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ORIGINAL RESEARCH ARTICLE

Habitat assessment of mangrove planting on coral rubble coasts caused by earthquake

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ABSTRACT

BACKGROUND AND OBJECTIVES: Coastal elevation changes from seismic activity can expose coral-rubble surfaces suitable for mangrove establishment; however, these substrates differ from mature mudflats due to their coarse composition, developmental immaturity, and lack of fine silt. The study objectives were to evluate the percentage of living planted mangroves and the conditions of habitats on earthquake-uplifted coral-rubble coastal terrain in Nias Island, Indonesia.

METHODS: A total of 77 plots were observed at eight locations for 3, 6 and 12 months measurement. Analysis of the relationship between habitat characteristics and percentage of living plants was carried out at the location level (n = 8) and interpreted as an exploratory analysis. Plant survival and replenishment records at six and twelve months post-planting accounted solely for living specimens, as deceased plants were replaced following each monitoring interval. The habitat assessment included water temperature, salinity, dissolved oxygen, substrate potential of hydrogen, texture, organic carbon content, carbon-to-nitrogen ratio, total nitrogen, available phosphorus, and available potassium.

FINDINGS: The planting substrate was primarily composed of sand, with site mean sand ratio ranging from 82.00 percent to 93.25 percent. The substrate at the planting sites had not transitioned into organic-rich mangrove soil, as indicated by depleted soil nutrient levels and low organic carbon concentrations. The percentage of live plants in Botohilitano ranged from 39.60 percent to 87.86 percent after one year. Differences in habitat conditions among locations underscore the necessity of targeted habitat evaluations, while the correlation between habitat traits and the proportion of live plants necessitates additional.

CONCLUSION: Notwithstanding the uniform planting density, the effectiveness of mangrove cultivation in coral fragment-covered regions raised by the earthquake differs. Prior to scaling up restoration initiatives, it is critical to conduct site-specific habitat suitability assessments, continuously monitor plant survival rates, and systematically document the ecological rehabilitation process. The ecological mangrove restoration approach must incorporate suitable species, and community involvement in restoration management is essential to improve the sustainability of mangrove ecosystem services and the efficacy of rehabilitation efforts.

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INTRODUCTION

Mangrove restoration is widely used on tropical coasts to recover degraded habitats, support coastal protection, and rebuild ecological function (Mohan *et al.,* 2025). Although planting represents the most highly visible phase of restoration, initial planting records are insufficient indicators of long-term mangrove establishment under localized field conditions (Ray *et al.*, 2024). Early monitoring is needed because planted mangroves may face unsuitable hydrology, substrate instability, salinity stress, or poor rooting conditions after planting (Friess *et al*., 2019). Although mangrove cultivation is frequently associated with coastal hazard mitigation, its protective efficacy is contingent upon the long-term persistence of the restored stand under local hydrodynamic and sedimentological conditions (O'connell *et al*., 2022). This is important because a planted area does not automatically become a functioning protective mangrove belt (Gijsman *et al*., 2021). Early establishment is the most critical phase for planted mangroves. Seedlings and propagules have to remain anchored, tolerate tidal exposure, and develop roots in the available substrate. Despite high initial planting densities, restoration failure may occur if the target site lacks substrate stability and appropriate hydrological conditions (Balke *et al*., 2011). Weak site selection remains one of the main causes of poor restoration outcomes. Planting targets can be achieved in terms of area or number of seedlings, while field performance remains low because the site does not match the ecological requirements of mangrove establishment (Kodikara *et al*., 2017). This issue is equally pertinent in Southeast Asia, where ecological restoration initiatives frequently encounter obstacles regarding site suitability, planting design, monitoring protocols, and long-term maintenance. Consequently, evaluating restoration efficacy must extend beyond administrative planting records to incorporate empirical assessments of post-planting field performance (Gerona-Daga and Salmo III, 2022). The Nias planting sites also need a clear baseline. The planting surface was reef-flat ground exposed by the 2005 earthquake, not a degraded mangrove stands with old mangrove mud. Restoration targets for these substrates must avoid the assumption that all unvegetated coastal expanses historically supported mangrove ecosystems. At the Nias sites, the baseline issue was concrete: the planting surface was reef-flat ground exposed by the 2005 earthquake, so open coastal space could not be treated automatically as former mangrove habitat (Dahdouh-Guebas and Cannicci, 2021). The coastal locations evaluated in this study present a highly atypical ecological restoration context. The 2005 Nias–Simeulue earthquake uplifted reef-flat surfaces along parts of the Nias coast and exposed coral-rubble and sandy coastal land. Some of these newly exposed surfaces were later used for mangrove planting, although their suitability as planting habitat had not been clearly assessed (Briggs *et al*., 2006). Spatial variability in post-seismic deformation and uplift along the Nias–Simeulue segment accounts for the highly heterogeneous nature of the newly exposed coastal substrates, which failed to yield a uniform cultivation environment (Meltzner *et al*., 2015). Earthquake-uplifted coral-rubble land is different from abandoned ponds, degraded mangrove stands, or fine-sediment tidal flats. The surface is coarse, uneven, and weakly developed as soil. Recent work on coral response after the Nias–Simeulue uplift also shows that the uplifted reef setting remained geochemically and physically distinct from ordinary mangrove sediment environments (Sosdian *et al*., 2024). Although tectonic coastal uplift has generated extensive stretches of coral-rubble deposits targeted for mangrove restoration, the emergence of new subaerial land does not inherently guarantee its biophysical suitability for long-term mangrove establishment. The success of mangrove stand formation is largely determined by the suitability of elevation to tidal range, hydroperiod, and hydrological connectivity which regulates the frequency and duration of inundation

(Friess *et al.,* 2019). Consequently, the present study is more appropriately framed as a preliminary assessment centered on physicochemical water and soil characteristics. Future research evaluating habitat suitability for mangrove restoration on tectonic uplift-generated coral rubble must integrate comprehensive hydrological data, tidal elevations, and geomorphological conditions (Cerri *et al.,* 2026). This substrate condition is central to the Nias planting sites because coral rubble and sand were the main planting medium, not developed mangrove mud. Coral rubble and sand can provide space for planting, but they may offer limited fine sediment, low organic matter, weak anchorage, and poor root-zone development. Under these conditions, planting success depends not only on species choice or planting density, but also on whether the substrate can support early establishment (Lee *et al*., 2019). Fine-grained sediments and organic matter play a critical role in pedogenesis, surface stabilization, and vertical elevation dynamics within tidal wetlands. Consequently, in environments dominated by coarse substrates, initial mangrove establishment may be hindered by low sediment retention and the poor development of a stable rooting metrix (Morris *et al*., 2016). Soil fertility was included in this study as part of the habitat diagnosis. Nitrogen (N), phosphorus (P), and potassium (K) were not treated as single causal factors, but as indicators that strengthen the description of site condition. Together with organic carbon, substrate texture, and water quality, these variables help show whether uplifted coral-rubble land provides a suitable medium for planted mangroves (Alongi, 2018). The percentage of live plants served as the primary field indicator for planting outcomes. Because deceased specimens were systematically replaced following each monitoring event, the survival metrics recorded at six and twelve months reflect the combined cohort of original surviving plants and replanted individuals under active maintenance. It should not be read as live plant percentage of the original planting cohort alone (Gann *et al*., 2019). Mangrove species have different adaptability to extreme habitat conditions, including areas of coral rubble that have been uplifted due to tectonic activity. In Indonesia, *Rhizophora apiculata* and *Rhizophora stylosa* are two species commonly used in rehabilitation programs because they have viviparous propagules, the ability to form strong supporting roots, and high tolerance to salinity and tidal inundation (Friess *et al.,* 2019). Specifically, *R. stylosa* is reported to have better adaptability to sandy substrates and coral rubble in open coastal areas, while *R. apiculata* thrives better on more stable muddy substrates. However, the long-term survival and growth of these two species are not governed solely by their physiological traits; rather, they remain highly contingent upon habitat suitability, particularly local hydrology, substrate stability and tidal connectivity. Therefore, evaluating habitat characteristics is an important aspect in determining the success of mangrove restoration in coastal areas experiencing tectonic uplift. While localized to Nias Island, the foundational ecological principles for mangrove restoration in areas of tectonic uplift are applicable to other tropical coastlines sharing similar geomorphological characteristics. However, the success of restoration still depends on hydrological conditions, tidal elevation, substrate characteristics and coastal dynamics that are specific to each location. Consequently, the ecological mangrove restoration (EMR) framework, which prioritizes the rehabilitation of natural hydrological regimes prior to revegetation, is recognized as a more effective and sustainable alternative to conventional planting practices that overlook site suitability (Friess *et al.,* 2019). Thus, evaluating habitat characteristics is an important step to determine appropriate restoration strategies in coastal areas that are experiencing landscape changes due to tectonic activity. This study aims to assess habitat conditions and survival rates of mangroves planted on seismically uplifted coral-rubble substrates. Specifically, the

study evaluated: i) water, substrate, and soil fertility conditions across planting sites; ii) plant survival rates at three, six, and twelve months post-planting; and iii) site-specific relationships between key environmental indicators and mangrove survival. The study was carried out in village-level coastal planting sites in North Nias and South Nias Regencies, Indonesia, during 2024–2025.

MATERIALS AND METHODS

The study was conducted on earthquake-uplifted coral-rubble coastal land in Nias Island, North Sumatra, Indonesia, during 2024–2025. The study area covered selected coastal planting sites in North Nias and South Nias Regencies. These coastal surfaces were associated with reef-flat uplift after the 2005 Nias–Simeulue earthquake (Briggs *et al.*, 2006). Site selection followed a purposive sampling design based on three primary criteria: the presence of tectonically uplifted coral-rubble substrates, active mangrove planting initiatives, and accessibility for recurring monitoring. Preliminary screening was conducted via the interpretation of post-uplift coastal landforms, which was subsequently validated through field verification. The monitored areas represented planting sites on coarse coral-rubble and sandy substrate, not on developed muddy mangrove soil. Eight village-level coastal sites were included. Four sites were located in South Nias Regency: Bawonahono, Sondregeasi, Botohilitano, and Botohilisalo'o. Four sites were located in North Nias Regency: Sisarahili Teluk Siabang, Sifahandro, Balefadoro Tuho, and Hiligawolo. Fig. 1 illustrates the spatial distribution of the monitored sites and experimental planting plots.

Planting design and observation units

Mangroves were planted at a density of 2,500 plants per hectare (ha). Monitoring was conducted in 77 planting plots, each covering 0.5 ha and observed in eight research location villages. Each plot contained 1,250 planting points. The total monitored area encompassed 38.5 ha. Plot allocation was distributed based on the spatial extent of mapped coral-rubble coastal substrates across the two regencies, resulting in 32 plots established in South Nias and 45 plots in North Nias. In South Nias, each of the four sites had eight plots. In North Nias, Sisarahili Teluk Siabang, Sifahandro, Balefadoro Tuho, and Hiligawolo had 15, 14, 6, and 10 plots, respectively. The plot distribution is detailed in Table 1. To match the scale of the environmental data, evaluations of habitat characteristics and mangrove survival rates were conducted using aggregated mean values at the village level (n = 8). This approach was necessitated because key environmental parameters—including water quality, soil physicochemical properties, and soil fertility levels, were originally measured or represented at the village level resolution. This data aggregation was carried out to align the scale between the response variables and the explanatory variables and to avoid pseudoreplication which could occur if each plot was treated as an independent unit of analysis, while the habitat variable had the same value for plots in the same village. Consequently, the village is designated as the primary unit of analysis for the correlation assessment, whereas individual plots served as the foundational observation unit. Given the relatively limited number of analysis units (n = 8), the correlation results were interpreted as an exploratory analysis to identify patterns of relationships between habitat characteristics and the percentage of live plants at the site level, rather than as evidence of a cause-and-effect relationship. Mangrove cultivation was conducted in strict accordance with the localized rehabilitation protocols established by the executing agency at each location. Planting density, plant spacing, planting position, and planting techniques are applied uniformly at each location in accordance with the rehabilitation guidelines used. The type of planting material used is in the form of propagules or nursery seeds, depending on availability in each location, while

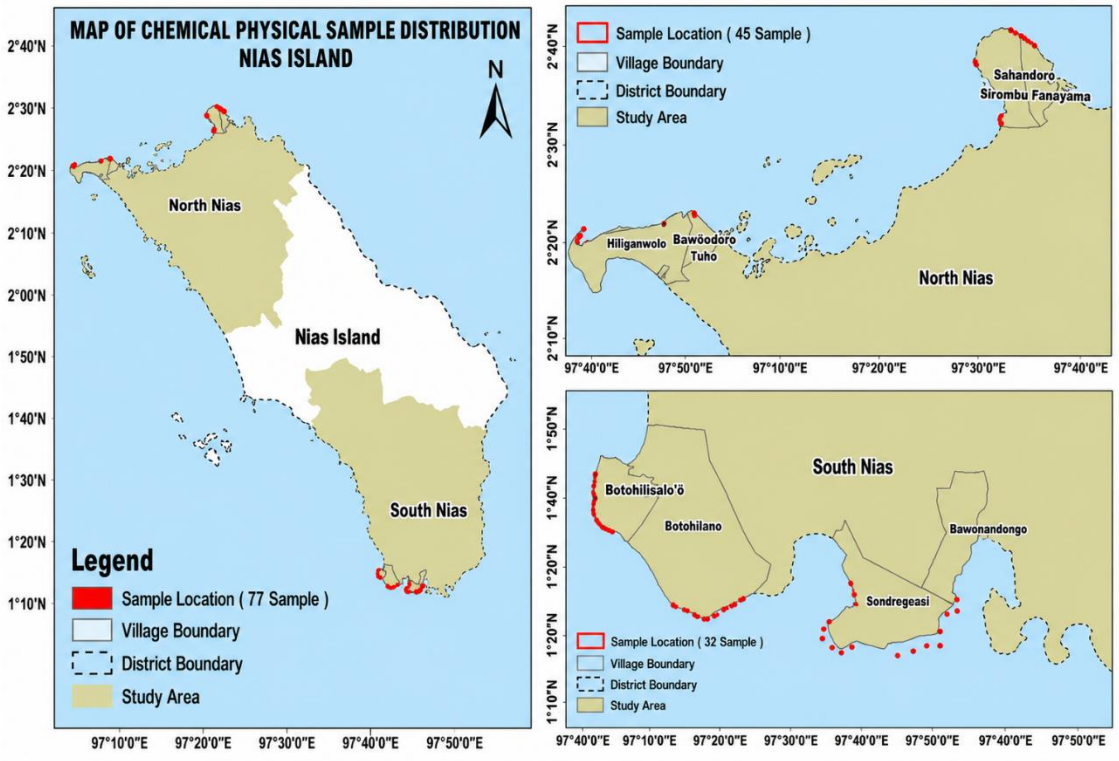


Fig. 1: Geographical location of the study area and distribution of monitored mangrove planting plots on earthquake-uplifted coral-rubble coastal land in Nias Island, Indonesia

Table 1: Distribution of monitored mangrove planting sites and plots

Regency	Village-level site	Plot number	Number of plots	Monitored area	Planted species
South Nias	Bawonahono	1–8	8	4.0 ha	*Rhizophora apiculata*
	Sondregeasi	9–16	8	4.0 ha	*Rhizophora apiculata*
	Botohilitano	17–24	8	4.0 ha	*Rhizophora apiculata*
	Botohilisalo'o	25–32	8	4.0 ha	*Rhizophora stylosa*
North Nias	Sisarahili Teluk Siabang	33–47	15	7.5 ha	*Rhizophora apiculata*
	Sifahandro	48–61	14	7.0 ha	*Rhizophora stylosa*
	Balefadoro Tuho	62–67	6	3.0 ha	*Rhizophora stylosa*
	Hiligawolo	68–77	10	5.0 ha	*Rhizophora apiculata*
Total	Eight sites	1–77	77	38.5 ha	

replanting is carried out if there are plants that die during the monitoring period. The planted species were *R. apiculata* and *R. stylosa*. *Rhizophora apiculata* was planted in Bawonahono, Sondregeasi, Botohilitano, Sisarahili Teluk Siabang, and Hiligawolo. *Rhizophora stylosa* was planted in Botohilisalo'o, Sifahandro, and Balefadoro Tuho. The planting stock comprised both propagules and nursery-reared seedlings, selected in accordance with localized site conditions and historical field implementation records. For monitoring purposes, each experimental plot served as the primary observation unit to document plant survival throughout the twelve-month monitoring period. The village-level site was used as the analytical unit for comparing live plant percentage with habitat indicators using site-level mean values. This scale was used because plots within the same site belonged to the same planting block or adjacent coastal planting area and shared similar coral-rubble and sandy substrate conditions, thereby minimizing within-site environmental variability.

Live plant monitoring and replacement planting

Live plant percentage was recorded when the planted mangroves reached three, six, and twelve months after planting. At each monitoring period, live plants were counted in each plot and compared with the target number of planting points. Following each monitoring event, documented plant mortalities were systematically replaced as a routine component of field maintenance. Because replacement planting was conducted after monitoring, values at six and twelve months represented living planted and replanted individuals under maintenance conditions. Consequently, these data were treated as plant survival percentages, with the complete monitoring and replenishment sequence illustrated in Fig. 2. Live plant percentages were derived from counts recorded during each monitoring cycle. Plot layouts comprised 1,250 planting points across a 0.5 ha area, corresponding to a standard planting density of 2,500 plants/ha. Monitoring was carried out at 3, 6, and 12 months after planting, using Eq. 1 (Field, 1999):

$$\text{Live plant percentage}_t = \left(\frac{N_{live,t}}{N_{target}}\right) \times 100 \quad (1)$$

Where: $N_{live,t}$ is the number of live plants recorded at monitoring time t, and N_{target} is the target number of planting points in each 0.5 ha plot. In this study, N_{target} was 1,250. Plot-level values were averaged to obtain village-level site values. Dead planting points were replaced during field maintenance. The six and twelve-month monitoring records incorporated surviving individuals from both primary and replacement plantings; consequently, these data are reported as live plant percentage.

Water, substrate, and soil fertility measurements

Water, substrate, and soil fertility measurements were used to describe habitat conditions across the monitored planting sites. Water variables consisted of water temperature, water potential of hydrogen (pH), salinity, and dissolved oxygen. These variables were measured in situ in the water surrounding planted mangroves using portable handheld water-quality instruments. Substrate pH was measured to characterize the pH condition of the planting medium. The pH value of the substrate was determined potentiometrically in a soil suspension: 1 normal K chloride (N KCl) solution at a ratio of 1:2.5. Substrate samples were taken at a depth of 0–20 centimeters (cm), then air-dried, homogenized, and sieved using a 2 millimeters (mm) sieve before analysis. Measurements were carried out using a pH meter that had been calibrated with a standard buffer solution before use. This method is used to obtain a pH value that reflects the potential acidity level of the substrate. Substrate texture was analyzed from 77 soil samples representing the planting plots. Sand, silt, and clay fractions were determined using the hydrometer method. These variables characterized the physical properties of the uplifted coral-rubble substrate, highlighting the marked prevalence of coarse material and the corresponding paucity of the fine-sediment fraction. Soil fertility indicators, including organic carbon, were integrated as site-level habitat variables. The organic carbon content and corresponding carbon-to-nitrogen ratio were evaluated using one representative soil sample obtained from each designated village-level site. Total N, available P, and available K were analyzed from 16 soil samples, with two samples representing each site. Total N was determined using the Kjeldahl method. Available P was determined using the Bray 2 method. Available K was determined using ammonium acetate extraction followed by atomic absorption spectrophotometry. Organic carbon was quantified using the dichromate oxidation method with K dichromate. Rather than being evaluated as isolated causal determinants of plant survival, these variables characterized broader planting habitat conditions. Measured habitat variables, sampling scale, sample number, and analytical methods are summarized in Table 2.

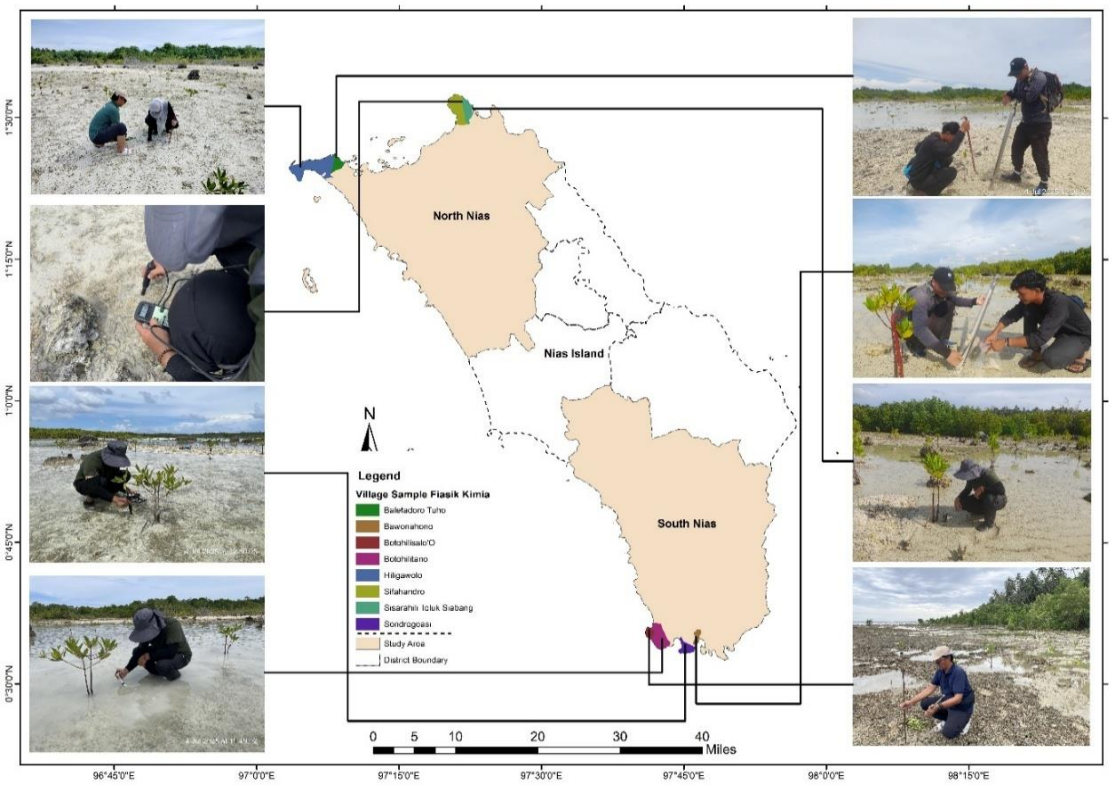


Fig. 2: Monitoring and replacement planting sequence used to calculate live plant percentage at three, six, and twelve months after planting

Table 2: Habitat variables, sampling scale, sample number, and analytical methods

Variable group	Variable	Sampling scale	Number of samples or plots	Method
Water quality	Water temperature	Plot level	77 plots	In situ field measurement
	Water pH	Plot level	77 plots	In situ field measurement
	Salinity	Plot level	77 plots	In situ field measurement
	Dissolved oxygen	Plot level	77 plots	In situ field measurement
Substrate chemistry	Substrate pH	Plot level	77 plots	Field or laboratory measurement
Substrate texture	Sand, silt, and clay fractions	Plot level	77 samples	Hydrometer method
Organic matter	Organic carbon	Site level	8 samples	Dichromate oxidation
	Carbon-to-nitrogen ratio	Site level	8 samples	Derived from carbon and nitrogen values
Soil fertility	Total N	Site level	16 samples	Kjeldahl method
	Available P	Site level	16 samples	Bray 2 method
	Available K	Site level	16 samples	Ammonium acetate extraction and atomic absorption spectrophotometry

Data aggregation and statistical analysis

Data were organized according to the sampling scale of each variable. Live plant percentage, water quality, substrate pH, and substrate texture were recorded or calculated at the plot level and then summarized as site-level means. Organic carbon, carbon-to-nitrogen ratio, total N, available P, and available K served as site-level environmental indicators, as these parameters were quantified from representative soil samples collected at each village-level site. Live plant percentage was analyzed at three monitoring periods: three, six, and twelve months after planting. For each monitoring interval, village-scale mean values were computed across the eight designated study sites. These values were

compared with site-level habitat indicators to evaluate whether vegetation establishment outcomes varied in response to differences in hydrological, substrate, and soil fertility conditions. Pearson correlation analysis was used to examine site-level associations between habitat indicators and live plant percentage. The habitat indicators included water temperature, water pH, salinity, dissolved oxygen, substrate pH, sand, silt, clay, organic carbon, carbon-to-nitrogen ratio, total N, available P, and available K. The analysis used eight village-level sites as analytical units (Field, 2018). A series of correlation analyses was executed to assess the association between key environmental variables and the percentage of surviving plants at each observational phase (3, 6, and 12 months post-planting. Considering that the number of analysis units at the village level is relatively limited (n = 8) and there are several habitat parameters tested simultaneously, the results of the correlation analysis are interpreted as an exploratory analysis to identify initial relationship patterns between variables. Consequently, the interpretation of the these findings extends beyond mere statistical significance value ($p < 0.05$), to evaluate the magnitude of the correlation coefficient, the consistency of the observed relationship between observation, and the broader ecological relevance of each habitat parameter. This approach was taken to reduce the possibility of over-interpretation of findings resulting from multiple statistical comparisons conducted on a relatively modest sample size. Considering the relatively limited number of analysis units at the village level (n = 8) and the existence of several correlation tests carried out simultaneously, the results of the statistical analysis were interpreted as an exploratory analysis to identify initial relationship patterns between habitat characteristics and the percentage of living plants. Therefore, the interpretation of the results is not only based on the statistical significance value ($p < 0.05$), but also considers the magnitude of the correlation coefficient, the consistency of the relationship between observation periods, and the ecological relevance of each variable. Consequently, these correlational findings serve not as definitive confirmatory evidence, but rather as a foundation for generating hypotheses to be rigorously tested in future, larger-scale investigations.

RESULTS AND DISSCUSSION

Water physicochemical conditions and substrate pH

Water conditions differed among the eight planting sites. Site-level mean water temperature ranged from 29.51 degrees Celsius (°C) in Botohilitano to 32.56 °C in Hiligawolo. Water pH ranged from 7.50 in Sondregeasi to 8.05 in Botohilitano. Salinity ranged from 31.33 part per thousand (ppt) in Botohilitano to 34.20 ppt in Sondregeasi. Dissolved oxygen ranged from 9.10 milligrams per liter (mg/L) in Bawonahono to 10.99 mg/L in Sisarahili Teluk Siabang (Table 3).

Substrate texture, organic matter, and soil fertility conditions

Sand dominated all site means. Botohilisalo'o had the lowest sand fraction at 82.00 percent (%), while Sondregeasi had the highest at 93.25%. Silt ranged from 4.50% to 13.13%, and clay from 1.00% to 5.00%. The monitored planting surfaces consisted of coarse coral-rubble and sandy substrate, rather than traditional, mature mangrove mud (Table 4).

Live plant percentage across monitoring periods

Live plant percentage already differed at three months. Hiligawolo recorded 98.19%, Botohilisalo'o 96.72%, and Sisarahili Teluk Siabang 93.16%. The lowest early survival rates were recorded in Sifahandro (38.66%) and Balefadoro Tuho (45.88%). Similarly, Botohilitano exhibited a lower establishment rate (63.76%) at the three-month mark compared to the highest-performing sites (Table 5). At six months, Hiligawolo had the highest record, at 94.17%. Four other sites were above 75%: Botohilisalo'o (87.06%), Sisarahili Teluk Siabang (83.38%), Sifahandro (82.24%), and

Table 3: Water physicochemical conditions and substrate pH across monitored mangrove planting sites

Regency	Site	Water temperature	Salinity	Dissolved oxygen (mg/L)	Water pH	Substrate pH
South Nias	Bawonahono	30.53	34.11	9.10	7.81	5.65
	Sondregeasi	30.60	34.20	9.90	7.50	5.23
	Botohilitano	29.51	31.33	9.83	8.05	5.48
	Botohilisalo'o	31.03	32.51	9.64	7.93	5.34
North Nias	Sisarahili Teluk Siabang	30.81	31.94	10.99	8.04	5.57
	Sifahandro	30.59	32.16	10.46	7.88	5.38
	Balefadoro Tuho	31.00	31.97	9.67	7.85	5.92
	Hiligawolo	32.56	32.41	9.63	8.00	5.66

Note: Values are site-level means.

Table 4: Substrate texture, organic carbon, and soil fertility indicators across monitored planting sites

Regency	Village-level site	Sand (%)	Silt (%)	Clay (%)	Organic carbon (%)	C/N ratio	Total N (%)	Available P (ppm)	Available K (m.e/100 g)
South Nias	Bawonahono	91.75	4.50	3.75	0.24	6	0.04	3.81	0.26
	Sondregeasi	93.25	5.75	1.00	0.11	4	0.04	2.76	0.19
	Botohilitano	92.50	5.50	2.00	0.21	4	0.05	2.30	0.27
	Botohilisalo'o	82.00	13.13	4.88	0.17	2	0.07	2.43	0.41
North Nias	Sisarahili Teluk Siabang	92.73	5.40	1.80	0.05	1	0.06	2.30	0.24
	Sifahandro	92.36	5.43	2.14	0.18	3	0.04	4.22	0.32
	Balefadoro Tuho	88.67	8.67	2.67	0.34	5	0.07	3.23	0.17
	Hiligawolo	90.00	5.00	5.00	0.11	2	0.05	2.89	0.22

Table 5: Site-level live plant percentage at three, six, and twelve months after planting

Regency	Village-level site	Planted species	Number of plots	3 months (%)	6 months (%)	12 months (%)
South Nias	Bawonahono	*Rhizophora apiculata*	8	86.20	62.75	46.05
	Sondregeasi	*Rhizophora apiculata*	8	84.60	61.15	48.50
	Botohilitano	*Rhizophora apiculata*	8	63.76	55.65	39.60
	Botohilisalo'o	*Rhizophora stylosa*	8	96.72	87.06	77.16
North Nias	Sisarahili Teluk Siabang	*Rhizophora apiculata*	15	93.16	83.38	75.91
	Sifahandro	*Rhizophora stylosa*	14	38.66	82.24	75.42
	Balefadoro Tuho	*Rhizophora stylosa*	6	45.88	76.05	70.00
	Hiligawolo	*Rhizophora apiculata*	10	98.19	94.17	87.86

Balefadoro Tuho (76.05%). Bawonahono, Sondregeasi, and Botohilitano stayed lower, at 62.75%, 61.15%, and 55.65%. At twelve months, Hiligawolo still had the highest record at 87.86%. Botohilisalo'o recorded 77.16%, Sisarahili Teluk Siabang 75.91%, Sifahandro 75.42%, and Balefadoro Tuho 70.00%. The three lowest final records were Sondregeasi (48.50%), Bawonahono (46.05%), and Botohilitano (39.60%). The gap between Hiligawolo and Botohilitano was 48.26 percentage points. In contrast to the high-record sites, Sifahandro and Balefadoro Tuho exhibited distinct historical monitoring profiles. At three months, Sifahandro recorded 38.66% and Balefadoro Tuho 45.88% after planting with nursery seedlings. Failed planting points were later replanted with propagules. Monitoring patterns in South Nias and North Nias exhibited significant heterogeneity (Fig. 3). In South Nias, Botohilisalo'o stayed higher than Bawonahono, Sondregeasi, and Botohilitano through twelve months. In North Nias, Hiligawolo maintained elevated metrics across a three- to twelve-month duration, whereas Sifahandro and Balefadoro Tuho exhibited increases subsequent to the remediation of failed points. The inclusion of Gann *et al*. (2019) urther justifies this methodology, as monitoring and post-intervention management are fundamental components of standard restoration practice.

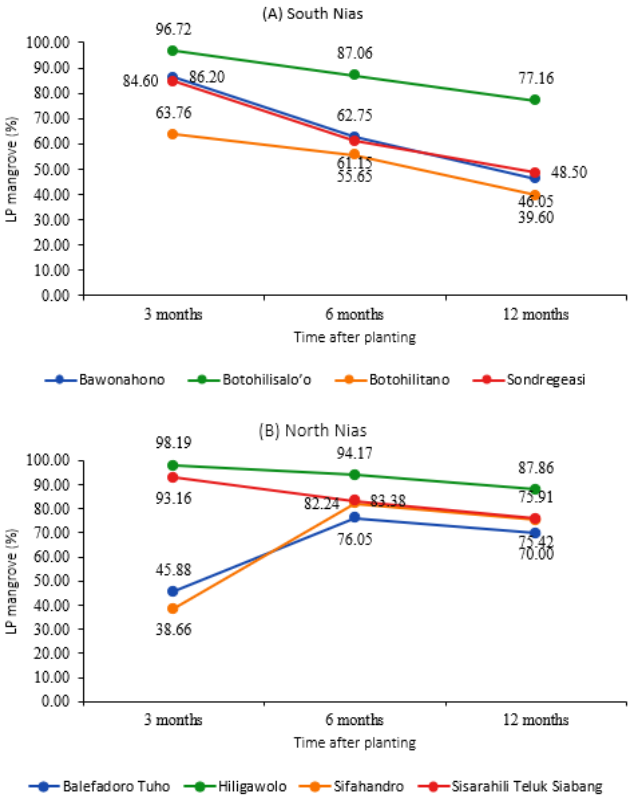


Fig. 3: Live plant percentage of planted mangroves across village-level sites at three, six, and twelve months after planting: (A) South Nias and (B) North Nias. Figure note: Values at six and twelve months represent live plant percentage under field maintenance and replacement planting

Site-level associations between habitat indicators and live plant percentage

Pearson correlation coefficients were calculated utilizing data aggregated at the village-level site scale. The analysis used eight sites, not plot-level observations. The values in this section are site-level associations between habitat indicators and live plant percentage. Water temperature exhibited the strongest positive correlation with the percentage of live plants during the latter phases of the monitoring periods. At six months, the correlation was r = 0.805 with p = 0.016. At twelve months, the correlation was r = 0.792 with p = 0.019 (Table 6). At three months, the correlation was weaker. These data indicate that water temperature represents the most robust site-level association identified within this dataset. The carbon-to-nitrogen ratio had a negative direction. At six months, the correlation was r = -0.712 with p = 0.048. At twelve months, the value was r = -0.697 with p = 0.055. The carbon-to-nitrogen ratio was evaluated as an indicator of substrate condition, rather than as an isolated determinant of live plant percentage. Alongi (2018) is used for the nutrient and substrate function context. The full correlation pattern is presented in Fig. 4. The raw worksheet values are excluded from the main text of the manuscript and are utilized exclusively for the construction of the heatmap.

Restoration performance and replacement planting

Both the initial planting and replacement planting were included in the six- and twelve-month datasets, as tracking replacement

Table 6: Main site-level Pearson correlations between habitat indicators and live plant percentage

Habitat indicator	Monitoring period	Pearson r	p-value	Interpretation
Water temperature	6 months	0.805	0.016	Significant positive association
	12 months	0.792	0.019	Significant positive association
Carbon-to-nitrogen ratio	6 months	-0.712	0.048	Significant negative association
	12 months	-0.697	0.055	Near-significant negative tendency

Note: The analysis used eight village-level sites as analytical units. Correlations are interpreted as exploratory site-level associations, not causal relationships.

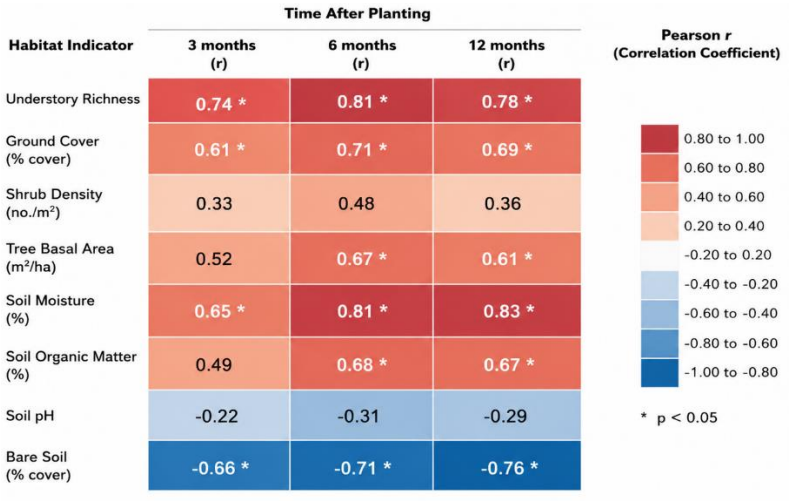


Fig. 4: Heatmap of site-level Pearson correlation coefficients between habitat indicators and live plant percentage at three, six, and twelve months after planting. Figure note: Color intensity indicates correlation strength and direction. Asterisks indicate significant correlations at $p < 0.05$. The analysis used eight village-level sites as analytical units

dynamics is essential to this study. The increase in the percentage of live plants in the 6th and 12th months of observation not only reflects the adaptability of the seeds planted at the start of the study, but also shows the contribution of management intervention through replanting to the success of restoration. The observed shifts in live plant percentages across monitoring periods reflect a combination of habitat conditions, replanting success, and management practices, rather than natural survival patterns. These findings confirm that the success of mangrove restoration is not only determined by habitat suitability, but also by adaptive management through monitoring and replanting dead plants, as recommended post-planting management to increase the success of restoration (Friess *et al.*, 2019). Therefore, evaluations of restoration success should separately consider initial plant survival and replantation success. The term was utilized by Sloey *et al*., (2022) to characterize one-year mangrove seedling performance across under varying abiotic site conditions. The Nias records also separate monitoring age, species, and planting material. Hiligawolo used *Rhizophora apiculata* and ended at 87.86% after twelve months. Botohilisalo'o, Sifahandro, and Balefadoro Tuho used *Rhizophora stylosa* and ended at 77.16%, 75.42%, and 70.00%. Species ranking was not performed using these values due to inherent heterogeneity in site conditions and replacement planting protocols across study sites. Comprehensive records of species and planting materials were instead utilized to account for these variables, ensuring that subsequent live plant percentages were not attributed solely to species-specific performance (Su *et al*., 2021). The increase in the percentage of live plants in several

locations, such as in Sifahandro (38.66% to 82.24%) and Balefadoro Tuho (45.88% to 76.05%). This condition also effected by replanting activities (replacement planting), not merely the survival of plants planted at the start of the study. Thus, changes in values between periods better reflect the effectiveness of management interventions in maintaining plant cover rather than the natural dynamics of seedling survival. These results indicate that mangrove restoration success depends on both habitat suitability and adaptive replanting; therefore, restoration evaluations should account for both factors (Bosire *et al.,* 2008). The mangrove types, planting materials, habitat conditions, and management interventions are not applied uniformly at all research locations. *R.apiculata* and *R. stylosa* is planted in different locations, with variations in the use of propagules and nursery seeds, and in some locations replanting is carried out using propagules. These conditions mean that the influence of species, type of planting material, habitat characteristics and embroidery cannot be separated independently. Consequently, spatial variations in the percentage of live plants are best understood as the product of multifactorial interactions rather than the isolated effect of a single variable. Future research needs to use a more controlled experimental design so that the influence of each factor can be evaluated separately.

Substrate limitation

Substrate pH was acidic at all sites, from 5.23 in Sondregeasi to 5.92 in Balefadoro Tuho. Despite the dominance of carbonate-rich coral fragments within the study substrate, the observed acidic pH is likely driven by post-successional substrate development—specifically the accumulation of organic material, litter decomposition processes, root respiration, and the subsequent formation of organic acids. In addition, alkaline leaching due to high rainfall in tropical regions can also reduce the pH of surface substrates even though the parent material comes from carbonates. The planting surface was coral-rubble and sand, so the pH record describes the rooting medium rather than ordinary mangrove mud. This medium, previously utilized by Balke *et al*., (2011) for early mangrove establishment on unstable tidal substrates, experienced salinity levels ranging from 31.33–34.20 ppt during the monitoring period. In the Pearson test result, salinity was not a significant site-level variable for live plant percentage. The salinity describes the water condition around the planted mangroves. Kodikara *et al*., (2018) reported that mangrove seedling responses to salinity and can change with age. Organic carbon stayed low across the eight sites. The lowest value was recorded in Sisarahili Teluk Siabang at 0.05%, and the highest in Balefadoro Tuho at 0.34%. Total N was 0.04–0.07%, available P 2.30–4.22 part per million (ppm), and available K 0.17–0.41 *milliequivalents per 100 grams* (m.e./100 g). The N, P, and K values were recorded to track substrate fertility, as nutrient dynamics are key to overall mangrove habitat function (Alongi, 2018). Five sites had organic carbon below 0.20%: Sisarahili Teluk Siabang, Sondregeasi, Hiligawolo, Botohilisalo'o, and Sifahandro. The initial rooting medium exhibited low levels of stored organic material. This highlights the significance of the low organic carbon values in the Nias plots, as below-ground production and root biomass are primary drivers of mangrove soil formation (Adame *et al.,* 2014). Balefadoro Tuho had the highest organic carbon value, but it was still only 0.34%. Most sites were below 0.25%. The field setting explains that range: the planting medium was mainly coral-rubble and sand, with little fine material to hold organic matter. This study relies on the principles of carbon cycling and storage in mangrove ecosystems as delineated by Alongi (2018). Total N stayed low at every site. Botohilisalo'o and Balefadoro Tuho had the highest total N values at 0.07%, while Bawonahono, Sondregeasi, and Sifahandro were 0.04%. These records describe a weak fertility background for early root-zone development. Nutrient limitation in these disturbed mangrove systems was evaluated following Feller *et al*. (2003). In the field, substrate texture and organic carbon varied in the same field

direction. Sites with more than 90% sand had little fine material for holding organic matter. Sondregeasi had 93.25% sand and 1.00% clay; its organic carbon was 0.11%. This study draws on Morris *et al*. (2016) to contextualize the role of mineral and organic matter in tidal-wetland sediment volume. Botohilisalo'o differed texturally from the other sites in texture, having the lowest sand fraction (82.00%) and the highest silt fraction (13.13%). Despite the higher fine fraction, organic carbon was only 0.17%, showing that the substrate was still weakly developed. Sediment and substrate adjustments in these mangrove settings were evaluated following Krauss *et al*., (2014).

Environmental association

Water temperature was the only measured indicator with significant positive correlations at both six and twelve months. The values were r = 0.81 and r = 0.79 in the heatmap. These correlations are not evidence that temperature alone controlled live plant percentage. The warmer locations may also have experienced differences in water movement, exposure, and local residence times near the planted mangroves. For planted *Rhizophora* on coral-rubble substrate, the temperature result has to stay linked with the rooting condition. Most sites had sand above 90%, clay no higher than 5.00%, and organic carbon below 0.34%. A warm site still needs enough substrate stability for anchorage and root-zone development. Mangrove physiological responses to varying environmental conditions were evaluated following Lovelock *et al*., (2016). Sand and clay did not reach the significance threshold, but their directions followed the substrate record. Sand was negative at six and twelve months, while clay was positive. The site data support that reading: sand reached 93.25% in Sondregeasi, while clay was only 1.00% at that site. The roles of mineral and organic matter in determining tidal-wetland sediment volume are evaluated based on the principles established by Morris *et al*., (2016). Total N, available P, and available K were not significant as single site-level variables. Total N was 0.04–0.07%, available P 2.30–4.22 ppm, and available K 0.17–0.41 m.e/100 g. These values remain in lower compare to muddy mangrove ecosystem. They are not treated as direct causal drivers of live plant percentage. Pearson correlation was calculated from the eight village-level site means. Following Field (2018), the Pearson coefficients were interpreted strictly as measures of correlation. Water temperature showed a relatively strong positive correlation with the percentage of live plants at the 6th month (r = 0.805) and the 12th month (r = 0.792). Physiologically, temperature influences metabolic activities, photosynthesis, respiration and nutrient absorption which play an important role in the growth and adaptability of mangroves to environmental stress (Wang and Gu, 2021; Kang *et al.,* 2024). Caution is required when interpreting this relationship, as the small number of locations (n = 8) makes the correlation coefficient highly sensitive to site-specific differences. In addition, the range of water temperatures between locations is still within the tolerance range for tropical mangrove growth, so water temperature is probably not the main limiting factor, but rather reflects more complex habitat conditions, such as hydrology, inundation frequency, tidal dynamics, substrate stability and water circulation. According to prior studies, the success of mangrove growth and restoration is more influenced by the interaction of various environmental factors than by temperature alone (Alongi, 2018). Therefore, the relationship between water temperature and percentage of live plants in this study is more appropriately viewed as an exploratory association at the location level rather than a cause-and-effect relationship. Although these results point to water temperature as a key habitat component for restoration success, further research is required. Validating the role of all habitat factors will demand a larger sample size, complete hydro-geomorphological metrics, and stronger statistical approaches. The percentage of live plants was measured on the same plots in the 3rd, 6th, and 12th months, so conceptually the data have a repeated

measures structure. This study evaluated the relationship between habitat characteristics and live plants independently for each observation time. Therefore, the resulting correlations reflect specific time points rather than temporal dependencies between time periods. This approach was chosen because the analysis focused on evaluating habitat conditions at each monitoring stage, while the limited number of analysis units and the presence of replanting activities during the study period meant that the data did not meet the assumptions required for a more complex longitudinal analysis. As a result, these findings represent an exploratory, period-by-period analysis. Future studies should use mixed-effects models or generalized linear mixed models (GLMM) to handle repeated data and better evaluate the effects of time and interacting habitat variables.

Implication for the ecological mangrove restoration

While both sites utilized the same planting density, their twelve-month plant survival rates differed dramatically. Hiligawolo recorded an 87.86% survival rate compared to 39.60% at Botohilitano, resulting in a 48.26 percentage point difference. In coral-rubble planting land, a hectare count alone is not enough. The site name and the twelve-month record have to stay together. The substrate values also have to be checked before planting is expanded. With sand ranging between 82.00% to 93.25%, clay between 1.00% to 5.00%, and organic carbon between 0.05% to 0.34%, the textural profile denotes a coarse early-stage planting medium as opposed to highly developed mangrove mud. Lewis (2005) placed hydrology and site condition before planting technique; that order matches the Nias sites. Sifahandro and Balefadoro Tuho had different monitoring histories from the high-record sites. At three months, Sifahandro recorded 38.66% and Balefadoro Tuho 45.88% after planting with nursery seedlings. Failed planting points were later replanted with propagules. The six- and twelve-month values included both the first planting and the replacement planting. Similarly, Kodikara *et al*. (2017) evaluated restoration success based on actual field performance rather than relying on mere planting metrics. N, P, and K worked as habitat information in this study. Total N was 0.04–0.07%, available P 2.30–4.22 ppm, and available K 0.17–0.41 m.e/100 g. None of these variables was significant as a single site-level correlation with live plant percentage. These values remain lower when compared to those of natural mangrove stands established in mud-dominated ecosystems (Friess *et al.,* 2019). Alongi (2018) treated nutrient dynamics as part of mangrove habitat function. For the coral-rubble block, the field sheet should be completed before planting starts. The sheet should list substrate texture, substrate pH, organic carbon, water condition, planting material, field exposure, and expected replacement planting. The eight Nias sites were in one monitoring program, but their field records were not the same. Schmitt *et al*., (2013) used site-specific planning for mangrove coasts with local variation. Keeping Botohilitano and Hiligawolo as separate site records also keeps the restoration target tied to field evidence (Friess *et al.,* 2022). Sifahandro, Balefadoro Tuho, and Botohilitano need different follow-up notes in the site sheet. By replanting the dead individuals with new propagules, Sifahandro's live plant percentage increased from 38.66% at three months to 82.24% at six months. Balefadoro Tuho increased from 45.88% to 76.05% in the same monitoring interval. Botohilitano did not show the same response; it was 63.76% at three months, 55.65% at six months, and 39.60% at twelve months. The maintenance record was kept with each monitoring period so field counts could guide replacement planting (Ellison *et al.,* 2020). Botohilitano and Hiligawolo should be classified as independent site records within national restoration databases. Although subjected to the same planting density, their twelve-month survival rates diverged significantly; Hiligawolo recorded 87.86% survivorship, surpassing Botohilitano's 39.60% by a substantial 48.26 percentage points. A planted-area total would not

show that gap. Sasmito *et al*., (2023) discussed Indonesia's mangrove restoration targets together with field constraints, and the Nias data show why site-level records are needed on coral-rubble planting land. Planting in Nias was done on reef-flat ground exposed after the earthquake. It was not old mangrove mud. The substrate still showed that origin: sand 82.00–93.25%, clay 1.00–5.00%, and organic carbon 0.05–0.34%. With little clay and organic carbon, the plots had little material for first-year root-zone development. Lovelock *et al*., (2015) reported the role of elevation and sediment supply in Indo-Pacific mangroves. Subsequent site assessments must separate open coastlines from habitats where planted mangroves can successfully survive their first year. Hiligawolo and Botohilitano cannot be placed in the same management class after the twelve-month record. Hiligawolo reached 87.86%, while Botohilitano stayed at 39.60%. Romañach *et al*., (2018) linked mangrove restoration outcome with site condition, restoration design, and follow-up management. The mortality of mangrove seedlings at this location likely stems from a combination of diverse environmental and biological factors, rather than a single variable. In coral rubble habitats, low substrate stability can inhibit root penetration, increase the risk of plants collapsing, and reduce the ability of seedlings to obtain water and nutrients. In addition, variations in hydroperiod, inundation frequency, wave exposure, and tidal conditions can increase physiological stress, especially in the early stages of seedling growth (Lewis, 2005). Biological stressors, including crab herbivory, pest and pathogen infestations, and interspecific competition-are well-documented impediments to the early-stage success of mangrove restoration (Friess *et al.,* 2019). Because this study did not determine the direct drivers of seedling mortality or delineate the relative influence of each environmental variable, the identified association between habitat quality and plant survival must be approached with caution. Future research needs to integrate monitoring of the causes of seedling death, hydrological measurements, substrate stability, and biotic disturbances to gain a more comprehensive understanding of the factors that determine the success of mangrove restoration in coral rubble habitats. The low content of organic matter in the coral fragment substrate indicates that habitat improvement has the potential to increase the success of mangrove restoration. The addition of organic matter, compost, or sediment enrichment can increase organic carbon content, water holding capacity, nutrient availability, and support the development of the root system and the activity of soil microorganisms, thereby increasing the ability of seedlings to adapt to sediment-poor substrates. However, the efficacy of these potential interventions remains unassessed in this study. Consequently, future research must systematically evaluate diverse habitat improvement techniques within an adaptive restoration framework to enhance mangrove establishment success in tectonically uplifted coral fragment substrates (Lewis, 2005; Friess *et al.,* 2019).

Study limitation

This study focuses habitat assessment on water quality and soil fertility parameters because these two groups of parameters are environmental indicators that can be directly measured during the monitoring period and have the potential to influence the success of mangrove planting. However, this study does not include quantitative measurements of hydrological and geomorphological parameters, such as elevation relative to sea level, frequency and duration of inundation, and tidal dynamics. These factors are critical determinants of habitat physical conditions, influencing sediment distribution, substrate aeration, and the success of mangrove stand establishment, particularly in earthquake-uplifted coral fragment substrates (Lewis, 2005; Friess *et al.,* 2019). Therefore, the relationship between habitat characteristics and percentage of living plants in this study needs to be interpreted taking these limitations into account. To achieve a more comprehensive assessment of habitat suitability and the factors governing mangrove

restoration, future research must integrate hydrological and geomorphological metrics with detailed water quality and soil analyses. The relatively low nutrient concentrations in the study substrates do not necessarily indicate that mangrove growth is limited by nutrient availability. Biogeochemical profiles of mangroves in carbonate and coral-rubble environments reflect lower levels of organic matter, N, and P, which can be attributed to the restricted deposition of organic litter and fine-textured sediments characteristic of these substrate types (Feller *et al.,* 2003). For example, mangroves on carbonate islands in Belize and the Caribbean have been reported to have organic carbon contents generally <2%, total N <0.20%, and available P <10 milligrams per kilogram (mg/kg), yet they maintain growth through efficient nutrient use, nutrient recycling, and physiological adaptation to oligotrophic conditions (Feller *et al.,* 2003). Therefore, the nutrient values obtained in this study are more appropriately viewed as a natural characteristic of the coral rubble substrate rather than as evidence of nutrient limitation. Proving nutrient limitation requires robust experimental validation, such as the implementation of nutrient-enrichment tests or the use of reference sites controlled for geomorphological and hydrological similarity (Alongi, 2018). Mangrove restoration in coral fragment habitats due to tectonic uplift has the potential to provide significant ecological benefits, such as increasing coastline stability, providing habitat for coastal biota, supporting biodiversity recovery, and increasing long-term carbon storage capacity (Friess *et al.,* 2019). In contrast to restoration efforts within natural, mud-dominated mangrove habitats, interventions on coral-rubble substrates encounter significantly greater challenges. Due to the less conducive physical habitat conditions, these environments necessitate more intensive monitoring, supplementary replanting, and rigorous adaptive management strategies. This condition has the potential to increase the costs of implementing and maintaining restoration. However, this study did not evaluate economic costs or long-term cost effectiveness, so it cannot directly compare the efficiency of restoration in coral rubble habitats with conventional mangrove restoration sites. Therefore, future research needs to integrate analyzes of costs, ecological benefits, and ecosystem services to evaluate the effectiveness of restoration more comprehensively. The sustainability of mangrove restoration in coral rubble habitats due to tectonic uplift also needs to be considered in the context of climate change. Rising sea levels, changes in tidal patterns and increasing wave intensity have the potential to change the effective elevation, hydroperiod and substrate stability which are the main factors in the suitability of mangrove habitat (Lovelock *et al.,* 2015; Alongi, 2018). In coral rubble habitats, these changes can increase erosion, reduce root stability, and limit sediment accumulation necessary for long-term development of mangrove stands. Conversely, successful mangrove establishment and the subsequent accumulation of sediment and organic matter can significantly bolster coastal protection, increase adaptive capacity to sea level rise, and augment the overall resilience of coastal ecosystems to climate change (Friess *et al.,* 2019; Sasmito *et al.,* 2023). Therefore, the success of restoration in coral rubble habitats is not only determined by the initial conditions of the habitat, but also by the ability of the ecosystem to maintain its ecological function against environmental changes in the long term. To properly assess the sustainability of restoration in tectonically uplifted ecosystems, long-term monitoring of hydrological changes, sediment dynamics, and shoreline stability is essential. The frequency, duration, and depth of tidal inundation, along with wave exposure and coastal hydrodynamic conditions, are the main factors determining habitat suitability, seedling stability, and the success of mangrove restoration. Variations in hydroperiod affect oxygen availability in the root zone, salinity, sediment deposition, and nutrient supply, while exposure to high waves can increase substrate instability, inhibit root formation, and cause seedlings to be

uprooted or fall over, especially in coral rubble habitats (Lewis, 2005). Given that hydrological parameters were beyond the scope of this study, their relative contribution to the differences in live plant percentages between locations remains unquantified. Therefore, the relationship between habitat characteristics and percentage of live plants in this study needs to be interpreted carefully. Future research needs to integrate measurements of hydroperiod, elevation relative to tides, wave dynamics, and sedimentation processes to obtain a more comprehensive assessment of habitat suitability and the factors that influence the success of mangrove restoration (Friess *et al.,* 2019). Root penetration, seedling anchorage, and the accumulation of sediment and organic material—all of which are vital to mangrove development—are fundamentally influenced by the physical attributes of coral-fragment substrates, such as surface stability, fragment size, and layer thickness (Lewis, 2005). In addition, coastal uplift due to tectonic activity can change elevation and hydroperiod, thereby affecting the suitability of habitat for mangrove growth (Friess *et al.,* 2019). Since these parameters were not measured, the differences in plant survival across locations are likely explained by variations in the physical characteristics of the substrate. Therefore, future research needs to integrate analysis of substrate physical properties, elevation, and sedimentation dynamics to evaluate the success of restoration more comprehensively.

CONCLUSION

Mangrove planting on earthquake-uplifted coral-rubble land in Nias gave uneven first-year records across the eight village-level sites. The twelve-month live plant percentage differed by 48.26 percentage points between sites, with Botohilitano recording 39.60% and Hiligawolo 87.86%, despite both receiving identical planting densities. Planted area and planting density alone did not describe the condition of each site. The substrate record separated these sites from mature mangrove mud. Sand ranged from 82.00% to 93.25%, clay from 1.00% to 5.00%, and organic carbon from 0.05% to 0.34%. Substrate pH was acidic, with values from 5.23 to 5.92. Total N, available P, and available K were also low. These variables describe a coarse, low-carbon, low-fertility planting medium. Live plant percentage has to be read with the replacement record. Three-month survival rates were low at both Sifahandro (38.66%) and Balefadoro Tuho (45.88%) after initial planting. To improve site coverage, failed planting points were replaced with new propagules. The six- and twelve-month records included the first planting and the replacement planting. They are reported as live plant percentage, not original-cohort survival. The Pearson analysis used eight village-level sites, so the results are site-level associations only. A positive association was observed between water temperature and seedling survival rates at six and twelve months post-planting. The carbon-to-nitrogen ratio showed a negative association, especially at six months. Total N, available P, and available K were not significant as single variables, but they remain part of the habitat diagnosis. For uplifted coral-rubble planting land, the next planting decision should keep site records separate. Live plant percentage, replanting history, substrate texture, substrate pH, organic carbon, water condition, fertility values, field exposure, and planting material need to be checked together before expansion. For this coastal typology, site assessment should extend beyond mere consideration of the planted area or the total number of planting units. The study results show variations in the success of mangrove restoration between locations, which emphasizes the importance of specific habitat assessments before restoration activities are carried out. However, these results warrant cautious interpretation, as seedling survival percentages were confounded by supplemental replanting activities. Furthermore, the relationship between habitat characteristics and survival remains exploratory; therefore, these findings cannot yet establish definitive predictors for restoration success. Therefore, future research needs to

integrate measurements of hydrology, elevation relative to tides, hydroperiod, and geomorphological characteristics to gain a more comprehensive understanding of the factors that determine the success of mangrove restoration in coral rubble habitats due to tectonic uplift.

AUTHOR CONTRIBUTIONS

E. Tuhono, contributed to conceptualization, field investigation, data collection, data analysis, methodology, visualization, and writing the original draft. Z. Nasution, the corresponding author, contributed to supervision, methodology review, scientific interpretation, and manuscript review. D. Delvian contributed to supervision, ecological interpretation, and manuscript review. N.M. Noor contributed to scientific review, manuscript editing, and critical revision.

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CONFLICT OF INTEREST

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

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ABBREVIATIONS

%	Percent
°C	Degree Celcius
AAS	Atomic absorption spectrophotometry
cm	Centimeter
C/N ratio	Carbon-to-nitrogen ratio
DO	Dissolved oxygen
EMR	Ecological mangrove restoration
g	Gram
ha	Hectare
K	Potassium
KCl	Potassium chloride
kg	Kilogram
L	Liter
LP	Live plant percentage
m.e.	Milliequivalent
mg	Milligram
mg/kg	Milligram per kilogram
mg/L	Milligrams per liter
mm	Millimeter
N	Nitrogen
P	Phosphorus
pH	Potential of hydrogen
ppm	Parts per million
ppt	Parts per thousand

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