribution of total aboveground biomass was ranked in the following order: stem > branch > leaf (see Table 5).

#### 3.3.2. Allometric relationships

The coefficient of determination ($R^2$) for the D model ranged from 0.63329 to 0.94293, while for the $D^2H$ model, it ranged from 0.63357 to 0.95766 (Fig. 6). Lower $R^2$ values were observed for leaf biomass, indicating that the mixed species stand found in the SPRF significantly influences biomass allocation and crown distribution. This variability, introduced by the mixed mangrove stand, also affected the overall $R^2$ values of the derived equations, particularly when compared to single-species stands or equations derived from single-species studies. The differences in wood density and branch structure among species contribute to the variability in individual species' values. Nonetheless, each model formulation in this study was well-fitted, with the $D^2H$ model generally proving to be a more accurate predictor of aboveground biomass in this mangrove forest. While it is true that the improvement in the coefficient of determination ($R^2$) for Model $D^2H$ over Model D is not highly significant, the inclusion of height in the $D^2H$ model ensures more precise biomass estimation, particularly in mixed-species mangrove ecosystems where structural variability is prominent. This additional accuracy can be crucial in research contexts requiring detailed and reliable biomass estimates. The study was conducted in an open mangrove ecosystem comprising mixed-species stands. Due to this ecological setting, we did not develop separate allometric equations for each species. Instead, we derived site-specific allometric equations that account for the variability within the mixed-species composition.

#### 3.3.3. Tree standing biomass and carbon stock

The total aboveground biomass for trees ≥5 cm DBH, estimated using the $D^2H$ and D approach, was 183.30 t $ha^{-1}$ and 187.06 t $ha^{-1}$ respectively. This value falls within the range Kauffman and Donato (2012) recorded for six Micronesian mangrove forests (169–517 t $ha^{-1}$). However, it is lower than the values reported by Putz and Chan (1986), Hazandy Abdul Hamid et al. (2015), and Khan et al. (2020) but slightly higher than those recorded by Juliana and Nizam (2004) in Matang. This study's lower total aboveground biomass can be attributed to the lower stem density (approximately 701.5 stems per hectare) in this mixed-species forest. Standing biomass was calculated using average dry mass for trees below 5 cm DBH, including seedlings. Based on 20 randomly selected samples, the average dry mass was approximately 0.36 kg $tree^{-1}$. Extrapolating this to the number of trees below 5 cm DBH in 2-m radius plots, the standing biomass for this size class was estimated at 1.93 t ha-1. Carbon content analysis was performed on various tree components: 314-disc samples for stem carbon content, 30 composite samples for branch and leaf carbon content, and 20 for trees below 5 cm DBH. Using these carbon content values, we calculated the total aboveground carbon stock per hectare for standing trees. The carbon stock value using the $D^2H$ approach was 87.90 t $ha^{-1}$, while for trees below 5 cm DBH, the carbon stock value per hectare was 0.79 t. The $D^2H$

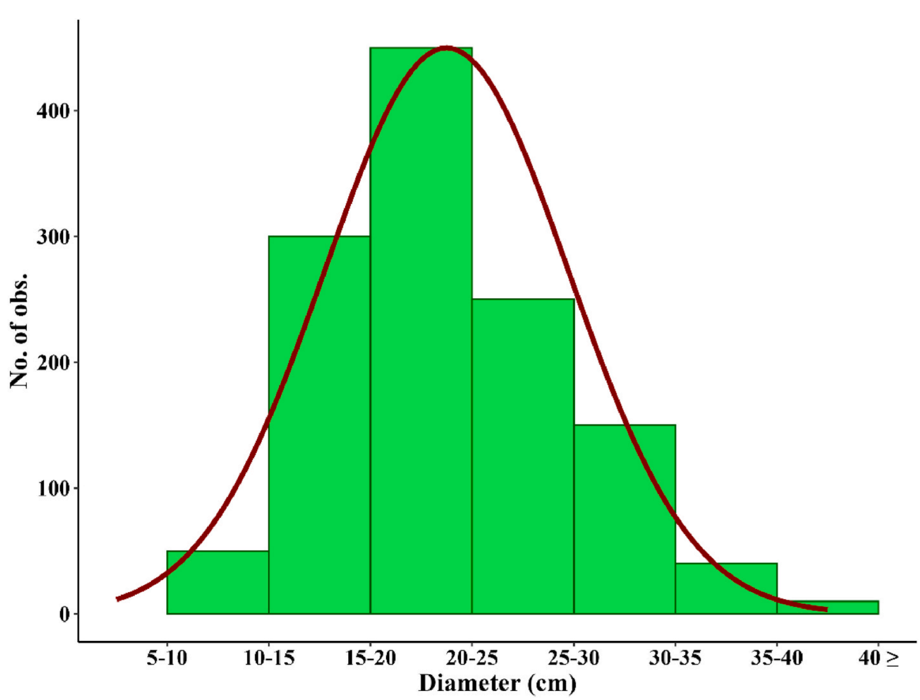


**Fig. 3.** Frequency distribution of size classes for trees found in the study area.

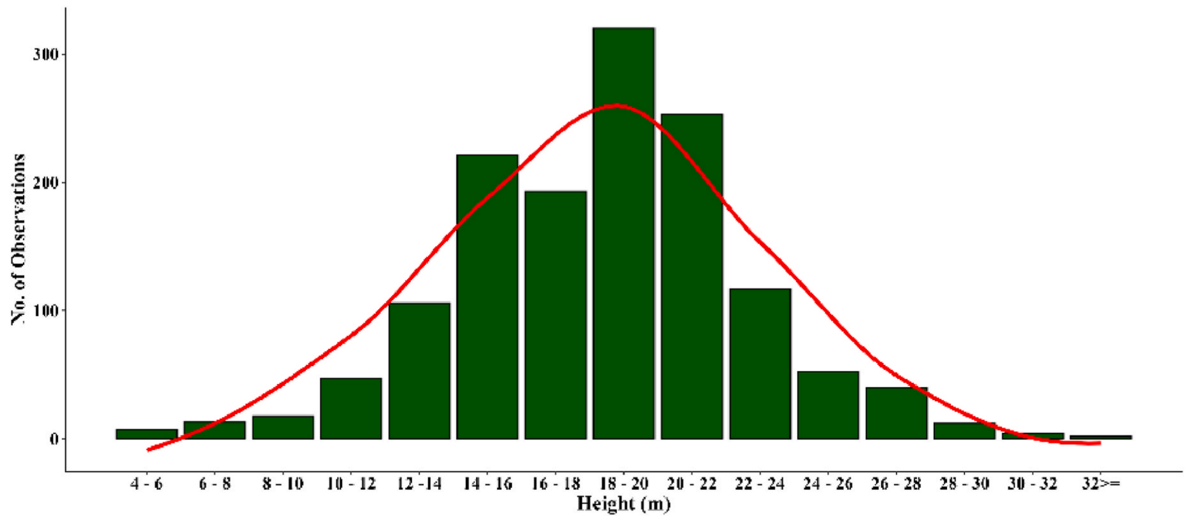


**Fig. 4.** Frequency distribution of height classes for trees found in the study area.

**Table 3**
Summary of descriptive statistics for trees <5 cm diameter.

| Species | No. of tree | Diameter (cm) | | | Height (m) | | |
|---|---|---|---|---|---|---|---|
| | | Mean (±SD) | Min | Max | Mean (±SD) | Min | Max |
| *Bruguiera cylindrical* | 49 | 2.14 ± 0.13 | 0.8 | 4.3 | 2.19 ± 0.17 | 0.3 | 6.0 |
| *Bruguiera parviflora* | 7 | 2.39 ± 0.16 | 2 | 3.2 | 2.40 ± 0.10 | 2.0 | 2.8 |
| *Bruguiera sexangular* | 10 | 1.35 ± 0.15 | 1 | 2.4 | 1.56 ± 0.19 | 0.9 | 3.0 |
| *Rhizophora apiculata* | 103 | 1.11 ± 0.04 | 0.4 | 3.2 | 1.03 ± 0.07 | 0.11 | 6.0 |
| *Rhizophora mucronata* | 11 | 1.48 ± 0.18 | 0.8 | 2.2 | 0.98 ± 0.09 | 0.6 | 1.8 |
| *Xylocarpus granatum* | 36 | 1.74 ± 0.13 | 0.8 | 4.8 | 1.59 ± 0.11 | 0.8 | 4.2 |
| **TOTAL** | **216** | **1.52 ± 0.05** | **0.4** | **4.8** | **1.46 ± 0.06** | **0.11** | **6.0** |

**Table 4**
Biomass of each of the tree components and total aboveground biomass.

| Species | Height (m) | DBH (cm) | Volume ($m^3$) | Stem Biomass (kg) | Branch Biomass (kg) | Leaves Biomass (kg) | Total ABG Biomass (kg) |
|---|---|---|---|---|---|---|---|
| *Rhizophora apiculata* | 13.5 | 9 | 0.04 | 31.78 | 6.20 | 2.48 | 40.46 |
| *Rhizophora apiculata* | 14 | 10.7 | 0.10 | 44.53 | 8.29 | 2.55 | 55.36 |
| *Rhizophora apiculata* | 16.4 | 12.7 | 0.09 | 71.21 | 7.65 | 2.38 | 81.23 |
| *Rhizophora apiculata* | 17.6 | 16.8 | 0.19 | 153.35 | 27.11 | 6.86 | 187.32 |
| *Bruguiera cylindrical* | 15.6 | 10.8 | 0.11 | 58.01 | 8.92 | 3.97 | 70.89 |
| *Bruguiera cylindrical* | 15.5 | 13.5 | 0.13 | 89.03 | 9.58 | 5.94 | 104.55 |
| *Rhizophora apiculata* | 22.8 | 22 | 0.38 | 293.66 | 52.15 | 22.66 | 368.47 |
| *Avicennia* spp. | 21 | 26 | 0.49 | 344.43 | 177.15 | 42.41 | 563.99 |
| *Bruguiera sexangula* | 20 | 23.8 | 0.50 | 359.19 | 119.05 | 40.59 | 518.83 |
| *Rhizophora apiculata* | 19.9 | 14.6 | 0.16 | 194.81 | 16.54 | 2.58 | 213.93 |
| *Rhizophora apiculata* | 14.4 | 12.9 | 0.09 | 69.98 | 11.28 | 3.43 | 84.69 |
| *Rhizophora apiculata* | 21.7 | 25.6 | 0.48 | 371.73 | 71.71 | 28.05 | 471.49 |
| *Rhizophora apiculata* | 24.7 | 22.6 | 0.38 | 350.65 | 71.32 | 34.50 | 456.47 |
| *Rhizophora apiculata* | 23.3 | 33 | 0.99 | 800.69 | 131.30 | 24.42 | 956.41 |
| *Rhizophora apiculata* | 20.5 | 16.5 | 0.22 | 203.54 | 18.84 | 15.95 | 238.33 |
| *Rhizophora apiculata* | 18.1 | 16.8 | 0.17 | 140.40 | 29.55 | 8.84 | 178.79 |
| *Rhizophora apiculata* | 19.99 | 20.2 | 0.26 | 188.75 | 20.69 | 7.27 | 216.72 |
| *Bruguiera cylindrical* | 16.3 | 16.5 | 0.17 | 132.02 | 47.04 | 13.31 | 192.37 |
| *Rhizophora apiculata* | 21.2 | 18.2 | 0.25 | 198.72 | 23.68 | 14.33 | 236.72 |
| *Bruguiera parviflora* | 18 | 18.7 | 0.27 | 202.69 | 45.56 | 12.52 | 260.77 |
| *Bruguiera cylindrical* | 17.3 | 17.9 | 0.17 | 152.65 | 38.85 | 5.09 | 196.60 |
| *Xylocarpus granatum* | 16.5 | 18.8 | 0.17 | 109.30 | 48.61 | 2.80 | 160.71 |
| *Ceriops tagal* | 18.8 | 17.4 | 0.19 | 165.47 | 32.27 | 15.54 | 213.27 |
| *Ceriops tagal* | 14.5 | 15.5 | 0.14 | 101.35 | 42.43 | 10.57 | 154.35 |
| *Ceriops tagal* | 15.5 | 13.4 | 0.08 | 76.34 | 13.10 | 5.28 | 94.72 |
| *Xylocarpus granatum* | 11.25 | 10.6 | 0.05 | 36.98 | 35.71 | 6.37 | 79.06 |
| *Rhizophora apiculata* | 19 | 22.3 | 0.35 | 289.57 | 108.29 | 14.06 | 411.92 |
| *Bruguiera cylindrical* | 17.02 | 22.5 | 0.33 | 259.97 | 92.99 | 22.03 | 374.99 |
| *Rhizophora apiculata* | 23.3 | 37 | 0.91 | 575.12 | 160.64 | 28.23 | 763.99 |
| *Bruguiera cylindrical* | 19.6 | 24.1 | 0.42 | 368.32 | 96.90 | 10.31 | 475.53 |

**Table 5**
Standing biomass and Carbon Stock for Tree Components and Total Aboveground Biomass in Sg. Pulai Permanent Reserved Forest Using the $D^2H$ Parameter.

| Component | Mass (t ha$^{-1}$) | CC (%) | CS (t ha$^{-1}$) |
|---|---|---|---|
| **Trees > 5 cm** | | | |
| Stem (1) | 143.38 | 49.82 | 71.43 |
| Branch (2) | 31.66 | 41.22 | 13.05 |
| Leaf (3) | 8.26 | 41.38 | 3.42 |
| (A) Total aboveground (1 + 2+3) | **183.30** | – | **87.90** |
| (B) Total aboveground | **187.06** | 44.14* | **82.57** |
| **Trees < 5 cm** | **1.93** | 41.29 | **0.79** |

Note: Values of (A) were calculated from tree component biomass equations(2 and 3) and (B) values were calculated directly from total aboveground biomass equations (1 and 3). CC – carbon content where * was an average of CC of (1), (2), and (3), CS – carbon stock.

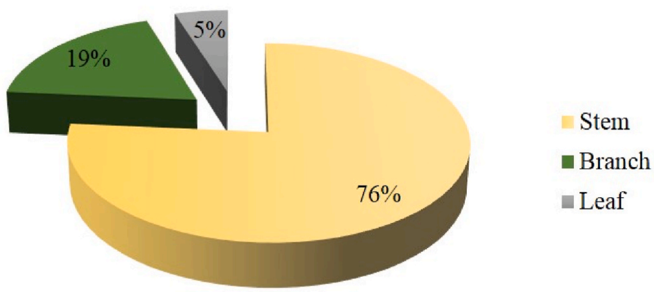


**Fig. 5.** Distribution of aboveground biomass components in the Sg. Pulai Forest Reserve.

model integrates tree height, providing a more precise representation of tree biomass by accounting for structural variability in mixed-species mangrove stands. As shown in our results, the $R^2$ values for the $D^2H$ model were generally higher than the D model, indicating superior predictive performance. This difference suggests that the $D^2H$ model reduces estimation error, particularly in taller or structurally diverse trees, yielding more reliable carbon stock estimates. In our study, total aboveground biomass using the $D^2H$ model was 183.30 t ha$^{-1}$, whereas the D model showed slightly lower consistency in capturing this variability. Consequently, the carbon stock derived using the $D^2H$ model was more robust, minimizing under- or over-estimation risks.

The economic implications are directly tied to the accuracy of carbon stock estimates. Whether using the social cost of carbon or market-based prices, the valuation of carbon stocks relies heavily on biomass estimates. An underestimation of carbon stock (potentially resulting from the D model) would undervalue the economic benefits of carbon sequestration. Conversely, the $D^2H$ model, with its greater accuracy, supports more credible economic valuations.

### *3.4. Dead and downed wood*

Table 6 summarizes the data on dead and downed wood collected from 32 subplots, which cover an area of 100.48 m$^2$ within the 2-ha study area. The total amount of dead and downed wood was 29.77 kg, found in a 100.48 m$^2$ subplot area with a total value of 2.96 t ha$^{-1}$. The carbon content value ranged from 38.8% to 44.9%, averaging about 41.87%. The total carbon storage of dead and downed woody was estimated at 1.24 t ha$^{-1}$ (2.96 t ha$^{-1}$ X 41.87%).

### *3.5. Litter*

Table 7 presents the data on litter collected from a total subplot area of 32 m$^2$ (32 subplots) within a 2-ha plot. The total dry weight of litter in the 32 m$^2$ subplot area was 8.97 kg, translating to an overall dry weight of 2.80 tons per hectare. The carbon content of the litter ranged from 30.2% to 43.5%, with an average of approximately 38.61%. Consequently, the total carbon storage in the litter was estimated at around 1.08 tons per hectare (2.80 t ha$^{-1}$ × 38.61%).

### *3.6. Total aboveground carbon*

The total aboveground carbon, encompassing all aboveground components, accounted for 91.01 t ha$^{-1}$ (Table 8).

### *3.7. Economic value of carbon*

We estimated 91.01 t C ha$^{-1}$ of carbon to be stored in the SPFR aboveground across three major pools: vegetation, dead and downed wood, and litter. Based on this carbon stock, the carbon\u2019s economic value is estimated at MYR 17,098.96 (3824.85 USD) per hectare using the EPA price of MYR 51.24 (11.46 USD) (Table 8). Alternatively, using the market price of MYR 13.45 (3.01 USD), the carbon value is estimated at MYR 4488.31 (1003.99 USD) per hectare.

The results of these valuations highlight the societal and practical perspectives on carbon's economic value. The social cost approach estimated the carbon value at MYR 17,098.96 (3824.85 USD) per hectare, reflecting the long-term societal costs of carbon emissions. Meanwhile, the market-based approach provided a valuation of MYR 4488.31 (1003.99 USD) per hectare, offering a practical perspective for carbon credit trading schemes. The substantial difference between these values underscores the complexity and variability in carbon valuation methodologies, emphasizing the importance of context when interpreting these figures.

Table 9 highlights the economic valuation of aboveground carbon stocks in the Sg. Pulai Forest Reserve uses two approaches: the social cost of carbon and market-based pricing. The estimated carbon stock of 91.01 t C ha$^{-1}$ translates to a monetary value of MYR 17,098.96 (USD 3824.85) per hectare under the social cost method, which reflects the broader societal benefits of carbon sequestration. Conversely, the market-based valuation, which uses the prevailing carbon credit price, estimates the value at MYR 4488.31 (USD 1003.99) per hectare. The substantial discrepancy between these methods underscores the variation in carbon valuation frameworks, with the social cost approach emphasizing long-term climate benefits. In contrast, market prices focus on immediate economic transactions. These results demonstrate the significant economic value of carbon sequestration in mangrove ecosystems and highlight the importance of selecting appropriate valuation methods based on policy or market objectives.

## 4. Discussion

This study provides valuable insights into the allometric relationships, standing biomass, carbon content, and carbon stock's economic valuation in mixed forests in Malaysia. The findings contribute to our understanding of carbon sequestration in these ecosystems and provide tools for more accurate assessments in the future. As global efforts to mitigate climate change intensify (Anees et al., 2024a; Mehmood et al., 2024a, 2024b, 2024c, 2024d, 2024e), the role of mangrove forests in carbon sequestration is likely to become increasingly important, underscoring the need for continued research and informed management of these valuable coastal ecosystems (Friess et al., 2020; Worthington et al., 2020; Khan et al., 2020).

### *4.1. Allometric relationships and biomass estimation*

Developing site-specific allometric equations for estimating aboveground biomass is vital to this study. While destructive, developing site-specific allometric equations were deemed critical for this study due to the mangrove ecosystem's unique species composition and structural variability. Existing equations often fail to capture these characteristics,

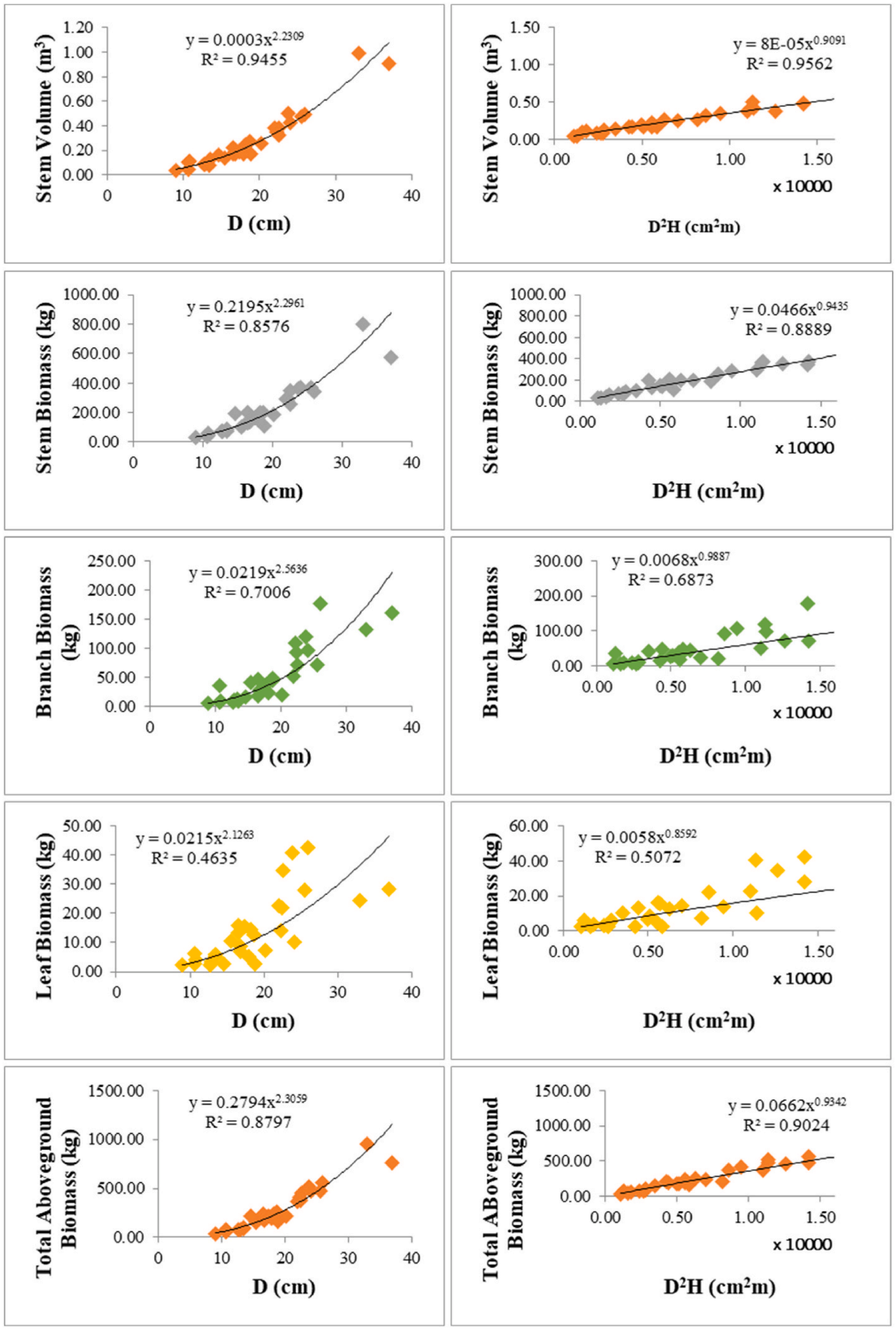


**Fig. 6.** Power regression of mangrove biomass was estimated using D (equation (1)) and $D^2H$ (equation (2)) against the corresponding tree parameter.

leading to potential inaccuracies in biomass and carbon stock estimations. Our approach aimed to address this gap and provide more precise estimates tailored to the local conditions. We acknowledge the trade-off involved and have minimized destructive sampling to the extent possible while ensuring the reliability of the derived equations. The equations derived using both diameter (D) and the combined parameter of diameter and height ($D^2H$) showed a good fit, with $R^2$ values ranging from 0.63 to 0.96. The $D^2H$ model generally performed better, indicating that incorporating tree height improves biomass estimations in these mixed mangrove stands. This aligns with previous studies that have found combined $D^2H$ models more accurate for biomass estimation across diverse forest types (Chave et al., 2014; Basuki et al., 2009). While we acknowledge the additional cost and time required for measuring plant height in the field, we believe that the inclusion of height in the $D^2H$ model is justified in this study. The improved coefficient of determination ($R^2$) observed with the $D^2H$ model, while not drastically higher than the D model, provides enhanced accuracy, particularly critical for mixed-species mangrove ecosystems with complex structural variability.

The D model may be recommended as a simpler alternative for practical applications where cost and time constraints are significant. However, the additional effort to include height measurements is warranted for research purposes where the highest precision is required to inform conservation and management strategies. Our findings are consistent with recent local studies in SPFR. For instance (Abdul-Hamid et al., 2022), reported $R^2$ values ranging from 0.93 to 0.99 for allometric equations, showing superior performance.

However, the lower $R^2$ values observed for leaf biomass equations

**Table 6**
Dry weight and carbon content of dead and downed wood collected from a two-hectare area.

| No. of Subplot | SFW | SDW | TFW | TDW | CC (%) |
|---|---|---|---|---|---|
| 1 | 160.00 | 59.00 | 1730.00 | 637.94 | 42.8 |
| 2 | 110.00 | 51.65 | 1590.00 | 746.58 | 44.7 |
| 3 | 150.00 | 62.00 | 1970.00 | 814.27 | 40.8 |
| 4 | 120.00 | 42.50 | 2100.00 | 743.75 | 42.1 |
| 5 | 120.00 | 77.30 | 1270.00 | 818.09 | 42.9 |
| 6 | 100.00 | 44.35 | 1450.00 | 643.08 | 42.5 |
| 7 | 110.00 | 58.00 | 1110.00 | 585.27 | 42.2 |
| 8 | 100.00 | 40.85 | 1320.00 | 539.22 | 43.0 |
| 9 | 100.00 | 41.00 | 2200.00 | 902.00 | 40.2 |
| 10 | 100.00 | 35.00 | 5100.00 | 1785.00 | 41.3 |
| 11 | – | – | – | – | – |
| 12 | 100.00 | 43.95 | 6300.00 | 2768.85 | 43.1 |
| 13 | 100.00 | 38.00 | 965.00 | 366.70 | 38.9 |
| 14 | 100.00 | 40.15 | 885.00 | 355.33 | 41.1 |
| 15 | 100.00 | 37.35 | 7570.00 | 2827.40 | 43.7 |
| 16 | 100.00 | 44.40 | 120.00 | 53.28 | 41.1 |
| 17 | 150.00 | 75.45 | 1640.00 | 824.92 | 41.4 |
| 18 | 140.00 | 48.40 | 1990.00 | 687.97 | 40.9 |
| 19 | 130.00 | 78.30 | 1930.00 | 1162.45 | 40.7 |
| 20 | 160.00 | 69.65 | 2060.00 | 896.74 | 44.9 |
| 21 | 150.00 | 65.55 | 1800.00 | 786.60 | 44.3 |
| 22 | 140.00 | 55.90 | 2000.00 | 798.57 | 41.0 |
| 23 | 120.00 | 75.75 | 1870.00 | 1180.44 | 43.3 |
| 24 | 150.00 | 79.15 | 2050.00 | 1081.72 | 41.9 |
| 25 | 200.00 | 112.35 | 1800.00 | 1011.15 | 43.7 |
| 26 | 160.00 | 91.85 | 1690.00 | 970.17 | 44.1 |
| 27 | 160.00 | 64.85 | 1860.00 | 753.88 | 40.3 |
| 28 | 120.00 | 49.65 | 1560.00 | 645.45 | 39.4 |
| 29 | 200.00 | 112.45 | 1780.00 | 1000.81 | 38.8 |
| 30 | 160.00 | 105.90 | 2150.00 | 1423.03 | 42.7 |
| 31 | 200.00 | 104.25 | 1670.00 | 870.49 | 40.5 |
| 32 | 210.00 | 121.60 | 1880.00 | 1088.61 | 39.7 |
| | **Total** | | | **29769.74** | |

Note: TFW-Total fresh weight, TDW-Total dry weight, SFW-Sample fresh weight, SDW-Sample dry weight, CC-Carbon content.

**Table 7**
Total dry weight and carbon content of litter collected from an area of one hectare.

| No. of Subplot | SFW | SDW | TFW | TDW | CC (%) |
|---|---|---|---|---|---|
| 1 | 110.00 | 38.30 | 835.00 | 290.73 | 38.3 |
| 2 | 130.00 | 36.75 | 970.00 | 274.21 | 39.1 |
| 3 | 100.00 | 34.55 | 1000.00 | 345.50 | 35.5 |
| 4 | 110.00 | 39.80 | 820.00 | 296.69 | 37.4 |
| 5 | 120.00 | 53.45 | 650.00 | 289.52 | 41.0 |
| 6 | 110.00 | 45.00 | 750.00 | 306.82 | 41.5 |
| 7 | 110.00 | 46.90 | 790.00 | 336.83 | 41.9 |
| 8 | 100.00 | 38.55 | 620.00 | 239.01 | 41.1 |
| 9 | 100.00 | 34.95 | 685.00 | 239.41 | 42.0 |
| 10 | 100.00 | 38.70 | 355.00 | 137.39 | 42.6 |
| 11 | 100.00 | 41.80 | 350.00 | 146.30 | 39.9 |
| 12 | 100.00 | 48.45 | 220.00 | 106.59 | 42.1 |
| 13 | 100.00 | 21.45 | 825.00 | 176.96 | 40.6 |
| 14 | 100.00 | 32.30 | 500.00 | 161.50 | 42.1 |
| 15 | 100.00 | 38.45 | 245.00 | 94.20 | 43.0 |
| 16 | 100.00 | 30.75 | 425.00 | 130.69 | 40.8 |
| 17 | 120.00 | 44.80 | 720.00 | 268.80 | 30.9 |
| 18 | 100.00 | 44.10 | 720.00 | 317.52 | 30.2 |
| 19 | 110.00 | 54.80 | 790.00 | 393.56 | 33.6 |
| 20 | 130.00 | 48.45 | 1190.00 | 443.50 | 36.6 |
| 21 | 120.00 | 57.50 | 710.00 | 340.21 | 31.4 |
| 22 | 110.00 | 65.60 | 850.00 | 506.91 | 43.5 |
| 23 | 100.00 | 54.75 | 790.00 | 432.53 | 37.8 |
| 24 | 130.00 | 56.20 | 850.00 | 367.46 | 32.6 |
| 25 | 110.00 | 39.20 | 830.00 | 295.78 | 38.4 |
| 26 | 100.00 | 48.10 | 860.00 | 413.66 | 39.1 |
| 27 | 100.00 | 38.85 | 690.00 | 268.07 | 41.4 |
| 28 | 120.00 | 42.65 | 740.00 | 263.01 | 40.5 |
| 29 | 110.00 | 37.90 | 840.00 | 289.42 | 35.4 |
| 30 | 100.00 | 38.10 | 860.00 | 327.66 | 43.1 |
| 31 | 110.00 | 41.55 | 660.00 | 249.30 | 34.8 |
| 32 | 120.00 | 36.00 | 730.00 | 219.00 | 37.2 |
| | | **Total** | | **8968.73** | |

Note: TFW-Total fresh weight, TDW-Total dry weight, SFW-Sample fresh weight, SDW-Sample dry weight, CC-Carbon content.

highlight the challenges in estimating this component, likely due to the variability in crown structure among different mangrove species. This variability in leaf biomass allocation is common in mixed-species forests and has been noted in other mangrove studies (Komiyama et al., 2008). Recent work by Chowdhury et al. (2024) in the Sundarbans mangroves also reported similar challenges, suggesting this is a widespread issue in diverse mangrove stands. Future research could explore species-specific leaf biomass equations or the use of crown dimensional parameters to improve estimates, as suggested by (Demie et al., 2024) in a global review of allometric models and UAVs can provide high-resolution aerial imagery, enabling non-destructive and efficient assessment of canopy structures and spatial variability. While this study primarily focused on ground-based measurements to develop site-specific allometric equations, we acknowledge the utility of UAVs and plan to explore their application in future research. The exclusion of species-specific equations in this study was driven by the mixed-species composition of the study area and logistical constraints. However, the importance of species-specific equations in improving biomass estimation accuracy is acknowledged, especially given the significant influence of wood density variations among species. While this study aimed to comprehensively assess mixed-species mangrove stands using component-based equations, future research should focus on developing species-specific allometric equations, particularly for dominant species. Such efforts would enhance the precision of biomass and carbon stock estimates and provide more robust data for mangrove conservation and management strategies.

### 4.2. Carbon content and stocks

The mean carbon content values determined for different tree components (41.22%–49.82%) are consistent with the generally accepted

**Table 8**
Total aboveground carbon stock in Sg. Pulai Forest Reserve.

| Component | Carbon Stock (t C $ha^{-1}$) |
|---|---|
| Trees >5 cm | 87.90 |
| Trees <5 cm | 0.79 |
| Dead and downed woody | 1.24 |
| Litter | 1.08 |
| **TOTAL** | **91.01** |

**Table 9**
The estimated value of aboveground carbon stock in Sg. Pulai Forest Reserves.

| Carbon Valuation Method | Estimated Carbon Stock | Carbon Price | Value per Hectare |
|---|---|---|---|
| Social Cost of Carbon (EPA, MYR 51.24 per t $CO_2$) | 91.01 t C $ha^{-1}$ (333.70 t $CO_2$ $ha^{-1}$) | MYR 51.24 (11.46 USD) | MYR 17,098.96 (3824.85 USD) |
| Carbon TradeXchange, Golden Standard CER (MYR 13.45 per t $CO_2$) | 91.01 t C $ha^{-1}$ (333.70 t $CO_2$ $ha^{-1}$) | MYR 13.45 (3.01 USD) | MYR 4488.31 (1003.99 USD) |

Note: Exchange rate RM1.000 MYR = $0.2237 USD. The represented amount shows only above ground carbon stock, below ground carbon stock has not been included.

range (between 41% and 50%) for woody biomass (Thomas and Martin, 2012). The higher carbon content in stem wood than in branches and leaves also aligns with patterns observed in other forest types (Martin and Thomas, 2011). This variability in carbon content across tree components emphasizes the importance of using component-specific values rather than a single conversion factor when estimating carbon stocks from biomass data. The inclusion of component-based allometric models in this study reflects the objective of capturing the structural variability in biomass distribution within tree components. While the whole-tree biomass estimation model demonstrated high accuracy, as evidenced by the $D^2H$ model's $R^2$ values (ranging from 0.63357 to 0.95766), the component-based approach allowed for the generation of component-specific carbon conversion factors. These factors facilitated a more detailed estimation of carbon stocks, particularly in a mixed-species mangrove ecosystem. This dual approach acknowledges the trade-offs between simplicity and precision, with component-specific models offering enhanced utility in understanding biomass allocation in diverse ecosystems. Recent studies have further supported this approach. For instance, Zhou et al. (2019) found similar patterns in Chinese mangroves, with stem wood showing higher carbon content than branches and leaves. These findings reinforce the need for global component-specific carbon content assessments in mangrove forests (Sharma et al., 2023). While substantial, the total aboveground carbon stock of 91.01 t C $ha^{-1}$ estimated is below some earlier estimations from other Malaysian mangrove forests. This value was found below the ones recorded in Kuala Sepetang and Kuala Trong mangrove forests (assessed respectively by Hazandy Abdul Hamid et al., 2015; Khan et al., 2020) because this mixed mangrove forest has low tree density and does not have a specific management system such as the ones practiced in Matang mangrove forest. The motivation for developing site-specific allometric equations lies in addressing the variability and limitations of existing general equations, which often fail to account for the unique structural and species composition of specific ecosystems. This study emphasizes the importance of improving the accuracy of carbon stock estimates through site-specific equations. Such improvements are essential for reliable biomass assessments, regardless of whether the ecosystem exhibits high or low carbon storage capacity. By focusing on precision, site-specific measurements ensure that conservation and management strategies are informed by accurate data, tailored to the ecological characteristics of the study area. The results highlight the need for site-specific assessments of carbon stocks in mangrove forests, as generalizations across large geographic areas may lead to inaccurate estimates (Rovai et al., 2022).

The contribution of dead and downed wood (1.24 t C $ha^{-1}$) and litter (1.08 t C $ha^{-1}$) to the total carbon stock, while relatively small, demonstrates the importance of including these components in comprehensive carbon assessments. These pools can be significant in some mangrove systems and may respond differently to disturbance or management interventions than live biomass (Adame et al., 2013). Recent work by Sasmito et al. (2020) has shown that these components can contribute up to 10% of total ecosystem carbon in some mangrove forests, highlighting their potential significance in carbon accounting.

### 4.3. Economic valuation of carbon stocks

The economic valuation of carbon stocks using both the social cost of carbon and market-based approaches provides a range of potential values for these mangrove forests' ecosystem service of carbon sequestration. The estimated values of MYR 17,098.96 (3824.85 USD) $ha^{-1}$ (social cost approach) and MYR 4488.31 (1003.99 USD) $ha^{-1}$ (market price approach) demonstrate the significant monetary value of carbon storage in these ecosystems. However, the large discrepancy between these estimates underscores the challenges and uncertainties in carbon valuation (Phelps et al., 2022). These two carbon prices per hectare highlight the substantial variation in valuing carbon stock, a factor that could potentially lead to controversy. However, the most crucial aspect of carbon valuation is accurately estimating standing biomass. The cost-based value, such as the social cost of carbon, is generally used in policy-making and environmental planning where the goal is to estimate the broader societal benefits of carbon sequestration or the long-term economic impacts of carbon emissions. It provides a comprehensive metric for assessing climate change mitigation strategies and informing national or global policy frameworks. In contrast, the market-based value is more appropriate for practical applications such as carbon trading, offset programs, or voluntary carbon credit schemes. It reflects the immediate economic value of carbon in active trading markets, offering a tangible incentive for conservation initiatives. Regardless of market carbon prices, the value of aboveground carbon remains fundamentally dependent on precise biomass information. In general, the cost of carbon varies from region to region. (Phat et al., 2004) estimated the price of carbon is USD19.7 per Mg C. Tschakert (2002) used a cost of USD15 per Mg C in her study in Senegal, and Kirschbaum (2001) assumed a cost of USD10 per Mg C. (Kulshreshtha et al., 2000) estimated the average value of carbon based on the replacement and substitute cost method. They found that the cost of carbon was $17.50 per tonne using the replacement cost method. Meanwhile, the cost using the substitute method is $16.25 per tonne. Using the total carbon stored of 488 Mt C, the economic value of stored carbon in Saskatchewan, Canada, equals USD 8540 (Mill USD) and $7930 (Mill USD). However, the U.S. Environmental Protection Agency (EPA, 2005) estimated an annual price of USD15 per tonne (Sandhu, 2018). This value is higher than (Bradley et al., 1991) value of USD 5.30 per tonne of carbon. Hence, selecting a single carbon valuation technique or price is daunting for any researcher, while its value varies from region to country.

The social cost of carbon approach likely provides a more comprehensive estimate of the true value of carbon sequestration, as it attempts to account for the full societal costs of carbon emissions. However, the market-based approach may be more relevant for immediate carbon offset or trading schemes. The variation in these estimates highlights the need for careful consideration when using economic valuations to inform policy decisions or management strategies (Sheehy et al., 2023). It is worth noting that these economic valuations focus solely on carbon sequestration and do not account for the myriad other ecosystem services provided by mangrove forests, such as coastal protection, fisheries support, and biodiversity conservation. A more comprehensive valuation of mangrove ecosystem services would likely yield significantly higher economic values (Barbier et al., 2011).

### 4.4. Implications for management and conservation

The findings of this study have several implications for the management and conservation of mangrove forests in Malaysia.

1. The site-specific allometric equations developed here can improve the accuracy of biomass and carbon stock estimates in similar mixed mangrove forests, supporting more informed management decisions. This is particularly important given the recent push for standardized carbon accounting methods in Southeast Asian mangroves.
2. The relatively lower carbon stocks compared to some other Malaysian mangrove forests suggest the potential for increased carbon sequestration through restoration or enhanced management practices. Recent successful restoration projects in Thailand (Suyadi et al., 2023) provide a valuable model for such initiatives.
3. The economic valuation of carbon stocks provides a tangible argument for conserving these ecosystems, potentially supporting their inclusion in carbon credit schemes or other incentive-based conservation programs. The recent development of blue carbon markets in Southeast Asia (Friis et al., 2024) offers new opportunities for mangrove conservation financing.
4. The variability in carbon content across tree components and the contributions of dead wood and litter highlight the need for comprehensive sampling approaches in carbon stock assessments. This aligns with recent international guidelines for blue carbon accounting, such as those detailed in the IPCC Wetlands Supplement (Crooks et al., 2018) and the Blue Carbon Initiative's assessment study (Stankovic et al., 2023). These guidelines emphasize the importance of comprehensive sampling approaches in carbon stock

assessments, particularly in complex ecosystems like coastal blue carbon habitats

This study contributes to the growing knowledge of mangrove carbon dynamics in Southeast Asia. By providing detailed, site-specific data on allometric relationships, carbon stocks, and economic valuations, it supports more accurate assessments of the role of Malaysian mangroves in climate change mitigation. Future research should focus on expanding these assessments to a broader range of mangrove ecosystems across Malaysia, integrating belowground carbon pools, and exploring the impacts of different management strategies on long-term carbon sequestration potential (Friess et al., 2022; Macreadie et al., 2024).

## 5. Conclusion

This study significantly advances our understanding of biomass density and carbon stock estimation in Malaysian mangrove forests by developing site-specific allometric equations and a comprehensive assessment of aboveground carbon pools. Our novel approach, combining in situ measurements across four compartments with multi-pool carbon analysis, yielded more accurate and locally relevant estimates than previously available. The site-specific allometric equations developed for dominant species like *Rhizophora apiculata* demonstrated high predictive power, significantly improving upon generic models. Importantly, our findings reveal significant structural heterogeneity within seemingly homogeneous mangrove stands, challenging traditional zonation-based stratification approaches. This insight suggests that future carbon reporting initiatives, including REDD+, should consider structural characteristics alongside species composition for more accurate stratification, particularly in areas lacking clear zonation patterns.

The economic valuation range of MYR 4488.31 (1003.99 USD) to 17,098.96 (3824.85 USD) per hectare underscores these ecosystems' substantial carbon service value. This valuation, coupled with our improved estimation methods, provides policymakers and forest managers with more accurate tools for assessing the climate mitigation potential of mangrove forests. Our approach can be adapted for other mangrove regions, facilitating more precise national and global carbon inventories and supporting the identification and conservation of High Carbon Stock (HCS) forests. While our study provides a robust methodology for carbon stock assessment, we recognize limitations in spatial and temporal scope. Future research should extend to broader geographical areas and incorporate temporal dynamics to capture seasonal and long-term variations in carbon sequestration rates. Additionally, the volatility of carbon markets presents a challenge for long-term economic projections based on our valuations. Integrating our findings into comprehensive blue carbon strategies and national climate action plans represents a crucial next step. By providing precise, locally derived data and methodologies, this study significantly enhances our ability to quantify and value the carbon sequestration services of Malaysian mangrove forests. These insights are crucial for informed forest management and conservation decision-making, ultimately contributing to more effective global climate change mitigation efforts.

## CRediT authorship contribution statement

**Waseem Razzaq Khan:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Michele Giani:** Writing – review & editing, Conceptualization. **Stanislao Bevilacqua:** Writing – review & editing. **Shoaib Ahmad Anees:** Writing – review & editing, Visualization, Validation, Software, Methodology, Investigation. **Kaleem Mehmood:** Writing – review & editing, Visualization, Software, Methodology, Investigation, Data curation. **M. Nazre:** Visualization. **Abdul Aziz Bin Abdul Haddy:** Writing – review & editing. **Abang Norizan Bin Abang Median:** Writing – review & editing. **Japanie Bin Bujang:** Writing – review & editing. **Fatin-Norliyana Mohamad-Ismail:** Writing – review & editing. **Johar Mohamed:** Writing – review & editing. **Zaiton Samdin:** Writing – review & editing. **Rambod Abiri:** Writing – review & editing. **Tuan-Marina Tuan-Ibrahim:** Writing – review & editing. **Lydia-Suzieana Mohammad:** Writing – review & editing. **Hamid-Reza Naji:** Writing – review & editing. **Seemab Akram:** Writing – review & editing. **Hazandy Abdul-Hamid:** Writing – review & editing, Conceptualization. **Timothy Dube:** Writing – review & editing.

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## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.indic.2025.100618.

## Data availability

Data will be made available on request.

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