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Mangroves, fauna compositions and carbon sequestration after ten years restoration on Flores Island, Indonesia

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Indonesia has extensively reforested mangroves to stabilize coastal ecosystems and mitigate climate change. Reforestation's long-term effects on recovering mangroves are not extensively established because most projects are only observed for two years. It raises the question of whether mangrove replanting aids biodiversity conservation and ecological recovery. This study will characterize Flores Island mangrove ecosystems after ten years of regeneration. The ecological survey took place at Bangkoor, Kolisia, and Talibura reforestation areas. Floristic composition, wildlife diversity, carbon sequestration, and energy storage were measured at each location. Field observations revealed 10 mangrove species and 11 species, which is varying by site. Flora diversity was highest in Kolisia and fauna diversity was highest in Talibura. Talibura and Kolisia have similar vegetation and wildlife than Bangkoor. Restored mangrove stands sequestered 28.69 – 70.02 Mg CO_2 ha^{-1} and stored 30.54 × 104 – 54.07 × 104 MJ ha^{-1} of energy. *Rhizophora apiculata* (47.37 ± 5.68 kg CO_2) had the most carbon sequestration, while *Bruguiera gymnorhiza* (645.22 ± 21.65 MJ) had the highest energy storage. Reforestation-induced mangrove ecosystems have biodiversity, carbon storage, and energy stock features.

Keywords *Mangrove*, *Restoration*, *Biodiversity*, *Carbon storage*, *Energy stock*

Mangrove habitats are crucial intertidal areas found in tropical and subtropical locations[1]. Mangroves exhibit exceptionally high levels of primary productivity, which sustains a diverse range of species and offers essential ecosystem services to coastal communities, including fishery resources and tourism opportunities[2–7]. The mangroves serve as effective barriers against the entrance of sea water and function as natural defenses against floods[2–4]. Furthermore, mangrove forests serve as carbon dioxide (CO_2) sinks and hence have a crucial role in assisting efforts to mitigate climate change[8]. Disturbed regions of mangrove forest can experience a significant reduction in primary productivity by up to 80% and a decrease in animal biodiversity by up to 40%. As a result, their ability to provide ecosystem services is greatly diminished, which has severe implications for human wellbeing[9,10]. Hence, safeguarding, and rejuvenating mangrove habitats are of utmost importance, for restoring macrofaunal communities along degraded coasts. This measure effectively prevents more ecological degradation and preserves the biodiversity within these habitats. Furthermore, mangrove restoration can enhance ecosystem services such as coastal protection, habitat creation, and biodiversity conservation. This is critical for maintaining healthy coastal ecosystems and supporting the livelihoods of people who depend on them.

Indonesia is one of the nations with mangrove forests, and its land area is 3.36 million hectares. Approximately 20–25% of the global mangrove ecosystem is in Indonesia[11]. However, Indonesia is currently facing the worst rate of mangrove loss worldwide. Indonesia's strategic location enables it to effectively contribute to the preservation of mangroves in efforts to mitigate climate change, conserve biodiversity, promote rural development, and foster

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renewable energy. Nevertheless, most mangroves in Indonesia are presently in a state of degradation because of the adverse effects of environmental pollution, changes in land use, and the illegal practice of logging[12]. Coastal populations often use wood from mangrove forests to produce charcoal, under strict regulations[13]. Nevertheless, the extensive deterioration of mangroves caused by many stressors is undermining the advantages for both biodiversity and socioeconomic welfare in coastal areas, despite the existence of restrictions. In 2050, it is estimated that the annual value of lost ecosystem services in Southeast Asia will be US$2.16 billion. Indonesia is expected to suffer the highest economic losses among the countries in the region[3].

Mangrove habitats exhibit a low inherent capacity for self-renewal. Consequently, when these ecosystems are cleared to produce commodities, the system's ability to recover is severely constrained[14]. Rehabilitation and replanting initiatives are employed to counteract loss and expedite recuperation. The management of mangroves is challenging due to their transitional and intertidal nature, leading to a lack of agreement on whether they should be treated as a terrestrial or marine ecosystem[15]. The government and various institutions, including the commercial sector and international organizations, work with local communities to carry out these endeavors[16]. Nevertheless, most mangrove reforestation efforts in Indonesia are typically monitored for a duration of only two years after establishment, in accordance with government policy outlined in the report of Directorate General of Forestry Planning and Environmental Management No. P.1/PTKTL/IPSDH/PLA.1/1/2017. By 2020, The Indonesia Ministry of Environment and Forestry and other affiliated entities will have planted 39,970 hectares of mangroves. Moreover, during the pandemic, the National Economic Recovery initiative expedited the restoration of 34,000 hectares of mangroves by 2021 with over 118,970 hectares of mangroves were rehabilitated between 2010 and 2021. However, there is generally a dearth of long-term monitoring or maintenance planning, as highlighted by[16]. Consequently, although the restoration of mangroves and reforestation are given high importance in Indonesian legislation, there is a scarcity of data regarding the lasting impacts of these restoration efforts on the recovery of ecosystems.

In 2013, the coastal area of Flores Island in Indonesia, stretching from Ende to Sikka, was reforested with native mangrove seedlings like *Rhizophora mucronata*, *Avicennia alba*, *Ceriops tagal*, etc[17]. This initiative, supported by the Amsterdam Institute for International Development, aimed to regenerate the mangrove ecosystem. The reforestation project was carried out through a collaborative effort with the local population. From 2015 onwards, mandatory evaluations were carried out to ascertain the viability of young plants following their establishment.

The assessment of restoration efforts in Indonesia typically spans a mere 2-year period and primarily focuses on survival rates, neglecting to examine the efficacy of ecosystem recovery or evaluate its long-term advantages. Hence, it is important to conduct extensive and ongoing monitoring and evaluation to ascertain the success of the ecosystem over an extended period. This study therefore aimed to determine the level of biodiversity in mangrove ecosystems after 10 years establishment; to examine the similarities in the plant and animal species found in mangroves between different sites after a decade of reforestation and to estimate the extent of energy storage and carbon sequestration that mangrove ecosystems can achieve during a ten-year timeframe in the Flores Island i.e. Bangkoor, Kolisia, and Talibura. The indicators were employed to authenticate the enduring impacts of reforestation on the restoration of mangroves, specifically in the realms of biodiversity preservation, mitigation of climate change, and advancement of renewable energy.

Materials and methods

Site description

This study was undertaken in three reforestation sites on the coast of Flores Island: Bangkoor, Kolisia, and Talibura (Fig. 1). The areas are administratively located in Sikka District, East Nusa Tenggara. The sites were the first areas for mangrove reforestation in 2013; thus, the mangrove stands are ten years old. The areas previously had natural mangroves, but they were degraded due to the impact of over-harvesting. The study site has a dry climate with an annual rainfall of 1,000 – 1,5000 mm year^{-} [18]. Dry periods occur more than seven months, starting from April to November. These sites have an average daily temperature of 31 °C with a mean air humidity of 75%. The total reforestation area (Table 1) in every site varies depending on the scale of the prior mangrove disturbance[8]. The water depth at three locations fluctuates between 98 and 155 cm during the mounting phase, and ranges between 18.6 and 32.3 during the downturn phase.

WD min and max (water depth), MD (mud depth), Sa (sand), Si (silt), Cl (clay).

Mangroves and animal inventory

Mangrove and animal surveys at the three sites were conducted based on the Regulation of the Director General of Natural Resources and Ecosystem Conservation, Republic of Indonesia Number: P.10/KSDAE/SET/KSA.O/9/20l6 concerning Guidelines for conducting inventories of potential natural areas and nature conservation areas.

The ecological survey used transect line and permanent plot quadrat (PSP) of 10 × 10 m across mangrove vegetation, which were arranged systematically to cover the environmental gradient of mangroves with a distance between plots of 50 × 50 m (Fig. 2)[8,18,19]. The number of plots in every site varied depending on the reforestation area but a minimum of 10 PSPs were included for every site. Mangroves inventory was conducted by establishing sub-plots within the PSP based on life stages: 2 × 2 m (seedlings), 5 × 5 m (saplings), and 10 × 10 m (poles and trees)[20]. In each PSP we recorded name of species, individuals number of species, and measured the diameter at breast height (DBH) and height (for poles and trees only) follows the Kaufmann method for mangroves. A fauna inventory was conducted in every PSP twice daily at 9 – 11 am and 2 – 4 pm using an observation method with a radius of 10 m, recording species identity and abundance[21].

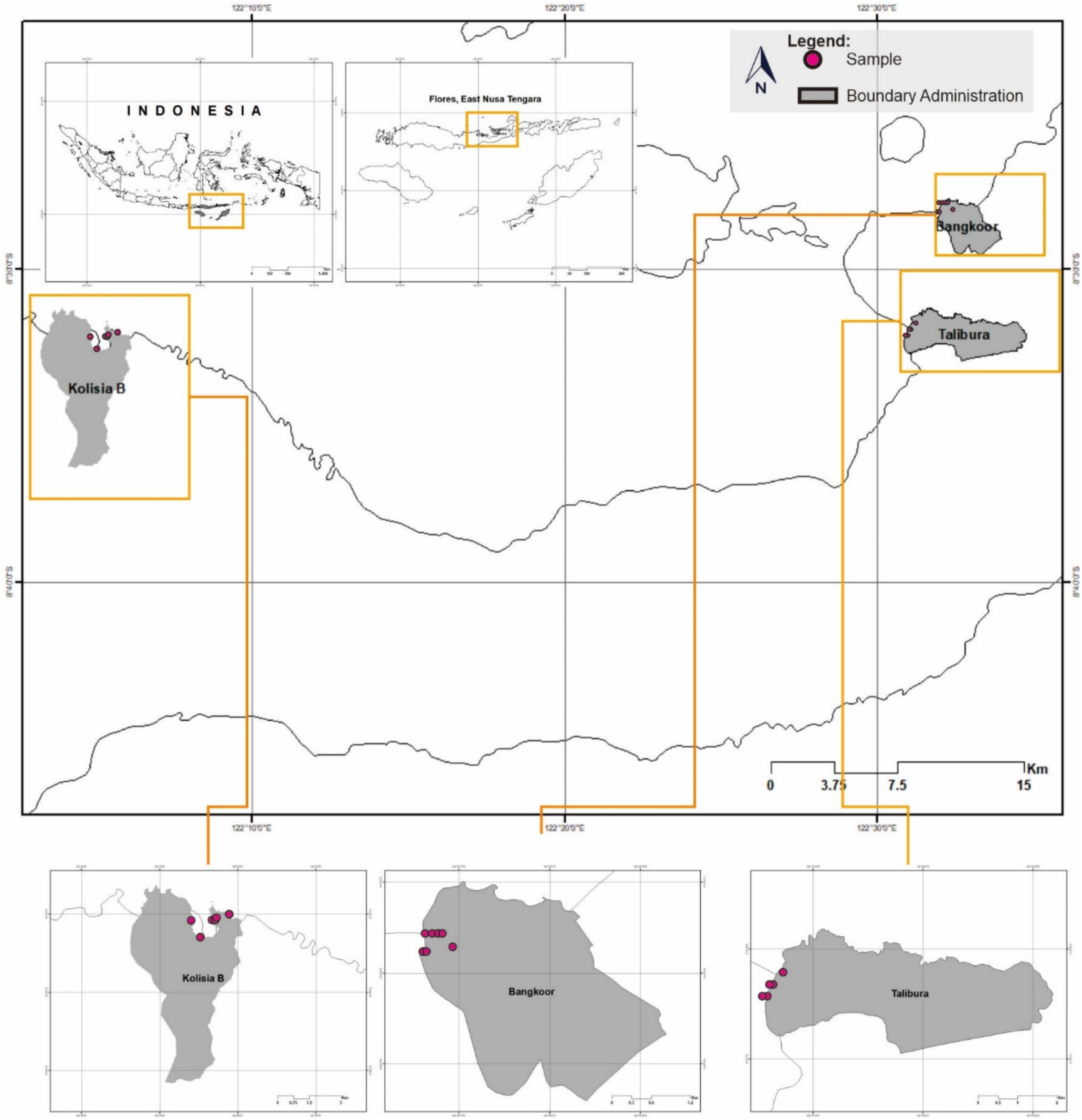

Fig. 1. The study site of mangrove reforestation is on Flores Island. The red polygon shows a site observation.

Site	WD (cm)	MD (cm)	Sa (%)	Si (%)	Cl (%)	Area (ha)
Bangkoor	18.6–98	40.4	51	26	23	8.4
Kolisia	16.3–120	17.2	43	40	17	12.3
Talibura	32.3–155	15.0	42	42	16	7.2

Table 1. Biophysical characteristics and total mangrove reforestation area in the study site.

Carbon sequestration and energy storage estimation

Our study used an approximate method to quantify carbon sequestration and energy storage. We did not conduct a destructive sampling method; therefore, carbon sequestration and energy storage estimation were only quantified for poles and trees. It was conducted step by step chronologically. First, individual tree biomass

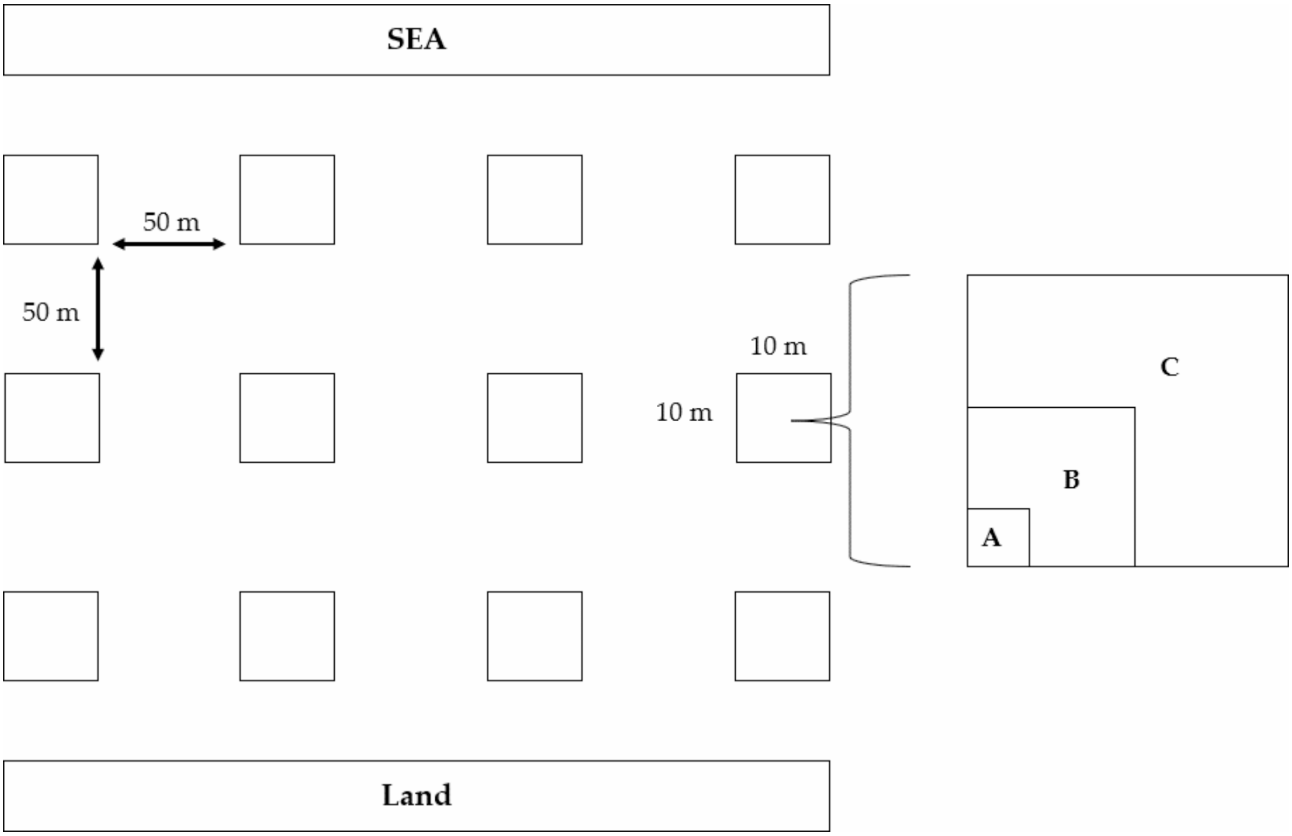

Fig. 2. The layout design of the ecological survey using permanent sampling plots to quantify observed parameters in the mangrove stands at three sites. The plots were made from the land toward the sea to represent mangrove zonation. The detailed sub-plots are A (sub-plot seedlings 2 × 2 m, B (sub-plot saplings 5 × 5 m, and C (sub-plot poles and trees 10 × 10 m).

Species	WD (kg m^{-3})	BEF	CV (MJ kg^{-1})
Aegizeras floridum	596.7	1.57	22.6
Avicennia alba	698.7	1.25	17.4
Avicennia marina	731.6	1.74	20.5
Bruguiera gymnorhiza	784.2	1.61	65.0
Ceriops tagal	885.9	1.53	37.0
Rhizophora apiculata	881.4	1.55	28.2
Rhizophora mucronata	848.3	1.53	21.4
Sonneratia alba	644.3	1.62	17.0

Table 2. Wood density, biomass expansion factor, and calorific value of each mangrove species.

was quantified based on the relationship between tree volume, wood density, and biomass expansion factor (Eq. 1)[8], . Data on wood density was derived from the World Agroforestry database and a literature search was used to find the biomass expansion factor value (Table 2) (http://db.worldagroforestry.org/wd). Then, the results of biomass estimation were converted to carbon storage using a constant factor of 0.47 (Eq. 2)[22], . In this context, we assume that approximately 47% of biomass was composed of carbon elements. This constant is determined based on Indonesia's national carbon accounting standard[22,23].

WD (wood density), BEF (biomass expansion factor), CV (calorific value), BEF was obtained from[19], while CV was derived from[24].

Carbon sequestration (CO_2) from every tree was calculated by multiplying between carbon stock and the number of relative molecules of CO_2 (Eq. 3)[25], . Meanwhile, energy storage for every tree was determined by multiplying the woody biomass in the stem and the calorific value (Eq. 4)[26], . Carbon sequestration and energy storage in every plot are computed by summing the value of every tree inside the plot. The results were converted into hectares units to estimate both parameters at stand levels. The detailed equations are presented below:

$$AGB = 0.25\pi \ x\, D^{2} x\, H\, x\, \rho \ x\, BEF \tag{1}$$

$$C = 0.46\, x\, AGB \tag{2}$$

$$CS = 3.67\, x\, C \tag{3}$$

$$ES = \ 0.25\pi \ x\, D^{2} x\, H\, x\, \rho \ x\, CV \tag{4}$$

where AGB was total aboveground biomass at the individual tree level (kg), *D* was diameter at breast height (cm), *H* was plant height (m), ρ was wood density (kg m^{-3}), *BEF* was biomass expansion factor, *C* was carbon stock at individual tree (kg), *CS* was CO_2 sequestration at individual tree (kg), *ES* was energy storage at individual tree (MJ), and *CV* was calorific value of species (MJ kg^{-1}).

Data analysis

Three indicators were selected to evaluate plant-animal diversity metrics in every site, i.e., richness, heterogeneity, and evenness. Species richness was quantified using the Margalef index (D_{mg}), while species heterogeneity was assessed using the Shannon-Wienner index (H')[27]. On the other hand, the species evenness was determined using the Pielou-Evenness index (J')[28]. We also calculated the Jaccard index to quantify the similarity of plant-animal composition between reforestation sites (SJ)[29]. The detailed equations for indices are presented below:

$$D_{mg} = \frac{S-1}{ln\,(N)} \tag{5}$$

$$H' \ = - \sum \left(\frac{n_i}{N}\, x \ln \frac{n_i}{N} \right) \tag{6}$$

$$J' \ = \frac{H\prime}{ln\,(S)} \tag{7}$$

$$SJ = \frac{c}{(a+b+c)} \tag{8}$$

where *S* was the number of species observed, *N* was the total species population, n_i was the sum of individuals for each species, *a* was the number of species only found in the first site, *b* was the number of species only discovered in the second site, and *c* was the number of similar species recorded in the first and second sites. The comparison mean of carbon sequestration and energy storage between species and site was also examined using a Kruskal-Wallis test due to lack of data normality, followed by the Nemenyi test ($\alpha < 0.05$).

Results

Floristic composition

Three growth phases of mangrove species were identified at the study sites (Fig. 3). The Bongkoor area exhibits a balanced distribution across all growth stages, signifying a robust ecosystem characterized by constant regeneration and the presence of mature trees. Kolisia demonstrated a significant prevalence of Poles/Trees, indicating a robust and mature mangrove population. Meanwhile, smaller numbers of seedlings and saplings may signify restricted recent regeneration or environmental stress impacting juvenile stages. Talibura exhibits a significant quantity of seedlings and saplings, indicating vigorous regeneration and initial growth processes. No poles or trees were documented, likely attributable to disturbances or an immature/recovering mangrove population. Ten mangrove species from 6 families were found across all three locations (Table 3). Mangroves belong to Rhizophoraceae were found dominant in the study areas, while most mangroves with IUCN status classified into Least Concern. However, our study noted a plant species listed in the IUCN database as near threatened: *Aegizeras floridum*. The mangrove species richness was recorded as 8 species in Kolisia, 7 species in Bangkoor, and 5 species in Talibura. Among these sites, mangroves in Kolisia consistently showed the higher in species richness, diversity index, and evenness index (Fig. 3a). There was high vegetation similarity between reforestation sites, wherein plant communities in Talibura relatively had a higher similarity (76.93) with Kolisia compared to the Bangkoor site (58.34%) (Fig. 4). Species driving inter-site differences were: *Avicennia marina*, which was only found at Kolisa, *Excoecaria agallocha* and *Lumnitzera rasemosa* which were only found at Bangkoor (Table 3).

Fauna diversity

Ten fauna species from eight classes were identified across the three mangrove reforestation sites (Table 3). Most of the wildlife were from classes Bivalvia, Reptilia, and Malacostraca, while some fauna species in these sites were not listed in the IUCN database. One endangered mammal species was identified *Macaca fascicularis*, the crab eating macaque. The highest fauna species richness was observed in Talibura (8 species), followed by Bangkoor (7 species), and Kolisia (6 species). Moreover, Talibura also had the highest fauna richness, heterogeneity, and evenness (Fig. 4b). There was high similarity in fauna diversity between sites, Talibura and Kolisia had a higher fauna similarity (71.43%) than Bangkoor (64.11%) as shown in Fig. 5. Species contributing to inter-site differences were *Argiope spp.*, *Chrysopelea spp.*, *Coenobita rugosus*, were only found in Talibura, while *Macaca fascicularis*, *Saccostrea cucullate* were only found in Bangkoor and *Varanus salvator* in Kolisia (Table 3).

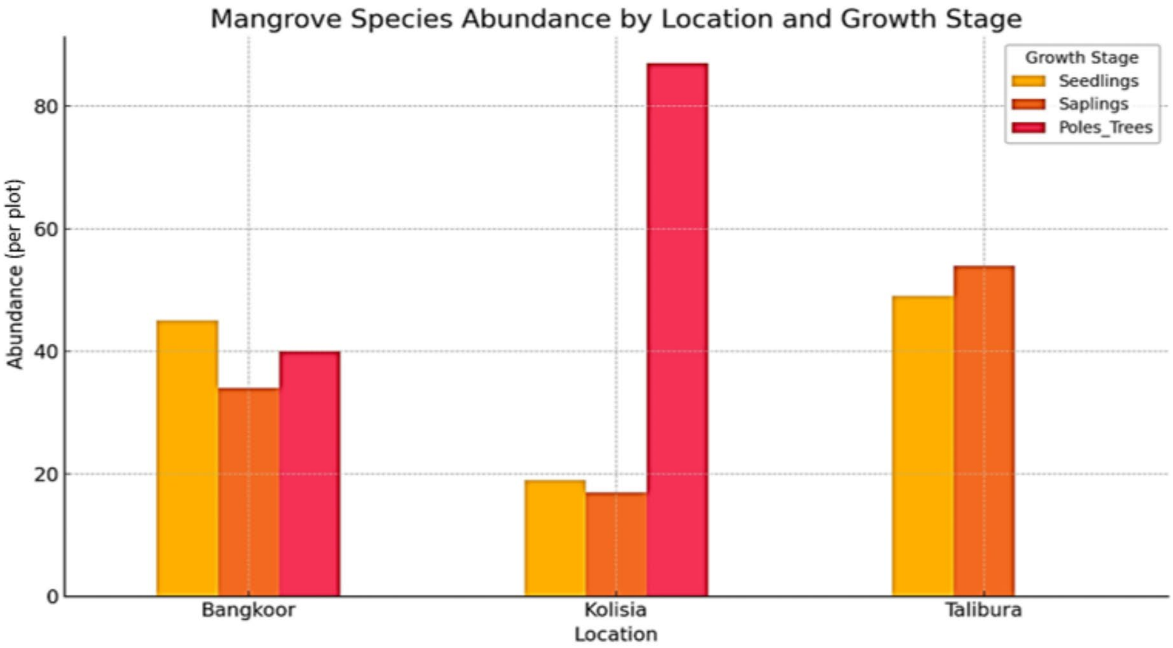

Fig. 3. The abundance of mangrove species in each growth stage at the reforestation site.

Species name	Family	IUCN status	Bangkoor	Kolisia	Talibura
Flora					
Aegizeras floridum	Primulaceae	Near threatened		x	x
Avicennia alba	Acanthaceae	Least concern	x	x	
Avicennia marina	Acanthaceae	Least concern		x	
Bruguiera gymnorhiza	Rhizophoraceae	Least concern	x	x	
Ceriops tagal	Rhizophoraceae	Least concern	x	x	x
Excoecaria agallocha	Euphorbiaceae	Least concern	x		
Lumnitzera rasemosa	Combretaceae	Least concern	x		
Rhizophora mucronata	Rhizophoraceae	Least concern	x	x	x
Rhizophora apiculata	Rhizophoraceae	Least concern	x	x	x
Sonneratia alba	Lythraceae	Least concern		x	x
Total flora species			7	8	5
Fauna					
Actitis hypoleucos	Aves	Least concern	x	x	x
Argiope spp.	Arachnida	Not available			x
Chrysopelea spp.	Reptilia	Least concern			x
Coenobita rugosus	Malacostraca	Not available			x
Macaca fascicularis	Mammalia	Endangered	x		
Pelecypoda spp.	Bivalvia	Not available	x	x	x
Periophthalmus gracilis	Actinopterygii	Not available	x	x	x
Saccostrea cucullata	Bivalvia	Not available	x		
Scylla serrata	Malacostraca	Not available	x	x	x
Telescopium telescopium	Gastropoda	Least concern	x	x	x
Varanus salvator	Reptilia	Least concern		x	
Total fauna species			7	6	8

Table 3. Distribution of flora and fauna species composition in every mangrove reforestation site.

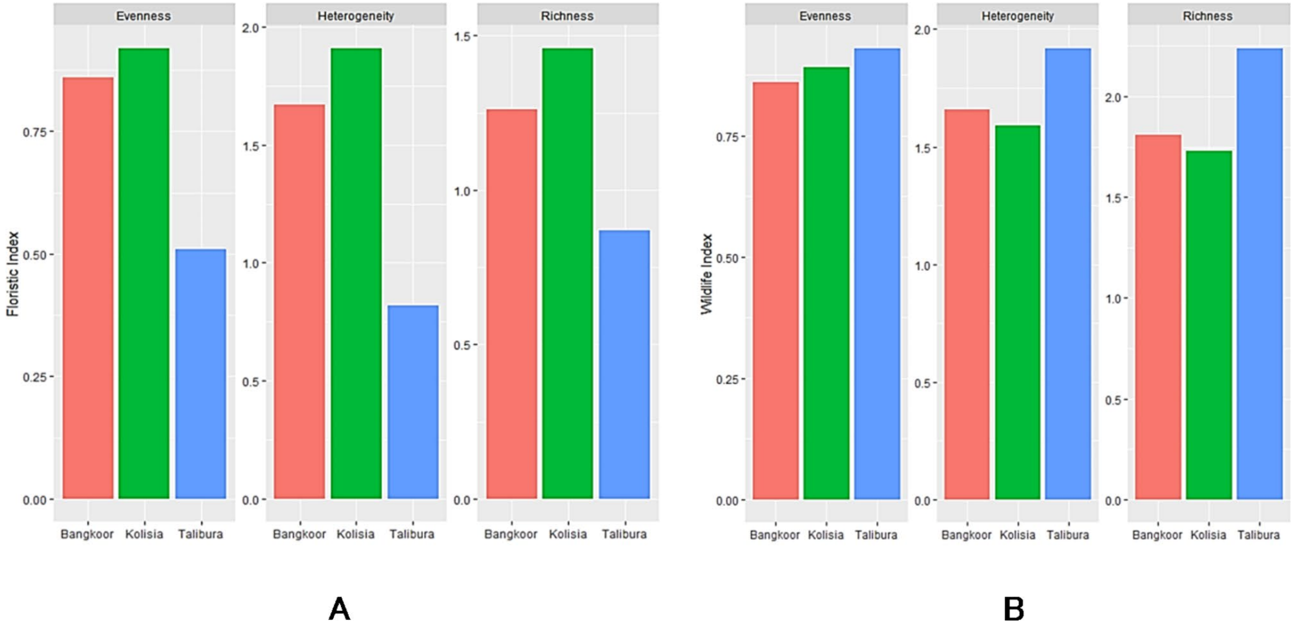

Fig. 4. Comparison of plant (**A**) and animal (**B**), species richness, species diversity, and evenness between reforestation sites.

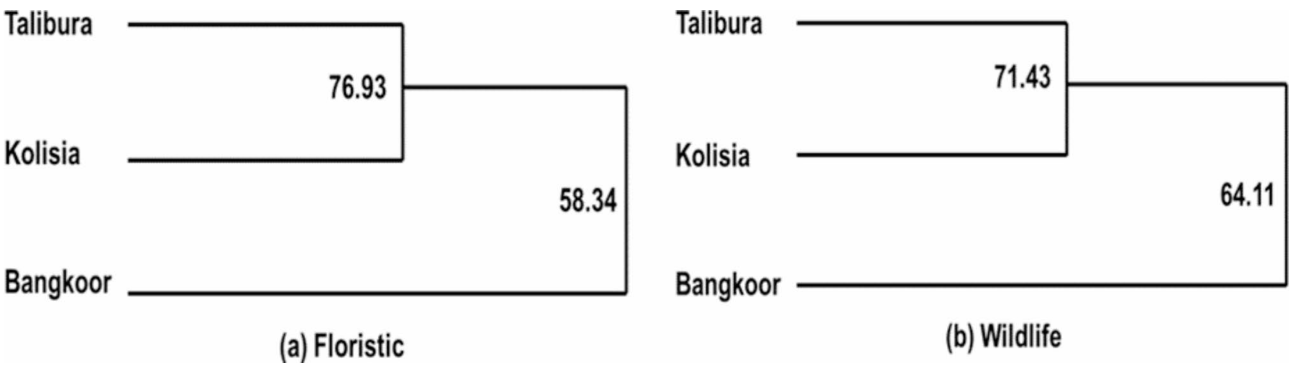

Fig. 5. The similarity level of (**a**) flora composition among and (**b**) fauna community between three sites.

Carbon sequestration and energy storage

After ten years of mangrove reforestation, carbon sequestration in restored mangrove stands reached 28.69 – 70.02 Mg CO_2 ha^{-1} with an energy storage of 30.54×10^4 – 54.07×10^4 MJ ha^{-1} (Fig. 6). However, both parameters were only calculated in Bangkoor and Kolisia since there were no poles, trees, or mangrove vegetation in Talibura. There was no significant difference between site carbon sequestration or energy storage. It could happen since the mangrove stand in both sites had a similar age distribution. However, the carbon sequestration and energy storage between mangrove species did not differ significantly (Table 4). Nevertheless, the species *Rhizophora apiculata* exhibited the greatest capacity for carbon sequestration, with a value of 47.37 ± 5.68 kg CO_2. On the other hand, *Bruguiera gymnorhiza* demonstrated the highest energy production, with a value of 645.22 ± 201.65 MJ (Table 5).

Discussions

Despite a decade passing since restoration, the mangrove ecosystems at the study site still exhibit a low level of variety, as determined by their richness, heterogeneity, and evenness (Fig. 4A and B). Talibura has the greatest water depth compared to the other locations when observed from the depths of the three locations (Table 1). This could have resulted in a reduced diversity of mangrove species in that area. The impact of rising sea levels on mangrove species is well-documented. Mangroves possess the ability to adjust to an increase in sea level, provided that the rise happens gradually, there is sufficient room for expansion, and other environmental factors are fulfilled. Mangroves have successfully acclimated to the increase in sea level by employing tree root expansion and sediment accumulation mechanisms, which enable them to preserve the elevation of the forest floor in relation to the rising sea level[30]. However, not all species are well adapted due to the anticipated acceleration in

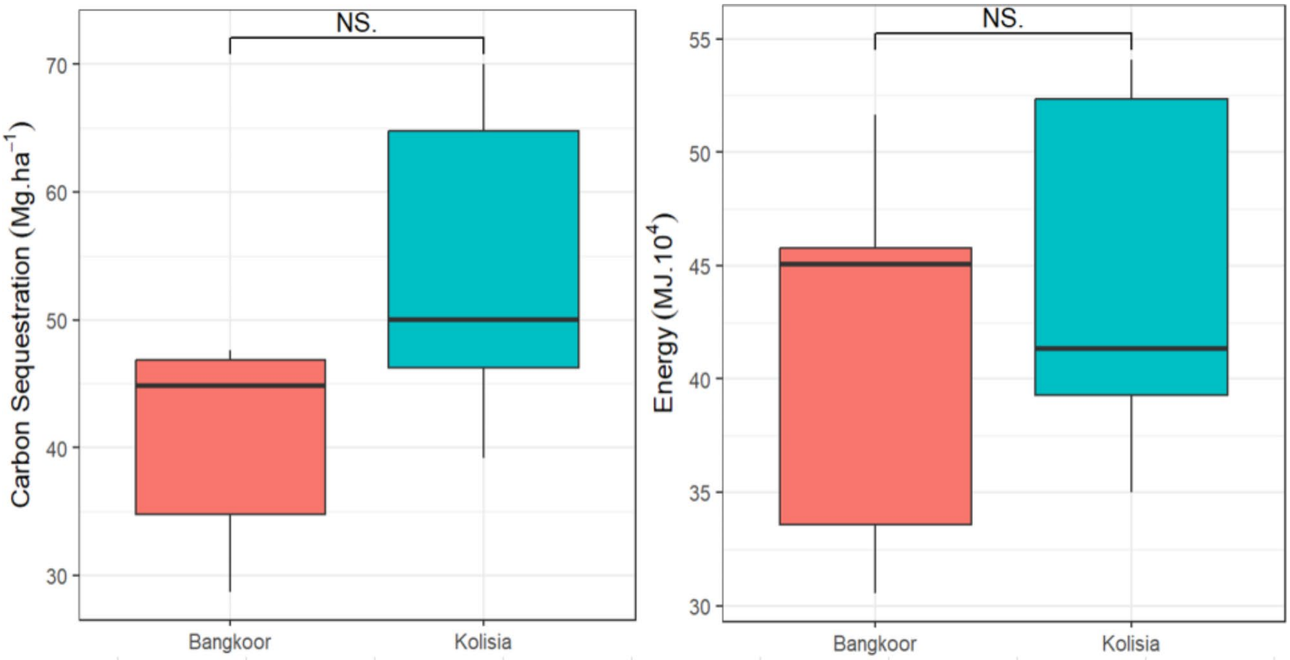

Fig. 6. Comparison of carbon sequestration and energy storage between reforestation sites. There were no poles and tree levels in Talibura; thus, it was not considered in calculating carbon and energy.

Site	AGB (Mg ha^{-1})	CS (Mg ha^{-1})	CO$_2$ Seq (Mg ha^{-1})	ES (x10^4 MJ ha^{-1})
Bangkoor	1.69 ± 0.48	0.78 ± 0.23	5.08 ± 1.06	5.17 ± 1.12
Kolisia	1.22 ± 0.23	0.56 ± 0.11	3.10 ± 0.32	2.55 ± 0.20
Talibura	–	–	–	–

Table 4. The carbon storage of each mangrove found in Bongkor and Kolisia.

Species name	AGB (kg)	CS (kg)	CO$_2$ Seq (kg)	ES (MJ)
Aegizeras floridum	10.32 ± 1.66	4.75 ± 0.77	17.42 ± 2.80	148.64 ± 23.90
Avicennia alba	19.64 ± 5.68	9.04 ± 2.61	33.16 ± 9.58	273.69 ± 79.03
Avicennia marina	27.67 ± 4.94	12.73 ± 2.28	46.71 ± 8.34	326.28 ± 58.24
Bruguiera gymnorhiza	15.99 ± 5.00	7.36 ± 2.30	26.98 ± 8.44	645.22 ± 201.65
Ceriops tagal	6.39 ± 0.50	2.94 ± 0.23	10.79 ± 0.84	154.43 ± 11.97
Rhizophora apiculata	28.06 ± 3.37	12.91 ± 1.55	47.37 ± 5.68	510.78 ± 61.25
Rhizophora mucronata	24.64 ± 2.11	11.34 ± 0.97	41.59 ± 3.56	344.14 ± 29.43
Sonneratia alba	25.75 ± 4.48	11.85 ± 2.06	43.47 ± 7.55	270.30 ± 46.94

Table 5. Comparison of carbon storage, carbon sequestration and energy storage in every mangrove species. **Indicated a significant difference based on the Kruskal-Wallis test. A similar letter in column showed non-significant results based on the Nemenyi-test.

the rate of sea level rise and alterations to the littoral environment that impede their ability to respond. Mangrove species capable of thriving and adjusting to rising sea levels should therefore be protected[30].

Previous study[29] also observed a limited range of species in mangrove forests following ten years of restoration efforts in the Kupang Gulf. The occurrence may arise due to the distinctive attributes of this ecosystem, which serve as inhibitory factors for species. In addition to their high salinity, mangrove forests are also affected by tidal cycles[7,22,31]. Mangroves' soil substrate exhibits gleization, as noted by[1], it generates harsh environmental conditions that challenge the survival of autotrophic organisms.

As a result, mangroves can support only a limited number of plant species that are able to develop and thrive in this environment. These plants possess inherent high salt tolerance and generate adapted root systems to adapt to tidal conditions[32]. The scarcity of vegetation in mangroves also influences a particular ecological niche for species, hence impacting their limited biodiversity. Nevertheless, alternative research posits that the abundance of animal species in mangrove ecosystems would progressively grow, contingent upon the stability of their ecological systems, with a particular emphasis on marine organisms[33]. In contrast, its vegetation is characterised by a limited number of distinct species.

Our study also observed a significant resemblance in the plant-animal composition of mangroves among reforestation locations. The state can be attributed to two primary factors: biophysical parameters and historical management. It is widely recognised that the physical circumstances in mangroves, such as salinity, flooding, and gleization, restrict the growth and survival of plant species[34–36]. Consequently, only a small number of plant species were selected to assist planting efforts. Furthermore, the capacity of plant materials to survive at each location is contingent upon the seed stock that local residents have collected. Seeds were gathered from the existing mangroves at each location throughout the restoration process, resulting in a diverse supply of seedlings for each species. Thus, the quantity of species during the first establishing phase has a significant impact on the present composition of vegetation. Furthermore, it has a direct impact on the habitat characteristics of species in different locations.

The carbon sequestration at our study site was much lower when compared to another restored mangrove ecosystem in Indonesia[29]. reported that the mean carbon storage of regenerated mangroves in Kupang, following twenty years of reforestation, was 454.71 Mg ha^{-1}. Additional research conducted in the Eastern Indonesian islands, specifically in Komodo National Park, revealed an average carbon storage value of 57.16 Mg ha^{-1}[37]. However, in the mangrove ecotourism area of West Lombok, a lower carbon storage value was found due to the mangrove plants being in the seedling and pole categories, specifically measuring 10,738 Mg ha^{-1}[38]. The carbon storage at our research location was 47.3 Mg ha^{-1}, which is suggests that the mangrove vegetation in Flores has a lower growth rate compared to the mangroves in Kupang, as carbon is the primary constituent of biomass derived from photosynthesis. Low energy storage is correlated with low carbon sequestration due to the fact that plants store energy in biomass[39,40]. Despite its limited carbon sequestration capacity, replanting efforts at each location nonetheless aid in the restoration of mangroves. Nevertheless, it may be necessary to implement enrichment planting in order to enhance biodiversity and enhance the process of carbon sequestration in the designated study area.

Conclusion

Following a decade of restoration efforts, the mangrove ecosystems on Flores Island exhibited notable fluctuations in the diversity of mangrove-fauna species, carbon sequestration, and energy storage. While the composition of flora and fauna was largely comparable across sites, certain species were unique to specific locations, indicating site-specific ecological dynamics. The reforestation efforts successfully increased carbon sequestration, with values ranging from 28.69 to 70.02 Mg CO_2 ha^{-1}, and enhanced energy storage between 30.54 × 10^4 and 54.07 × 10^4 MJ ha^{-1}. Despite these achievements, no significant differences were observed between the various sites, suggesting consistent reforestation success.

To further enhance our understanding, we recommend conducting comprehensive long-term studies to monitor mangrove health, resilience, and ecological transitions, as well as below ground carbon and sediment carbon stocks. These insights will be crucial for refining restoration practices and ensuring the sustained recovery and conservation of mangrove ecosystems. Overall, this study underscores the importance of sustained monitoring and adaptive management to maximize the ecological benefits of mangrove reforestation.

Data availability

The datasets used and/or analyzed during the current study available from the corresponding author on reasonable request.

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Author contributions

PW did the conceptualization. PW, LB and VH established the methodology. PW, BM, and BP did the data

collection. LB, BP prepared the data for analysis. PW, VH, and BM ran the data analysis. PW, VH, BP, and LB interpreted the data. PW, LB, and VH wrote the main manuscript text. JMS and LB did the language editing. PW, LB, JMS, HP, and VH revised the manuscript. PW, BP, SA, and VH acquired the funding. All authors reviewed the manuscript.

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Declarations

Ethical statements

The authors declare that this manuscript has never been published elsewhere or is not being considered for publication by another journal, and during the review process this manuscript will not be withdrawn and sent to another journal for evaluation. This manuscript does not contain unlawful, defamatory, or other statements and do not contain material that violates the personal rights or property rights of any other person or institution/organization.

Competing interests

The authors declare no competing interests.

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