CHAPTER III
MATERIALS AND METHODS

3.1 Workflow

The workflow diagram of this study is shown in **Figure 3.1.** Data were collected from both ground truth measurements and RS (UAV imagery) sources. Information concerning mangrove trees and their associated biodiversity indices was documented. AGB was estimated using species-specific allometric equations and then converted to AGC stock using a conversion factor. UAV imagery was utilized to calculate VIs and the canopy height model (CHM) for the development of mangrove AGB models via linear regression analysis. Finally, statistical methods were applied to assess the performance of the models.

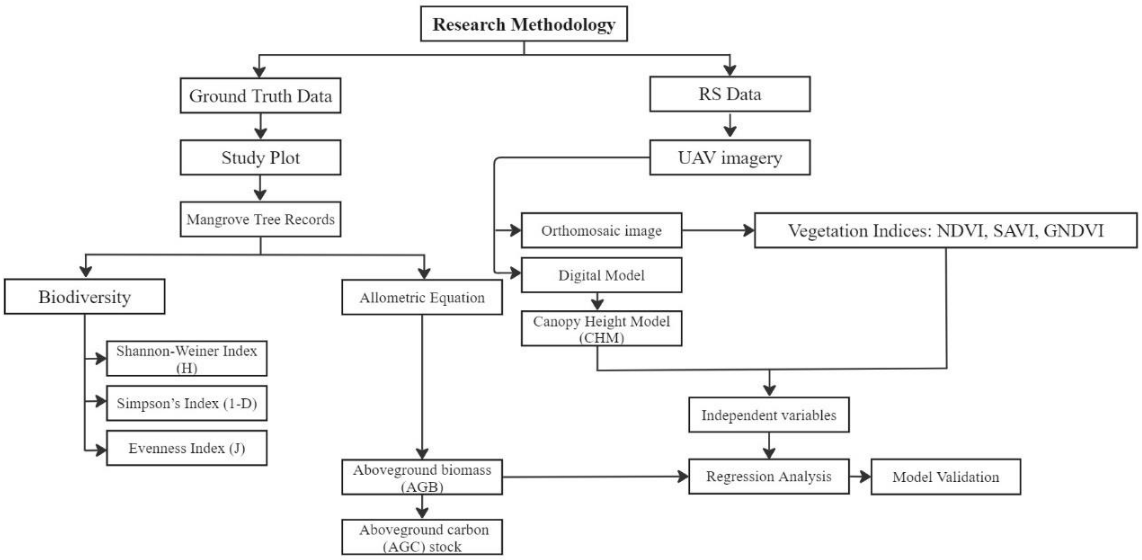

Figure 3.1 Workflow diagram of this study.

3.2 Study Site

The Banlaem mangrove forest, located at coordinates 8°36'32.7" N, 99°57'59.0" E, is situated within the Banlaem community in Moo 7, Tha Sala Subdistrict, Tha Sala District, Nakhon Si Thammarat Province, Southern Thailand, in a tropical region (**Figure 3.2**). The total area of the study site spans 123.5 ha, which is an ecotourism zone. The only species intentionally planted within the Banlaem mangrove forest is *Rhizophora mucronata*. For planting, propagules of *R. mucronata* are placed into the muddy soil, with each propagule spaced 1 to 1.5 meters apart and inserted to a depth of 15 to 20 cm (Minmun, personal communication, June 23, 2024) . However, observations from this study indicated that another species, *Avicennia marina*, dominates the upland areas as an interior species, while *R. mucronata* primarily occupies the peripheral zones as an edge species. In southern Thailand, the average annual rainfall ranges from 1,200 to 4,500 mm, with higher amounts observed on the windward side compared to the leeward side. The mean temperature in this region is 27.5°C (The World Bank Group, 2023)

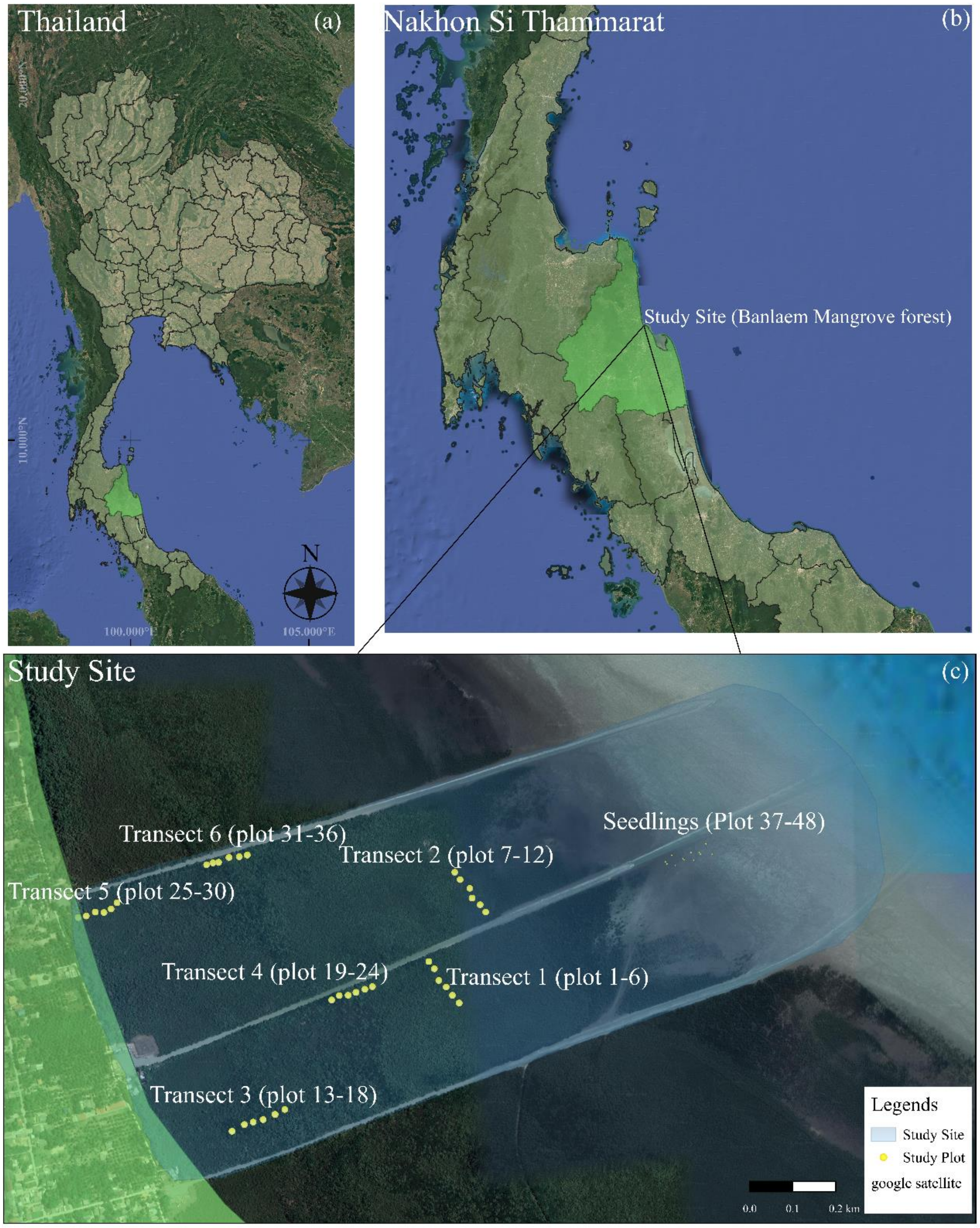

Figure 3.2 Study area in this study: a) Thailand map; b) Nakhon Si Thammarat province, southern Thailand; c) study plot arrangements in the study site (Banlaem mangrove forest).

3.3 Ground Truth Measurements

3.3.1 Data Collection

To assess AGB and AGC stocks within the Banlaem mangrove forest, six-line-transect plot configurations were established. The study was conducted from April 2023 to July 2024, following the plot design protocol outlined by Kauffman and Donato (2012). Each transect consisted of 6 circular plots with a radius of 7 meters (**Figure 3.3**), amounting to 36 plots in total (plots 1–36). Additionally, square plots (1×1 m²) were established to assess mangrove seedlings, identified as plots 37–48. This resulted in a total of 48 sampling plots (**Figure 3.2**). Plot locations and dimensions were constrained due to difficulties accessing the mangrove areas, therefore they were based on collecting in easily accessible areas (Nguyen et al., 2019). In each plot, data were collected on mangrove trees (**Figure 3.5**), including their species, diameter at breast height (DBH), tree height (H), tree density, and basal area (BA). Tree H will be collected with the laser distance meter and the Trees application (Forest Monitoring Tools), and DBH will be measured with the tape measure. The data collection form was designed and applied to record data in the study plots (**Figure 3.4**). Only mangrove individuals with a DBH greater than 5 cm were recorded (Zarawie et al., 2015). Species identification followed the handbook by Trakulsiriphanit (2009) and expert consultation. Data were systematically documented on collection forms, with unique codes assigned to each tree. Stratified random sampling was applied in the Banlaem mangrove forest due to its distinct mangrove tree composition. Stratified random sampling was employed in the Banlaem mangrove forest to account for its heterogeneous composition of mangrove tree species. The strata consisted of three groups: 1) a mixture of grey mangrove (*Avicennia mari*na) and loop-root mangroves (*Rhizophora* spp.), observed in plots 1, 2, 7, 13–22, and 31–36 (a total of 19 plots); 2) homogenous *A. marina*, in plots 3–6, 8–12, and 23–30 (17 plots in total); and 3) predominantly seedlings (with *Rhizophora mucronata* being dominant) in plots 37–48 (12 plots in total). The position of the study plots was recorded using the Geo Tracker application (version 5.3.4.3912).

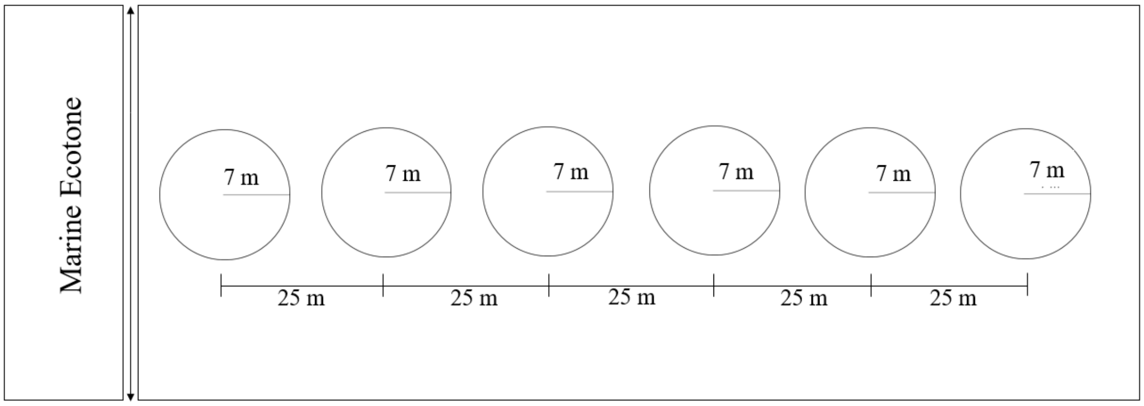

Figure 3.3 The study plot design implemented in the mangrove area (1 line transect).

Data Collection Sheet
Plot Identifier:
Location:
Date:
GPS coordinates and precision (± X m)
Crew Member Present:
Directions to the plot location:
Site Categories: forest, dwarf, scrub, others
Ecological Condition and land use: intact, degraded, deforested
Others:

No	Code	H (m)	Circumference (cm)	DBH (cm)	Latitude	Longitude	Note	Species	X_mamual_m	Y_mamual_m	Direction_manual

Figure 3.4 The ground truth collection form used in this study.

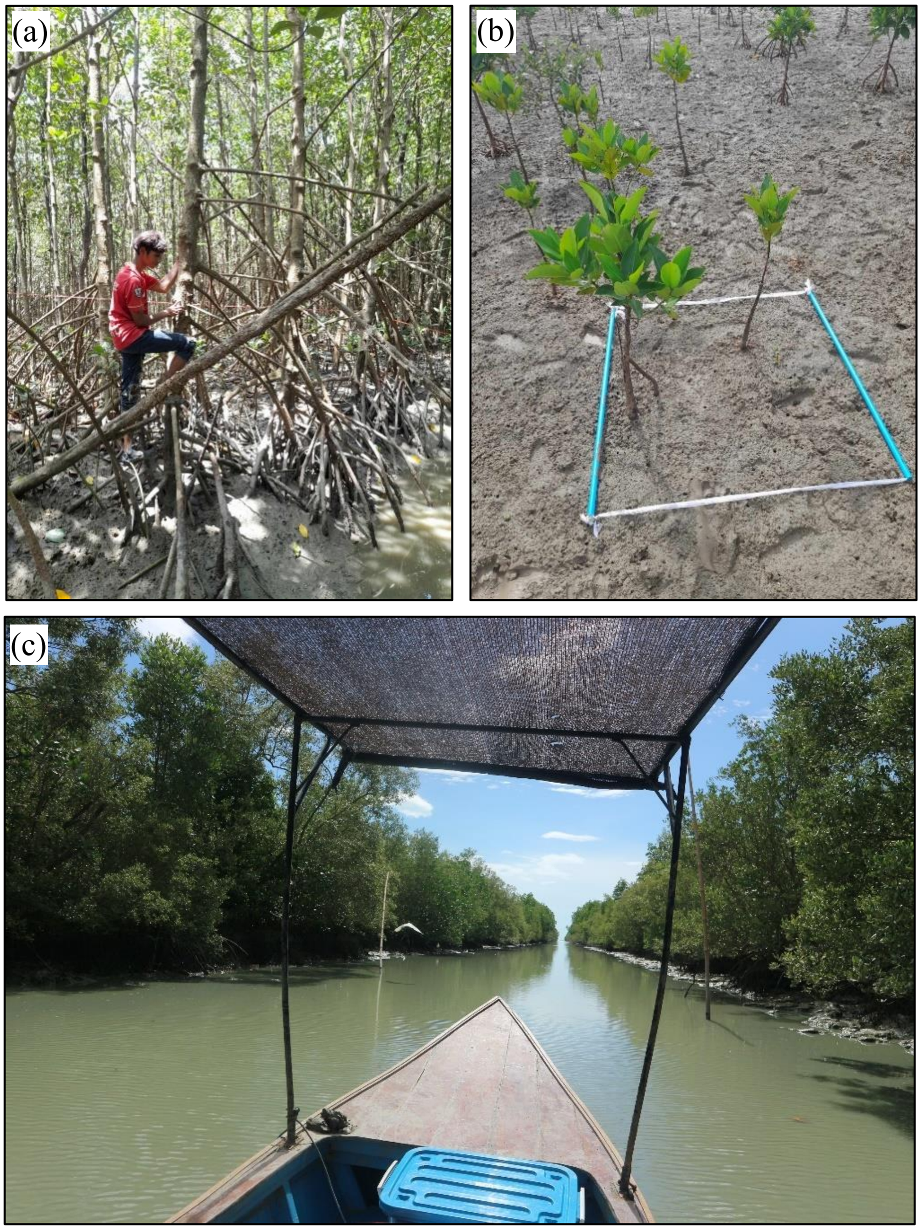

Figure 3.5 Ground truth records in this study: a) Data collection records for mangrove trees; b) Data collection records for mangrove seedlings; c) Transportation to the study plots by boat (used in this study).

Although plot locations and dimensions were constrained due to difficulties accessing the mangrove areas, the transect plot arrangement can capture the variation according to the mangrove ages. Mangrove ages were determined based on thematic classification maps derived from a previous study (Pungpa and Chumkiew, 2025).

The 30 to 28-year-old mangroves were represented by Transect 5 (Plots 25–30), while the 28 to 20-year-old mangroves were captured by Transect 3 (Plots 13–18). The 20 to 14-year-old mangroves were represented by Transect 4 (Plots 19–24) and Transect 6 (Plots 31–36). Transect 1 (Plots 1–6) and Transect 2 (Plots 7–12) captured the 14 to 10-year-old mangroves. Seedlings were represented by Plots 37–48. Overall, the transect plot arrangement in this study effectively captured the variation across mangrove age classes, thereby reducing potential bias in the estimation of the AGB and AGC stocks in the Banlaem mangrove forest.

3.3.2 Aboveground Biomass

The ground truth AGB of the mangroves was estimated using species-specific allometric equations, outlined by Komiyama, Poungparn and Kato (2005). The wood density values (ρ) used in these equations were sourced from the Global Wood Density Database (Zanne, Lopez-Gonzalez, Coomes, Ilic, Jansen, Lewis et al., 2009). The ρ values utilized in this study are presented in **Table 3.1**. Biomass measurements were taken for all individual trees with a DBH greater than 5 cm, as recommended by Zarawie, Suratman, Jaafar, Hasmadi and Abu (2015).

It is calculated using the following formula:

$$\mathrm{AGB\ (kg)} = 0.25 \times \rho\ (\mathrm{g/cm^3}) \times \mathrm{DBH}^{2.46}$$ Komiyama et al. (2005)

Where: AGB = aboveground biomass (kg)

ρ = wood density (g/cm^3)

DBH = diameter at breath height (at 0.3 m above prop root for Rhizophoraceae species)

Table 3.1 The wood density values (ρ) utilized in this study.

Scientific name	ρ (g/cm^3)
A. marina	0.65
R. mucronata	0.82
R. apiculata	0.85

3.3.3 Aboveground Carbon Stock

The AGC stock is estimated to be 50% of the biomass, as indicated by the Intergovernmental Panel on Climate Change (IPCC, 2006). Carbon contributions from understory vegetation, seedlings, and herbs were not included in the assessment due to their negligible impact within a mangrove ecosystem (Kauffman and Donato, 2012; Vinod, Anusu, Kunhikoya, Shilpa, Akosan, Zacharia, and Joski 2018).

3.3.4 Biodiversity

Additionally, this study calculated the diversity indices for mangrove tree species in the Banlaem mangrove forest. Biodiversity was assessed using the Shannon-Wiener Index (*H*) and Simpson's Index (*1-D*). The value of *H* varied among the sampling plots and was influenced by species richness (*S*). The Evenness Index (*J*) was employed to measure species dominance within the community.

The indices were calculated using the following formulas (Shannon, 1948; Simpson, 1949):

$$H = -\sum_{i=1}^{S} p_i \times \ln p_i$$

Where: p_i refers to the proportion of individuals belonging to species i, and $\ln$ represents the natural logarithm. The value of H ranges from 0 to H_{max}, with a higher H indicating increased diversity.

$$D = \sum_{i=1}^{S} \left(\frac{n_i}{N}\right)^2$$

Where: n_i represents the number of individuals of species i, and N is the total number of individuals across all species. The value of $1 - D$ ranges from 0 to 1, where 1 represents infinite diversity, and 0 indicates no diversity.

$$J = \frac{H}{H_{max}}$$

Where: the value of J ranges from 0 to 1, with a lower J value suggesting that one or a few species dominate the study areas.

3.4 Remote Sensing Measurements

3.4.1 UAV Photogrammetry

The study utilized UAV imagery obtained with a DJI Mavic 2 Enterprise Advanced, equipped with both visible and near-infrared (Vis/NIR) cameras. Data collection was carried out during ground truth surveys on April 28, 2023, and July 15, 2024. The UAV flight settings included a frontal overlap of 80%, a side overlap of 70%, and a flight altitude of 90 meters. Pix4Dmapper (version 4.8.4) was used to process the imagery, generating an ortho mosaic, a digital terrain model (DTM), and a digital surface model (DSM). The difference between the DSM and DTM, known as the canopy height model (CHM), was calculated by subtracting the DTM from the DSM. This calculation, which indicates vegetation height above ground level (Nasiri, Darvishsefat, Arefi, Pierrot-Deseilligny, Namiranian, and Le 2021), was performed using Quantum GIS (version 3.34.1-Prizren) via the raster calculator tool. Along with vegetation indices (VIs), the CHM derived from UAV data was included as a variable to develop the AGB model for the Banlaem mangrove forest. The maximum CHM value for each plot was used as an independent variable in the AGB model using the Zonal Statistics Plugin (Quantum GIS). This plugin enables the calculation of various pixel values from a raster layer using a polygonal vector layer as a reference. Thus, the polygons representing the study plots were used as reference areas for the calculations. The workflow is illustrated in **Figure 3.6**.

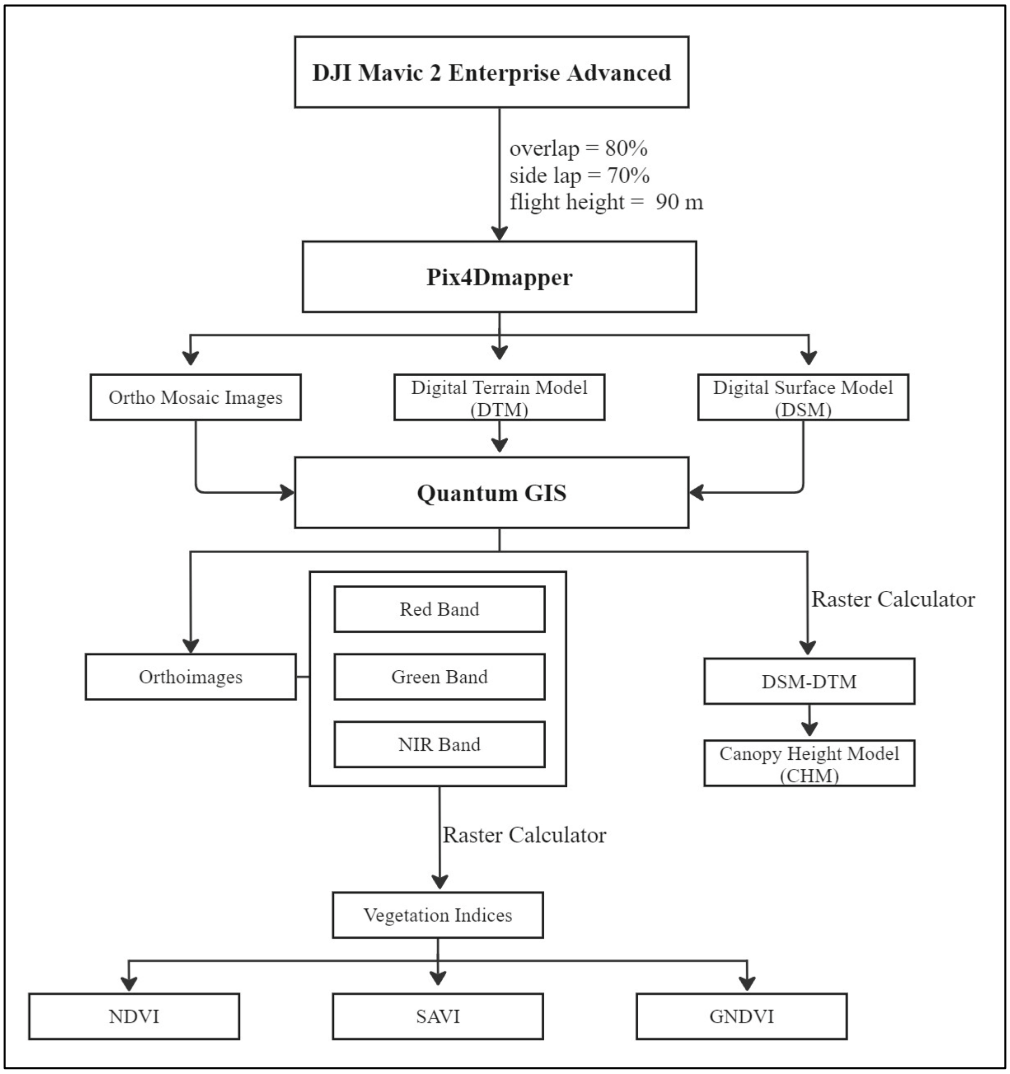

Figure 3.6 Workflow diagram for the remote sensing analysis.

3.4.2 Vegetation Indices

In this study, three different vegetation indices (VIs) were employed to develop AGB models for the Banlaem mangrove forest (**Table 3.2**). The specific VIs examined included NDVI (normalized difference vegetation index), SAVI (soil-adjusted vegetation index), and GNDVI (green normalized difference vegetation index), as referenced by Nguyen et al (2019). The red, green, and near-infrared (NIR) bands from UAV-derived orthoimages were used to compute the VIs. These calculations were carried out using Quantum GIS's raster calculator tool. The average VI values for each plot served as independent variables in the AGB models, with the Zonal Statistics Plugin (Quantum GIS) being used for the final calculations.

This study selected VIs based on their common use. NDVI is a widely used metric in plant studies; however, SAVI and GNDVI were also included to address some of the limitations associated with NDVI. SAVI is used to correct the NDVI for the influence of soil brightness, particularly in areas with low vegetative cover. GNDVI is also used to correct NDVI because it is more sensitive to chlorophyll and better at detecting plant stress and monitoring dense vegetation. NDVI can saturate in high biomass areas, while GNDVI performs better under those conditions. These three VIs, taken collectively, provide a comprehensive representation of mangrove canopy conditions, encompassing dense, typical, and sparse cover types.

Table 3.2 The vegetation indices used in this study.

No.	Vegetation Indices	Equations	References
1	NDVI	$\mathrm{NDVI} = \left(\frac{\mathrm{NIR} - \mathrm{RED}}{\mathrm{NIR} + \mathrm{RED}}\right)$	Zaitunah et al. (2018)
2	SAVI	$\mathrm{SAVI} = \left(\frac{\mathrm{NIR} - \mathrm{RED}}{\mathrm{NIR} + \mathrm{RED} + \mathrm{L}}\right) \times (\mathrm{L} + 1)$	Huete (1988)
3	GNDVI	$\mathrm{GNDVI} = \left(\frac{\mathrm{NIR} - \mathrm{GREEN}}{\mathrm{NIR} + \mathrm{GREEN}}\right)$	Gitelson et al. (1996)

Where: $\mathbf{L}$ represents soil brightness correction factor (0.5), $\mathbf{GREEN}$ represents green wavelength, $\mathbf{RED}$ represents red wavelength, and $\mathbf{NIR}$ represents near-infrared wavelength

3.5 AGB Model Development and Validation

Linear and multiple linear regression models were developed and validated to estimate mangrove AGB using Jamovi (version 2.6.2). A linear regression model was applied when there was a single independent variable, whereas a multiple regression model was used when there were multiple independent variables. Ground truth AGB served as the dependent variable, with the predetermined VIs (NDVI, SAVI, GNDVI) and

CHM used as independent variables for estimating AGB in the Banlaem mangrove forest. Subsequently, the models for ground truth AGB and predicted AGB were developed, validated, and presented in this study. The best model was selected based on the combination of the correlation coefficient (*r*), coefficient of determination (r^2), root mean square error (*RMSE*), probability value (p-value), and its residual plot. In a residual plot, if the residuals are randomly dispersed around zero without any noticeable pattern, it suggests that the model fits well, indicating that the linearity assumption holds true and the errors are both random and normally distributed. However, this study excluded certain plots (plots 13-18) from the AGB model development because the UAV could not access those areas. Additionally, the mangrove seedling plots (plots 37-48) that displayed a pattern in the residual plots were also excluded because their AGBs were considered to be 0 ton/ha, as their DBH was less than 5 cm.

The statistics were calculated using the following formulas:

Correlation coefficient (*r*):

$$r = \frac{\mathrm{n}(\sum \mathrm{xy}) - (\sum \mathrm{x})(\sum \mathrm{y})}{\sqrt{[\mathrm{n}\sum \mathrm{x}^2 - (\sum \mathrm{x})^2][\mathrm{n}\sum \mathrm{y}^2 - (\sum \mathrm{y})^2]}}$$

Where r ranges from -1 to 1, r = 1 is a perfect positive correlation, r =−1 is a perfect negative correlation, r = 0 indicates no linear relationship (Field, 2018).

Coefficient of determination (r^2):

$$r^2 = \frac{\mathrm{SS_{regression}}}{\mathrm{SS_{total}}} = 1 - \frac{\mathrm{SS_{residual}}}{\mathrm{SS_{total}}}$$

Where r^2 ranges from 0 to 1, the higher value, the better fit of model (Upton and Cook, 1996).

p-value: a p-value below the significance level of 0.05 suggests that the results are statistically significant (Wackerly et al., 2008).

Residuals:

$$\mathrm{residual} = \mathrm{y_i} - \mathrm{\hat{y}_i}$$

Residual analysis aids in evaluating model fit; when residuals are random, it indicates that the model is performing well (Kutner, 2005).