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Ecological carbon storage and socioeconomic utilization of *Nypa fruticans* in a mangrove restoration landscape

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ABSTRACT

BACKGROUND AND OBJECTIVES: Mangrove restoration landscapes can provide carbon storage and community resources, but these outcomes are often documented at different observational scales. The nipa palm (*Nypa fruticans*) constitutes an integral component of tropical mangrove ecosystems, featuring foliar structures that facilitate non-destructive biomass estimation alongside sap yields that sustain local community sugar production. The study objectives were to estimate carbon in living nipa fronds and documented community sugar processing at Pasar Rawa Village, Langkat Regency, North Sumatra, while defining the limits of reporting the two records together.

METHODS: Fifty vegetation plots, each 10 × 10 meters (0.50 hectare in total), were surveyed along 11 field transects within a 13.16-hectare landscape. The inventory comprised 2,427 visually distinguishable field units and 13,005 frond measurement entries. To estimate living-frond biomass, frond circumference measured at 130 cm was converted into an equivalent circular diameter and integrated with frond length using a validated species-specific allometric equation. Biomass was converted to carbon using a fraction of 0.47, with fractions of 0.44 and 0.49 applied as conditional sensitivity scenarios. Evidence regarding community utilization was derived from aggregated sap production metrics—specifically comprising records from a women's community demonstration group and a single documented sugar-processing batch—which maintained no spatial or analytical linkage to the vegetation sampling plots.

FINDINGS: Estimated living-frond biomass averaged 30.24 megagram per hectare (standard deviation 10.90 megagram per hectare; median 28.66 and range 7.12–49.74 megagram per hectare; coefficient of variation 36.0 percent), equivalent to 14.21 megagram carbon per hectare. Standing-stock carbon dioxide equivalent was quantified at 52.11, representing an accumulated carbon pool rather than an annual removal rate**.** Conditional carbon fractions of 0.44 and 0.49 gave 13.31 and 14.82 megagram carbon per hectare. A ten-member women's group reported approximately 25 liters of sap per day from about 25 tapped palms, while one 25-liter batch yielded approximately 5 kilograms of molded sugar (0.20 kilogram per liter). These observations did not establish per-palm yield dynamics, economic gains, restoration-attributable carbon sequestration, or the physiological impacts of sap tapping on frond biomass.

CONCLUSION: Living-frond carbon stocks and pilot-scale community production were documented at their respective observation scales. A proposed dual-value monitoring matrix delineates the paired and recurring ecological and production metrics required to evaluate restoration trajectories, harvesting impacts, and socioeconomic benefits in future investigations.

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INTRODUCTION

Mangroves are an important blue carbon ecosystem because they store carbon in plant biomass and, especially, in the soil, while also providing coastal protection, habitat for biota, food sources, and livelihoods for coastal communities. While substantial mangrove carbon densities have been documented across diverse tropical regions, the magnitude of these stocks is rigorously governed by vegetation composition, geomorphology, hydrology, land-use history, and the specific carbon pool quantified (Donato *et al*., 2011; Friess *et al*., 2019; Macreadie *et al*., 2021). Global mapping also shows that changes in mangrove area are ongoing, so conservation, restoration, and long-term monitoring remain priorities for coastal management (Bunting *et al*., 2022). Mangrove restoration can restore vegetation structure, ecosystem function, and carbon stocks, but outcomes differ among sites. Restoration may improve ecosystem functions relative to unvegetated areas without necessarily reaching the condition of natural mangroves (Su *et al*., 2021). Reforestation can also provide different carbon benefits than afforestation (Song *et al*., 2023), while restoration stands with higher species diversity tend to store more carbon than monospecific stands under certain conditions (Li *et al*., 2025). In Indonesia, carbon assessments need to consider the magnitude of soil carbon contributions and the uncertainty of emission factors (Murdiyarso *et al*., 2023; Soeprobowati *et al*., 2024). Consequently, the carbon stock residing within an isolated plant component cannot be extrapolated to represent total ecosystem carbon storage or annual sequestration dynamics. At the regional scale, assessments of Southeast Asian land-use emissions similarly underscore the critical role of mangrove conservation and restoration in climate change mitigation planning (Sasmito *et al*., 2025). A characteristic component of many tropical mangrove landscapes is the nipa palm (*Nypa fruticans* Wurmb). Characterized by creeping subterranean stems and rhizomes alongside an emergent frond canopy, *Nypa fruticans* delivers significant provisioning ecosystem services, derived from its sap, fruit, and foliage, in addition to its primary ecological functions. A recent review showed that nipa palm utilization in tropical regions includes natural stands, nipa palm gardens, nipa palm-aquaculture systems, and nipa palm-agriculture, with potential contributions to food, raw materials, and coastal income (Rahman *et al*., 2024a). In Thailand, nipa palm product development has long been associated with sustainable use (Cheablam and Chanklap, 2020), while in Bangladesh, nipa palm collection can be an alternative source of income for coastal households (Hossain *et al*., 2024). From a biogeophysical perspective, specific allometric equations for *N. fruticans* allow for non-destructive estimation of frond biomass. Matsui *et al*. (2014) developed a relationship between frond diameter at a height of 130 centimeters (cm), frond length, and dry weight. Recent research on *N. fruticans*-dominated stands in West Sumatra also demonstrated the species' significant contribution to coastal biomass and carbon stocks, but comparisons between locations must consider differences in stand structure, carbon pools, allometric equations, and sampling design (Fikri *et al*., 2026). Existing literature concerning nipa palm management similarly delineates key ecological and provisioning functions, which necessitate quantification through appropriate observational units (Rahman *et al*., 2024a). A persistent shortcoming in applied restoration monitoring is the lack of standardized frameworks for integrating ecological and local-use observations without conflating their disparate measurement units and evidentiary boundaries. Reporting of mangrove restoration projects remains more consistent for ecological interventions and indicators than for baseline conditions and socio-economic outcomes (Gatt *et al*., 2022). Studies in North Sumatra and Aceh have shown that functional indicators such as macrobenthic communities can strengthen restoration

evaluations and support community-based adaptive management (Basyuni *et al*., 2022). Evidence from West Kalimantan also shows that community-based rehabilitation can result in measurable growth of tree stands and carbon stocks (Astiani *et al*., 2024). Recent literature further emphasizes the need to incorporate social indicators, stakeholder values, and ecosystem function into restoration evaluations (Grimm *et al*., 2025; Rodríguez-Rodríguez *et al*., 2025; Janna *et al*., 2026). At Pasar Rawa, existing records of nipa fronds and community sugar processing had not been evaluated together using clearly separated units of observation. Accordingly, this study establishes Pasar Rawa as a representative case study of a mangrove restoration landscape characterized by *Nypa fruticans* stands and community-based nipa palm sugar production enterprises. Specifically, this study aims to: 1) characterize stand structural attributes and quantify live frond biomass and carbon stocks; 2) document nipa-sugar production at the group and batch scales; and 3) establish a dual-value monitoring framework that preserves distinct evidentiary limits of inference. The contribution is a case-derived proposal for keeping plant components, observation units and levels of inference distinct while documenting both pathways. It is not presented as a field-validated measurement, reporting, and verification (MRV) protocol or as evidence of a causal relationship between carbon and sap harvesting. The vegetation inventory was conducted in Pasar Rawa Village, Langkat Regency, North Sumatra in 2024.

MATERIALS AND METHODS

Research location and restoration interpretation boundaries

The study area is located in Pasar Rawa Village, Gebang District, Langkat Regency, North Sumatra (Fig. 1). The 13.16-hectare (ha) research polygon was delineated using satellite imagery and Google Earth Engine (GEE) and verified in the field. The polygon is stored in the geographic coordinate system, World Geodetic System 1984 (WGS 1984) (EPSG: 4326). The study site occupies a tidally influenced riverine zone characterized by brackish hydrology and an unconsolidated muddy substrate. The available data do not include stand age, planting year, or the origin of each nipah palm unit, whether it was planted or regenerated naturally. Therefore, the term "restoration landscape" is used to refer to the management context of Pasar Rawa and does not imply that each sampled *N. fruticans* unit originated from planting. Stand age was not used as an explanatory variable.

Sampling design and measurement of stand structure

Fifty 10 × 10 meter (m) plots were established across 11 field transects within the research polygon. Transect routes were aligned with site accessibility and vegetation patterns; survey protocols dictated that the origin of each transect was determined randomly, subsequent to which sampling plots were established at approximately systematic 10-m intervals. This is more accurately described as a field-adapted transect design with randomized starts than as a fully randomized, equal-probability sample of the entire polygon. The measured area was 5,000 square meters (m^2), with 0.50 ha, approximately 3.8 percent (%) of the delineated landscape. Because fine-scale habitat representation, inclusion probabilities and spatial autocorrelation could not be decoupled from the prevailing plot layout, resulting estimates are interpreted strictly within the context of the sampled plots. A coordinate-based assessment of plot-edge overlap was not available, and the plots are not assumed to be spatially independent. Operationally, each field sampling unit within a plot was defined as a visually distinguishable above-surface *Nypa* growth unit, designated by a unique plot–unit identifier (ID). Fronds arising from the same visibly identifiable unit were assigned to that unit. Because the sampling

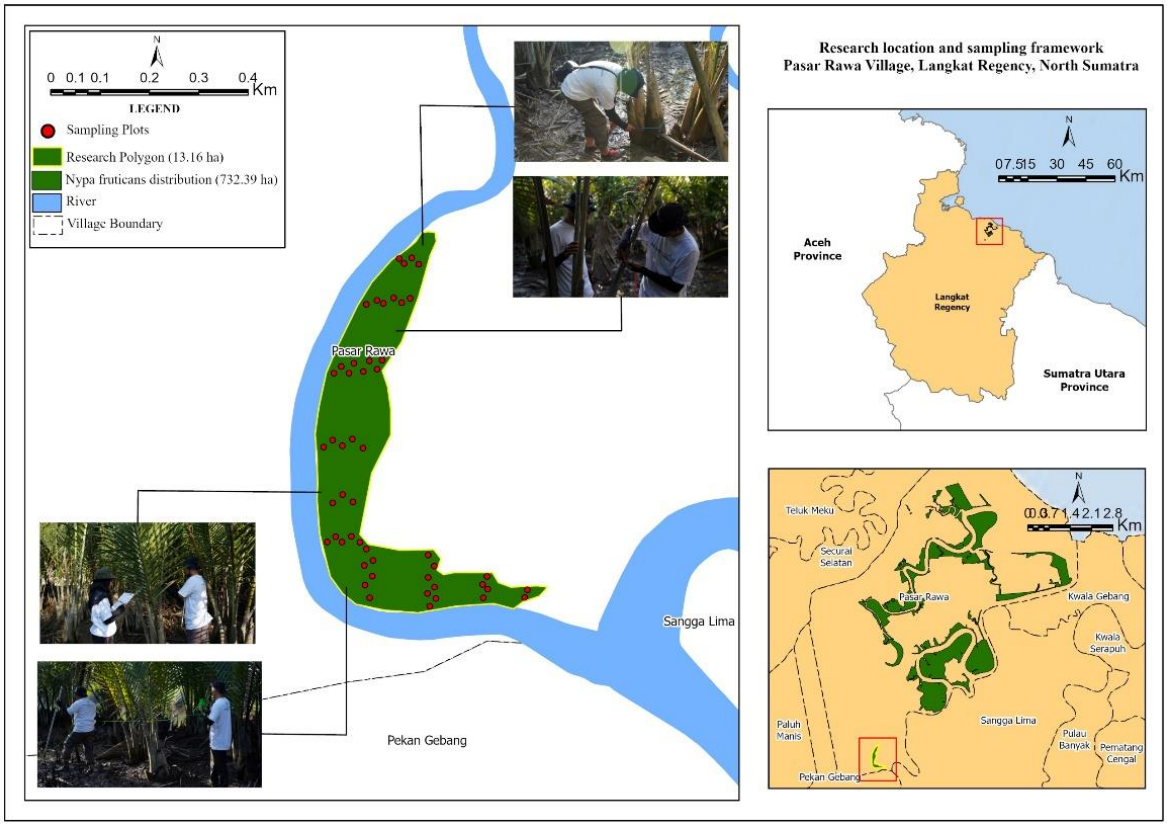

Fig. 1: Geographical location of the study area along with the sampling framework in Pasar Rawa Village, Langkat Regency, North Sumatra (The 13.16-ha research polygon contains 50 measurement plots with a total sample area of 0.50 ha)

protocol did not involve rhizome excavation or the mapping of genet boundaries, individual field units do not equate to genetically independent plants. The numbered transect–plot–unit records provide an internal inventory key, but they do not establish independence of rhizome-connected units or the absence of all boundary effects. Consequently, field-unit density must not be compared directly with genet, ramet or clump density reported under different definitions. For each unit, the number of living fronds and circumference (C, cm) at 130 cm above the substrate were recorded. Circumference was converted to the diameter of a circle with the same circumference, equivalent circular diameter at 130 cm (D130,eq) (D130,eq) = C/π, cm). Because this equivalent circular diameter functions as a geometric proxy rather than a directly validated circular rachis diameter, deviations from perfect circularity may introduce variability into the predictor. Frond length was measured from base to tip where available. When multiple length readings existed for one field unit, their mean was used for that unit in the calculation. Consequently, individual frond-diameter measurements were not consistently paired with independently recorded length values for every frond, an inherent source of methodological uncertainty that persists throughout the biomass estimation analyses (Table 1). This limitation should be considered when interpreting estimated biomass values and comparing results across field units and sampling locations. This constraint may also influence the representation of within-unit morphological variability in subsequent biomass calculations.

Table 1: Research question framework, data sources, indicators, and inference limits

Question	Data source	Key indicators	Inference limits
How were *Nypa fruticans* field units and fronds enumerated?	50 vegetation plots (0.50 ha)	Field-unit density; frond count, length and D130,eq	Sampled plots only; units are not identified genets
How much carbon is estimated in living fronds?	Recorded living-frond measurements	Live-frond aboveground biomass (AGB) and carbon stock	Not belowground or total ecosystem carbon; no temporal change
What community processing was documented?	One demonstration group and batch	Group sap record; kilogram (kg) sugar/batch; observed batch ratio	Not yield per palm, village income or profits
Can frond carbon and sap use be linked?	Two presently unlinked data streams	No statistical linkage tested	Requires matched palm ID and time series

Estimation of frond biomass and carbon stock

Dry mass of living fronds was estimated using the *Nypa fruticans* equation reported by Matsui *et al*. (2014), fitted to ten destructively measured fronds in southern Thailand (reported coefficient of determination (R^2) = 0.94 for total-frond mass). The regression was transferred to Pasar Rawa without local destructive calibration. Eq. 1 expresses the published fitted relationship; Eq. 2 defines the field circumference conversion, while Eqs. 3–4 provide accounting conversions, using Eqs. 1 to 4 (Matsui *et al*., 2014):

$$\log_{10}; \text{dry weight (DW)} = 0.85 \times \log_{10}(D130^2 L) + 1.54 \quad (1)$$

$$D130,eq = C/\pi \quad (2)$$

$$\text{Above-ground carbon (AGC)} = AGB \times 0.47 \quad (3)$$

$$\text{Carbon dioxide equivalent } (CO_2eq) \text{ mass of standing frond carbon} = AGC \times (44/12) \quad (4)$$

In Eq. 1, DW is estimated dry weight of a whole living frond gram (g), diameter at a height of 130 cm (D130) is entered in centimetres as an equivalent circular diameter at 130 cm, and L is entered in metres. Estimates were back-transformed from base-10 logarithms, converted to kg, summed across recorded fronds and scaled from each 0.01-ha plot to megagram per hectare (Mg/ha). The fitted equation corresponds to DW = 10^1.54 × D130^1.70 × L^0.85; it therefore responds nonlinearly to measurement and length-assignment errors. The species-specific source fit is not a local validation and does not provide a Pasar Rawa prediction interval. Quantifying model-transfer bias necessitates the acquisition of a locally harvested calibration subset. Frond carbon was estimated as AGB × 0.47 using a general Intergovernmental Panel on Climate Change (IPCC) default for aboveground forest biomass (IPCC, 2006), rather than a measured nipa-frond carbon fraction. The 44/12 conversion expresses the molecular-mass equivalent of standing carbon; it is not annual sequestration, net CO_2 removal or a basis for carbon credits. Only positive recorded circumference values are eligible for direct application of Eq. 1 in logarithmic form; an entry with circumference (C = 0) cannot be log-transformed. To evaluate how analytical assumptions influence interpretation independently of the observed plot inventory, conditional sensitivity analyses were performed at the reported mean biomass of 30.24 Mg/ha. Alternative general tropical/subtropical biomass carbon fractions of 0.44 and 0.49 (IPCC, 2006) give 13.31 and 14.82 megagram carbon per hectare (Mg C/ha), compared with 14.21 Mg C/ha at 0.47. Given the exponent of 1.70, changing all equivalent diameter inputs by ±10%, with other quantities held constant, changes predicted frond biomass by approximately −16.4% or +17.6%. The ±10% scenarios represent hypothetical measurement-perturbation tests rather than quantified local diameter errors. Because these sensitivity checks do not account for transferred-model residual variance or field-sampling uncertainty, they must not be mischaracterized as confidence interval. Results indicate directional sensitivity rather than statistically established biomass uncertainty.

Tapping palm sap and sugar processing

The community utilization component comes from a demonstration group of women who previously received training in nipa palm tapping and processing. Available records encompass group membership size, the tally of tapped trees, typical daily group-level sap yield, and a single documented processing batch; consequently, these datasets are treated as pilot-scale production metrics rather than reproducible experimental trials. The sap was collected from the reproductive stalks, then heated and concentrated to form a sugar syrup. Records were collected at the group and batch levels. Data on individual tree identities, tapping duration per tree, repeated measurements across seasons, chemical composition of each batch, energy input, production costs, selling prices, or household income were not available. Freshly harvested sap is susceptible to rapid biochemical degradation, while its compositional profile exhibits pronounced sensitivity to localized environmental parameters, including salinity (Saelee, 2022; Athirah *et al.,* 2025). The inventory measurements were undertaken on 8–11 March 2024, whereas the available processing record does not provide a comparable dated, replicated observation period. The tapped palms were not paired by permanent identifier with the vegetation plots. These group, and batch-level datasets preclude direct estimation of individual palm sap productivity or the physiological alterations in frond biomass resulting from sap extraction.

Data quality control and analysis

Data cleaning compared the number of fronds in the summary column with the number of filled frond circumference entries. Of the 2,427 field unit records, 60 showed discrepancies: 53 differed by one frond and seven differed by 2–4 fronds. For inventory reporting purposes, populated circumference cells were tabulated as recorded frond entries. Direct application of the logarithmic allometric equation was constrained to entries characterized by positive circumference values. The dataset contained 13,005 populated frond-circumference entries, including 13,004 positive values and one entry recorded as 0 cm, whereas the summary count column totaled 12,948 fronds; the net count difference was 57. Although digitized records facilitate the identification of discrepancies, this audit alone cannot verify individual handwritten field entries; consequently, the primary analysis remains strictly descriptive. Field unit and frond density were calculated per hectare. AGB was summarized using the mean, median, standard deviation (SD), coefficient of variation (CV), quartiles, minimum, and maximum. The relationship between frond density and AGB was excluded from inferential consideration because both metrics were derived from the same structural frond, violating the assumption of mathematical independence. The R^2 value of 0.956 from the initial analysis was treated only as an internal diagnostic of the data structure. No hypothesis testing was conducted linking AGB to palm sap production. Rather than being assigned an artificial positive diameter or subjected to logarithmic transformation, the 0-cm entry is retained as an unresolved measurement flag pending verification against original field logs; consequently, the inclusion of this populated cell in the inventory does not imply a contribution to positive modelled biomass value. The 60 discrepant field-unit records should not be confused with the net difference of 57 fronds between the summary and measurement columns; the count comparison alone cannot independently confirm every original field entry. The 50 plot estimates were used to describe the sampled distribution. Because plots followed field-adapted transects, no confidence interval assuming independent, equal-probability sampling of the entire 13.16-ha polygon is reported. Potential within-transect spatial dependence remains unresolved. Biomass was calculated by aggregating positive-predictor frond-level allometric estimates, rather than multiplying an average frond mass by the separate

summary-count field (Ketaren *et al.,* 2026). Consequently, a discrepancy in that summary-count field alone does not invalidate calculations derived from positively recorded measurements, however, auditing disputed source records remains necessary to ascertain whether individual entries were duplicated or erroneously transcribed. The primary mean biomass and carbon results remain 30.24 Mg/ha and 14.21 Mg C/ha, respectively; neither is claimed to be a locally validated estimate (Fadilah *et al.,* 2026; Utomo *et al.,* 2026).

RESULTS AND DISCUSSION

Nypa fruticans stand structure

The fifty 0.01-ha plots contained 2,427 distinguishable field units and 13,005 recorded living-frond measurement entries. Across the 0.50-ha sampled area, these correspond to descriptive densities of 4,854 field units/ha and 26,010 fronds/ha, with 5.36 fronds per field unit on average (range 2–9). Recorded frond length averaged 4.06 m (range 1.60–6.50 m), and the equivalent circular diameter at 130 cm averaged 3.81 cm (range 2.12–7.48 cm among valid positive values (Table 2). These are inventory descriptors, not a count of independent genetic individuals or an area-wide census of the entire 13.16-ha polygon. Although no alternative mangrove species were documented within the biomass plots, this restriction does not preclude their occurrence beyond the sampled plots. Of the populated circumference cells, 13,004 had positive recorded values suitable for direct allometric evaluation; the single 0-cm entry is reported as a quality-control exception, not imputed as a measured diameter. The density of 4,854 field units/ha refers only to visually separated inventory units. Rhizome connections were not determined, so the unit count is neither a count of genets nor directly comparable with studies enumerating palms, clumps or ramets. Because both frond count and dimensions were incorporated directly into the allometric aggregation; stand density alone was not employed as a proxy for measured frond architecture.

Biomass and carbon stocks of living fronds

The summed model-based dry mass of living fronds in the 0.50-ha plot sample was approximately 15.12 megagrams (Mg), giving a mean plot-scaled estimate of 30.24 Mg/ha. Across the 50 plots, the standard deviation was 10.90 Mg/ha, median 28.66 Mg/ha, interquartile range (IQR) 23.34–37.37 Mg/ha, range 7.12–49.74 Mg/ha and CV 36.0% (Fig. 2). Although these values summarize dispersion across sampled plots; the CV fails to isolate ecological variance from measurement errors in diameter and length or uncertainties inherent to transferred models; consequently, applying a carbon fraction of 0.47 yielded a live-frond carbon stock of 14.21 Mg C/ha (Table 3). As a supplementary mass conversion, that stock is equivalent to 52.11 megagrams of carbon dioxide equivalent per hectare (Mg CO_2eq/ha**)**, on a molecular-mass basis, not a rate of uptake or additional carbon removal. The estimated living-frond biomass of 30.24 Mg/ha is close in magnitude to the approximately 32 Mg/ha average reported by Matsui *et al*. (2014) for nipa farms other than their highest-biomass site, while biomass reported from the Mandeh area, West Sumatra was higher (Fikri *et al*., 2026). This comparison is contextual, as differences in biomass definitions, stand structures, allometry, vegetation, and sampling designs preclude direct inter-site benchmarking. The AGC value of 14.21 Mg C/ha in this study represents only the carbon content of living fronds. This value represents a fraction of the total ecosystem carbon stock, which in mangroves environments encompasses aboveground and belowground biomass, dead organic matter, litter, and predominantly soil carbon. In Indonesian mangrove, sediment constitutes a major proportion of this carbon reservoir (Murdiyarso *et al*., 2023; Soeprobowati *et al*., 2024). Therefore, 52.11 Mg CO_2eq/ha should not be treated as potential annual carbon sequestration or carbon credits.

Table 2: Structural attributes *of Nypa fruticans stands* in 50 plots

Attribute	Mark	Range/description
Number of plots	50	10 × 10 m per plot
Sample area	0.50 ha	0.50 ha (3.8% of polygon; sampled area only)
N. fruticans field unit	2,427	4,854 visually distinguishable field units/ha
Recorded frond entries	13,005	26,010 recorded frond entries/ha; one zero circumference flagged
Living fronds per field unit	5.36	5.36 fronds per field unit; range 2–9
Frond length (m)	4.06	Mean recorded frond length: 4.06 m; range 1.60–6.50
D130 equivalent (cm)	3.81	Equivalent circular D130: 3.81 cm; positive range 2.12–7.48

Table 3: Summary of biomass and carbon of living fronds *of Nypa fruticans*

Indicator	Mark	Interpretation
Total AGB at 0.50 ha	15.12 megagram (Mg)	The amount of live leaf biomass in all plots
Average AGB	30.24 Mg/ha	Arithmetic average of plot estimates; living fronds only
Median AGB	28.66 Mg/ha	Median of the plot-level biomass distribution
Standard deviation (SD)/ coefficient of variation (CV) AGB	10.90 Mg/ha / 36.0%	Descriptive among-plot dispersion; no spatial adjustment
IQR AGB	23.34–37.37 Mg/ha	25–75% quartile
AGB range	7.12–49.74 Mg/ha	Minimum–maximum plot
AGC	14.21 Mg C/ha	Biomass × 0.47 (generic IPCC conversion)
Standing-stock CO_2-equivalent mass	52.11 Mg CO_2eq/ha	CO_2-equivalent mass of standing frond carbon; not removal
Sensitivity: carbon fraction 0.44	13.31 Mg C/ha	Conditional conversion-factor scenario at fixed AGB, not a confidence interval
Sensitivity: carbon fraction 0.49	14.82 Mg C/ha	Conditional conversion-factor scenario at fixed AGB, not a confidence interval

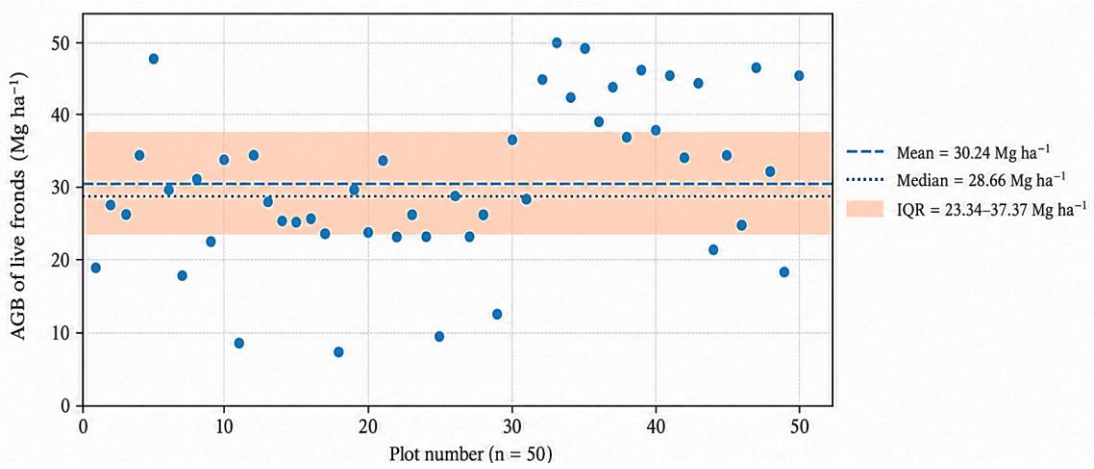

Fig. 2: Distribution of estimated living-frond biomass among 50 plots. Horizontal reference lines mark the mean and median; the shaded band indicates the IQR

Climate mitigation claims require measurements of stock changes, baselines, uncertainty, permanence, leakage, and other components of MRV. Although the interplot CV of 36.0% summarizes dispersion among the estimated plot values, it fails to partition genuine ecological variability from uncertainties associated with frond-length assignment, diameter proxy error, or allometric model-transfer. Microtopography, hydrodynamics, elevation relative to tide, salinity and sediment supply are plausible influences on nipa stand growth, rather than observed drivers in the present dataset. Recent modeling indicates that restoration placement and planting

configuration significantly influence sediment deposition patterns and carbon stock capacity (Beselly *et al.*, 2025). Because hydrological parameters were not measured per plot in Pasar Rawa, factors controlling AGB variation have not been identified. At a fixed mean AGB of 30.24 Mg/ha, using hypothetical carbon fractions of 0.44 and 0.49 yields 13.31 and 14.82 Mg C/ha, respectively, compared with the reported 14.21 Mg C/ha at 0.47. A uniform ±10% change to the equivalent diameter predictor would alter the modelled frond dry mass by approximately −16.4% or +17.6%, holding other variables constant. These conditional checks serve to illustrate predictor and carbon-conversion sensitivity rather tan site-validated allometric uncertainty or formal confidence interval; consequently, the reported carbon stock remains the primary estimate.

Production of palm sap and sugar on a pilot scale

The demonstration group consisted of 10 women. Group records indicate that approximately 25 nipa palms were tapped, producing approximately 25 liter (L) of sap per day during the follow-up period. One documented batch used approximately 25 L of sap and produced approximately 5 kg of molded sugar, equivalent to a ratio of 0.20 kilograms sugar per liter sap (kg/L) or 5.0 L sap/kg sugar (Table 4). Because these figures reflect operational metrics restricted to a single group and processing batch, they cannot be extrapolated to infer mean productivity per tree, aggregate village-level output, household income, or enterprise profitability (Fig. 3). The approximate 25 L/day value reflects the group record rather than a repeated, standardized palm-level yield series. The tapped palms may differ in tapping duration or collection effort, so dividing this volume by 25 palms would not establish a reliable yield per palm per day. A batch rate of 0.20 kg/L describes the documented processing batch, but actual productivity can vary depending on the crop, stalk age, season, salinity, rainfall, tapping frequency and technique, and post-harvest handling. Saelee (2022) showed that soil salinity can affect the nutrient composition of sap, while Athirah *et al.* (2025) showed that preservation methods affect the physical, chemical, and microbiological properties of sap. Consequently, subsequent production monitoring protocols should incorporate Brix, potential of hydrogen (pH), collection timestamp, elapsed duration prior to processing, and seasonal repeatability assessments. Evidence from Bangladesh suggests that nipa palm sap collection can contribute to household income and dietary diversity (Hossain *et al.,* 2024), but socioeconomic benefits depend on market access, infrastructure, institutions, and benefit distribution. The Pasar Rawa study did not measure prices, energy costs, labor hours, opportunity costs, process losses, or income streams. Although women's group participation constitutes a significant social context, it cannot be construed as empirical evidence of empowerment owing to the absence of baseline data, decision-making metrics, benefit sharing mechanisms, or documented shifts in workload.

Multiple values and separation of observation units

The proposed conceptual contribution of this case study is the explicit separation of two recorded pathways. AGB and carbon are calculated from standing live fronds, while sugar is produced from sap derived from reproductive stalks. Isolating these accounting components prevents the conflation of standing frond biomass with harvested sap into a single material pool; however, this division does not establish physiological autonomy, as tapping activities may still influence growth trajectories, reproductive output, or carbon allocation patterns within individual. Matsui *et al*. (2014) demonstrated that biomass and site conditions can be related to sap production in nipa palm cultivation systems. The Pasar Rawa dataset was not designed to test this relationship because tapping trees lack an identity linked to vegetation plots.

Table 4: Records of *Nypa fruticans* sugar-juice production at group and batch scale

Indicator	Carrying value	Limits of interpretation
Demonstration group	10 women	One group of training recipients
Reported tapped palms	≈25 trees	Number reported by group
Collected sap	≈25 L/day	Approximate group record; monitoring days not established
Molded sugar	≈5 kg per batch	One documented processing batch
Observed batch ratio	0.20 kg sugar/L sap	Single-batch arithmetic ratio, not general efficiency
Reciprocal of the ratio	5.0 L/kg sugar	Derived from the same single batch



Fig. 3: Nipah palm sugar production flow in Pasar Rawa: (a) cutting the reproductive stalk, (b) collecting the sap, (c) heating and thickening, and (d) molding the sugar. The documentation represents the batch-scale production flow and not plot biomass measurements

Consequently, conclusions are restricted to the documented coexistence of both forms of value and do not extend to assertions of carbon-production synergies or the absence of trade-offs. This disciplined inference is crucial to ensure that the integration of social and ecological indicators does not result in generalizations that go beyond the research design. This conceptual framework aligns with the existing literature recognizing the nipah palm as a provider of both regulatory and provisioning ecosystem services (Rahman *et al*., 2024a). At a broader restoration scale, community involvement is also crucial for maintaining the sustainability of ecological and social benefits (Kusumadewi *et al*., 2024; Sathiyamoorthy and Sakurai, 2024). Evaluations of community-based restoration in Indonesia have shown that stand growth and carbon stocks can be measured alongside local management processes, but both need to be monitored with appropriate indicators (Astiani *et al*., 2024).

Implications for socio-ecological monitoring and MRV

Mangrove restoration monitoring is evolving from simple structural indicators to more integrated indicators of ecosystem and social functions (Table 5). Gatt *et al*. (2022) demonstrated uneven reporting of indicators across projects, while Janna *et al*. (2026) found

Table 5: Proposed monitoring matrix derived from the Pasar Rawa case study (recommended measurements, not a validated MRV framework)

Domain	Current data status	Recommended minimum additions	Analytical output
Structure and biomass	50 plots; frond counts, length and D130,eq	Permanent plot–unit ID; measured frond predictors; repeat at least annually for multiple years	Frond stock trajectories, measurement and model uncertainty
Ecosystem carbon	Living leaf carbon	Belowground biomass, soils by depth, bulk density, litter and dead pools; repeated inventories	More complete carbon-pool coverage and stock changes
Hydrology and site	Qualitative description	Paired elevation, inundation, salinity, sediment and hydrological logs	Potential spatial controls subject to analysis
Tapping and production	≈25 trees; ≈25 L/day; one batch	Tagged tapped palms; per-palm daily volumes, effort, seasonal repeats for ≥1 annual cycle; quality and batch codes	Yield variability; tests of relationships only when matched
Economy	Not yet measured	Labor, fuel, equipment, material, prices, sales and transport over repeated batches	Observed costs, revenue and net returns
Social and gender equality, disability, and social inclusion (GEDSI)	10 women in one group	Participants, decisions, benefits, workload, household baseline and follow-up	Distribution and change in social outcomes
Integration	Two unlinked datasets	Shared georeferenced palm IDs, dates, matched tapped/untapped reference groups	Hypothesis tests for trade-offs with suitable controls

that carbon was one of the most frequently used functional indicators, while socio-cultural dimensions and a number of ecological processes were underrepresented. For Pasar Rawa, further monitoring frameworks could be structured into two distinct yet spatially and temporally integrated data modules, a carbon-ecology module and a livelihood-use module, with the proposed matrix delineating the requisite measurements and linkages for subsequent evaluation. It is a research-oriented monitoring proposal derived from this case study, not an empirically validated MRV system or a demonstration of livelihood impact. For climate mitigation claims, the system must distinguish stocks from fluxes, incorporate baselines and uncertainties, and consider permanence and land-use change in accordance with inventory principles (IPCC, 2019). Comprehensive mangrove carbon assessments additionally require pool-specific measurements and transparent protocols (Kauffman and Donato, 2012). When restoration management is the primary objective, longitudinal monitoring of permanent plots, hydrological metrics, and socio-economic indicators yields superior managerial utility compared to the mere conversion of biomass stocks to CO_2eq. A cohesive framework is likewise imperative to underpin Indonesia's blue carbon management, seamlessly integrating climate mitigation with local community well-being (Rahman *et al.,* 2024b). A practical future protocol would remeasure the same vegetation plots at least annually across multiple years, record palm-linked sap collection repeatedly across wet and dry periods for at least one full seasonal cycle, and summarize costs and participation over comparable periods. These values represent proposed starting frequencies rather than thresholds empirically validated by this study; the minimum duration needed to detect a statistically meaningful trend depends on observed variability, temporal autocorrelation and the expected effect size. Evaluating restoration efficacy necessitates historical baselines or appropriate reference sites, whereas assessing ecological–economic trade-offs would require paired tapped and untapped units coupled with quantified harvesting intensity. Full carbon MRV would additionally require soil and belowground pools, changes in stocks, model uncertainty and safeguards on permanence and attribution.

Study limitations and research agenda

The first limitation is that the carbon coverage only includes living fronds; soil carbon, roots/rhizomes, litter, dead matter, and reproductive structures were not measured. Second, the allometric equations were derived

from other locations and were not destructively calibrated at Pasar Rawa. Furthermore, diameter was calculated from circumference under the assumption of a circular cross-section, whereas frond length was incorporated as a mean value per field unit. Third, transect-based plot placement and possible spatial dependence limit the defensibility of landscape-wide precision claims, while stand age and unit origin, whether from planting or natural regeneration, could not be verified, making the dataset unsuitable for age-based restoration trajectory analysis. The fourth limitation is the absence of plot-level hydrological and physicochemical measurements precluded any direct testing of the environmental drivers underlying biomass heterogeneity. Fifth, the nipa sugar-processing data came from only one group and one documented batch, with no replication across seasons, groups, or individual trees. Sixth, the carbon and production data were not linked to the same tree unit or plot. Ultimately, the absence of data concerning costs, prices, labor, income, and social indicators constrains the interpretation of economic benefits and empowerment; however, these constraints do not invalidate the dataset's foundational utility as a baseline. Rather, they establish a more robust research agenda encompassing longitudinal monitoring in permanent inventory plots, local allometric calibration, quantification of primary carbon pools, hydrological tracking, and the development of structured production and household panels. Such repeated and matched observations could support a more robust analysis of whether palm sap utilization can be maintained in line with the ecological functions targeted by restoration.

CONCLUSION

This study investigates the nipah palm (*Nypa fruticans* Wurmb.) ecosystem in Pasar Rawa Village, Gebang District, Langkat Regency, North Sumatra, quantifying the biomass and carbon storage potential of living leaf components while documenting the species' role as an essential livelihood source for coastal communities. An inventory of 50 observation plots revealed 2,427 visually distinguishable nipah vegetation units in the field, with a total of 13,005 living leaves recorded. The estimated living leaf biomass averaged 30.24 Mg/ha, with variation between plots ranging from 7.12 to 49.74 Mg/ha. This variability reflects underlying heterogeneity in vegetation conditions and biomass distribution across the study site, likely driven by variations in stand architecture, growth dynamics, and microenvironmental parameters. Nevertheless, the determinants of this biomass variation warrant further investigation via comprehensive measurements of biophysical and environmental parameters. Based on a carbon fraction of 0.47, the estimated carbon stock stored in nipa palm live leaf biomass is 14.21 Mg C/ha, equivalent to 52.11 Mg CO_2-eq/ha. These finding indicates that live-leaf components of the nipa palm constitute a quantifiable vegetative carbon pool, offering substantial potential for integration into coastal ecosystem carbon monitoring frameworks. However, the CO_2-eq value obtained represents the equivalent mass of carbon stored in the live leaf biomass at the time of observation, not the amount of annual CO_2 uptake or additional carbon uptake due to restoration activities. Furthermore, this estimate does not capture the aggregate total organic carbon stock of the nipa palm ecosystem, as it excludes belowground biomass, soil carbon, litter, and dead organic matter pools. Therefore, interpreting nipa palm's contribution to climate change mitigation requires proportional analysis based on component limitations and the measurement methods used. Furthermore, single-period observations preclude the assessment of temporal carbon stock dynamics or the direct attribution of observed increases to restoration interventions. From a socioeconomic perspective, this study also documented the utilization of nipah palm through sap tapping and sugar processing by a ten-member women's group. According to activity records compiled independently of the vegetation inventory, the group reported a yield of approximately 25 L of sap per day harvested from an estimated 25 tapped nipah palms. In documented processing activities, one 25 L batch

of sap yielded approximately 5 kg of powdered sugar. These findings demonstrate the potential for utilizing non-timber forest products as an alternative economic activity in coastal communities, particularly through the involvement of women's groups in processing and increasing the added value of nipah palm products. Nevertheless, these data reflect a demonstration-scale activity and preclude definitive inferences regarding individual nipah palm productivity, sustainable production efficiency, enterprise financial viability, household net income gains, or long-term community empowerment. Conceptually, this study contributes by proposing a dual-value monitoring framework that integrates ecological and socioeconomic dimensions in nipah palm ecosystem management. This framework positions living leaf biomass carbon stocks and community nipah utilization activities as two distinct indicators distinct systematic monitoring, yet delineates them based on unit of observation, data coverage, and analytical scale. While this approach provides a foundational framework for developing an evaluation system for nipah ecosystem management and restoration, integrating both carbon storage capacity and potential local economic benefits, current data limitations preclude demonstrating a direct relationship, synergy, or trade-off between increasing carbon stocks and the intensity of community nipah utilization. Future research should focus on calibrating allometric equations based on local measurements, establishing permanent observation plots with repeated monitoring, and expanding the inventory of all components of the ecosystem's carbon stocks, particularly soil carbon and belowground biomass. Furthermore, evaluating the sustainability of nipa palm management necessitates tracking productivity, tapping intensity, vegetation regeneration, and utilization-induced biomass dynamics. On the socio-economic front, longitudinal data collection on production costs, value added, net income, market access, and distribution is needed.

AUTHOR CONTRIBUTIONS

M.S. Harefa conceptualized the study, developed the methodology, conducted the formal analysis and data interpretation, prepared the original draft, reviewed and edited the manuscript, supervised the research, and acquired the funding. E. Tuhono contributed to the methodology, reviewed and edited the manuscript, and supervised the research. A. Susilowati reviewed and edited the manuscript and supervised the research. M.M. Yusoff reviewed and edited the manuscript and supervised the research. M.T. Rahmadi performed the GIS analysis, reviewed and edited the manuscript, and supervised the research. F.Y. Pratama conducted the carbon-stock investigation, curated the data, performed the formal analysis, and contributed to the original draft. R.H. Harishun conducted the community-based production investigation, curated the data, performed the formal analysis, and reviewed and edited the manuscript. D. Irfansyah conducted the community-based production investigation, coordinated field logistics, and reviewed and edited the manuscript. N.A. Emilia conducted the community-based production investigation, curated the data, and reviewed and edited the manuscript. S.A. Emilia conducted the carbon-stock investigation and reviewed and edited the manuscript.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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POSITIVE AI STATEMENT

During the preparation of this work the author(s) have used Artificial Intelligence (AI) ChatGPT (OpenAI) to assist with English-language editing, preparation of responses to reviewers, restructuring and drafting selected revisions. The authors are responsible for checking the field data, calculations, references, scientific interpretations and the final submitted manuscript.

ABBREVIATIONS

%	Percent
AGB	Above-ground biomass
AGC	Above-ground carbon
C	Circumference (cm); carbon (on the Mg C/ha)
cm	Centimeters
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide equivalent
CV	Coefficient of variation
D130	Diameter of the frond at a height of 130 cm
D130,eq	Equivalent circular diameter of the frond at a height of 130 cm
DW	Dry weight
g	Grams
GEDSI	Gender equality, disability, and social inclusion
GEE	Google Earth Engine
ha	Hectares
ID	Identifier
IPCC	Intergovernmental Panel on Climate Change
IQR	Interquartile range
kg	Kilograms
kg/L	Kilograms per liter
L	Liters
m	Meters
m^2	Square meters
Mg	Megagrams
Mg/ha	Megagrams per hectare
Mg C/ha	Megagrams of carbon per hectare
Mg CO_2eq/ha	Megagrams of carbon dioxide equivalent per hectare
MRV	Measurement, reporting, and verification
pH	Potential of hydrogen
R^2	Coefficient of determination
SD	Standard deviation
WGS	World Geodetic System

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