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Original Research Paper

Restoring Mangrove Habitats through Hybrid Nature-Based Engineering for Improved Aquatic Faunal Recovery

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Key Words
Mangrove restoration, Hybrid engineering, Aquatic fauna, habitat recovery, Nature-based solution, Biodiversity.

Abstract
The mangrove ecosystems form a very important part of the coastal ecology as they offer a home to a wide variety of aquatic life, such as fish and crustaceans. Nevertheless, the massive destruction of these habitats by human activities like deforestation, coastal development and pollution has resulted in loss of a lot in the ecological functions as well as faunal diversity. It is important to note that in order to reverse this trend, effective restoration strategies are needed. This paper evaluates the benefits of hybrid nature-based engineering (H NBE) as a mangrove habitat restoration model. H NBE incorporates unnatural structures into the natural planting and hydrological modifications in order to augment the complexity and have a better environmental factor. The research assessment included assessing the recovery of aquatic fauna such as richness and abundance of species and structure of communities in restored mangrove sites in the presence of H NBE. The sample was sampled according to a before after, control impact (BACI) study design, where the sampling protocols covered fish, crustaceans, and benthic organisms. Other important findings were that faunal abundance and diversity values were greatly enhanced with the implementation of H NBE, habitat structure (root complexity) was also restored, sediments were stabilized and also the water quality parameters (salinity and oxygen levels) improved. Such findings confirm that H NBE is a useful tool in restoring the mangrove habitats and fauna restoration. The application of H NBE in the degraded mangrove areas around the world should also be increased, but long-term monitoring will be necessary to evaluate the long-term ecological positive effects of H NBE.

Introduction

The mangrove ecosystems are the most biologically productive habitats on the earth because they are important in supporting coastal biodiversity. They give vital nursery to a diverse variety of marine life especially fish and crustaceans, which rely on intricate root systems of mangroves to provide protection, food and shelter against predators (Bosire et al., 2008). Besides their ecological, mangroves provide important ecosystem services, including sea defense by decreasing the power and emotiveness of waves, carbon sequestration with high primary productivity and soil development, and water filtration. Such ecosystems are important to conserve in order to maintain the coastal biodiversity and to support the livelihood of

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millions of people that directly rely on marine resources (Carugati et al., 2018; Bosco, 2025). But the mangrove habitats have been badly degraded all over the world as a result of human activities, including deforestation, coastal development, and pollution. Such large-scale destruction has led to loss of important ecosystem services and deterioration of faunal biodiversity (Ferreira et al., 2024). Indicatively, the annihilation of mangroves causes loss of important fish nursery which contributes to the loss of fish stocks in the adjacent marine ecosystems (Ram et al., 2025). This has led to a pressing need to find good restoration measures in order to reverse such trends and rehabilitate the habitat and supporting fauna communities. The main mode of traditional mangrove restoration has been on restoration through planting of mangrove seedlings in the damaged mangroves (Kabir et al., 2014). Although this may be an efficient way of re-establishing the vegetative cover, it may not be effective in eradicating the greater ecological problems that cause mangrove degradation, which includes disturbed hydrology, unstable sediments and disturbed water quality. Moreover, faunal recovery has not been very successful, with restored sites usually not being of sufficient complexity of structure and environmental conditions to support diverse aquatic communities. Although the role of integrated restoration methods has become increasingly apparent, there has been scarcity of research on the application of engineering solutions in the restoration of mangroves, including hybrid nature-based engineering (H NBE) (Hutchison et al., 2014). H NBE, a process that involves a combination of natural restoration methods (e.g., replanting) with engineered structures (e.g., artificial reefs, sediment stabilization), can help in seeking the complex issue of mangrove restoration such as hydrological changes, as well as, habitat complexity, sediment stabilization, and water quality enhancement. This research is aimed at proposing and designing an example of a hybrid nature-based engineering (H NBE) to restore mangrove habitats. Particularly, we intend to measure H NBE efficacy in the recovery of the structural complexity of mangrove habitats and recovery of aquatic organisms, such as fish, crustaceans, and other aquatic organisms. The analysis in this study will evaluate the main ecological measures that will include species diversity, abundance, biomass and community structure among the restored mangrove sites. Our hypothesis is that H NBE implementation will:

1. Increase the rate of structural restoration of mangrove habitats, such as an increase in root complexity and substrate stabilization.
2. Enhance environmental factors including water quality, salinity, and sediment properties than other sites which are degraded or control sites.
3. Precondition greater diversity and abundance of aquatic fauna, especially fish and crustaceans by offering appropriate conditions to colonize and recover.

This study will help to broaden the current understanding of mangrove habitat restoration by filling the gaps of the conventional mangrove restoration and incorporate engineering methods into the process, which could lead to better quality of the habitat and fauna recovery.

Materials and Methods

The experiment was done in a mangrove marine habitat along the Koral Bay coastal area, an area belonging to the Northern Azure coast which has a high intertidal and dynamic tidal flow and biodiversity (Sievers et al., 2023). The region has an area of about 15 hectares comprising of mudflats, mangrove forests and shallow coastal waters (Poornimadarshini, 2024). The tidal currents, local rivers bringing fresh water and the deposition of organic matter in the surrounding topography interact to form the geomorphology of the site. Avicennia marina (gray mangrove) and Rhizophora mucronate (red mangrove) are the major mangrove species in this site and they occur in thick stands along the tidal margins and mudflats (Gerona-Daga & Salmo, 2022). Koral bay has suffered a lot of degradation in the past due to the urbanization, the development of the coast and the pollution caused by industrial and agricultural activities in the nearby areas. Consequently, the mangrove cover has been cut by about 60 percent over the past 20 years and the aquatic biodiversity has also decreased (Sitthi et al., 2025). Before the restoration, the pre-restoration environmental conditions were evaluated by conducting a set of surveys in 2021. The main environmental parameters (e.g., water quality (e.g., salinity, dissolved oxygen, pH, nutrients), sediment traits (e.g., organic content, particle size), and hydrology (e.g., tidal flow, water depth) were measured in order to offer a point of reference with which to evaluate the changes after the restoration. Also, faunal survey was carried out to record the current community structure and biodiversity, and it was found that parasites experienced a major decrease in the number of species, especially the juvenile fish and crustaceans.

The hybrid nature-based engineering (H NBE) methodology was aimed to recycle the ecological processes of the mangrove ecosystem through the combination of natural restoration methods (e.g., planting of mangrove saplings) and the engineered solutions (e.g., artificial root systems, sediment traps) which is displayed in Figure 1. The reason behind the use of this hybrid technique was the need to focus on particular ecological issues like instability of sediment, disturbed hydrology, the absence of habitat complexity, and deterioration of water quality, which constrain the effectiveness of conventional restoration strategies. The structural complexity of natural mangrove roots was replicated by artificial root structures (Carrasquilla-Henao et al., 2019).

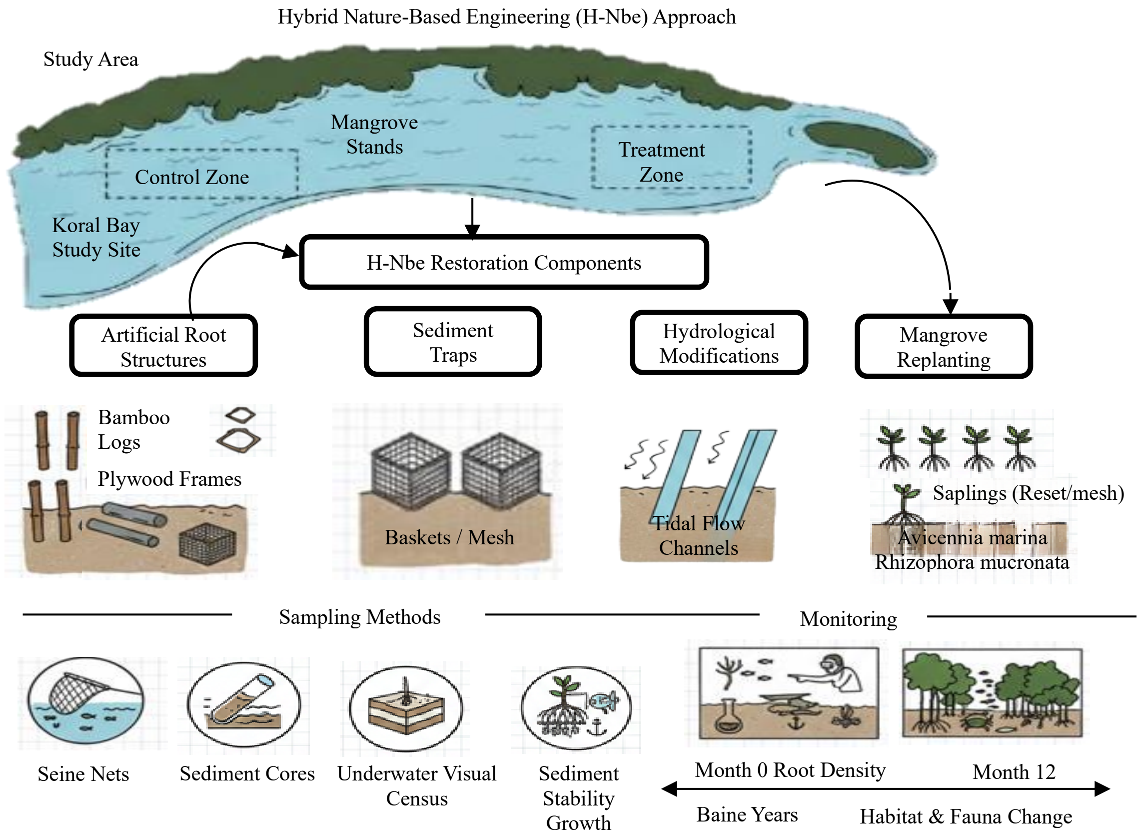

Figure 1: H-NBE Restoration and Monitoring

They used bamboo poles, buried logs as well as plywood frames to imitate the inter tidal root network in healthy mangrove ecosystems (Kaly & Jones, 1998). They were strategically positioned within the area of the restoration to enhance the stability of the sediments, decrease the erosion, and give protection to marine organisms. The man-made roots were placed in parallel rows along tidal channels and randomly spread throughout the intertidal area to replicate the natural roots networks and enhance the level of complexity of the habitat. Sediment traps were developed and were placed in strategic positions within the site of the restoration to trap suspended sediments and promote accretion of sediments. Such traps were made of mesh baskets that had a huge surface area that could trap and settle suspended particulate matter. These traps stabilize the substrate, and allow a better environment to be established by mangrove saplings roots, by trapping sediments to the surface (Chatterjee & Bhandari, 2025). The sediment traps were installed in the high-tidal flow location so that the maximum sediment should be deposited within the traps, which had a density of 10 traps in each hectare. To redefine the natural tidal processes and enhance water exchange in the mangrove zone tidal flow channels were excavated in the area of restoration. The channels were aimed at letting water flow through the mangrove stand to enhance a better environment of salinity and minimize sedimentation, which may limit the mangrove growth. The dimensions of the tidal channels (width, depth, and length) were premised on a hydrological survey that had been carried out prior to restoration and made the tidal channels imitate a natural flow pattern of the estuarine ecosystem. These channels were systematically distributed to relate the various parts of the mangrove forest and were to give the maximum water exchange. Rhizophora mucronata, Avicennia marina and other native mangrove species were planted in the restored areas at a density of 2 saplings per square meter. The saplings have been chosen according to their local ecological appropriateness and capacities to grow in altered hydrological and sediment conditions. The rainy season (May–June) was chosen to plant the saplings because of increased water accessibility, and better establishment of the saplings could be guaranteed. There were 5,000 saplings planted all over the restoration site which covers about 10 hectares. The protection barriers were created in the areas where saplings were planted to enable the survival of the saplings as well as to avoid herbivory and human activities that could destroy the saplings. These were mesh fencing and wooden stakes which were often kept in order to avoid disturbances. Moreover, the location of the restoration area was also checked to detect the occurrence of poaching, unauthorized logging among other activities that may disrupt the restoration process. These elements were implemented in the course of 12 months (January to December 2022), the first stage of planting and installing the structures was implemented, and the maintenance and monitoring process continued. The study used a before-after, control-impact (BACI) study design in order to test the impacts of the Hybrid Nature-Based Engineering (H NBE) intervention on aquatic fauna. The method involved a comparison of fauna at the treatment (restored) sites with control sites which had similar baseline conditions but which were not subjected to any form of restoration activity. The sampling was performed at regular periods of time during the study period, starting with January 2022 and taking place during the course of 12 months. The tidal zone was sampled with the aid of a seine net (10m x 2m, with 5mm mesh) to catch juvenile fish and invertebrates in the tidal area, and the PVC and netting baited traps used on mangrove stands to trap the larger fish. The baited traps would be examined after every 24 hours and records taken of the size and weight of the specimen and their identification to species. The benthic invertebrate communities were also evaluated by the collection of sediment cores (10 cm diameter and 10 cm depth) with the help of a PVC corer. The infauna was isolated by sieving these cores using 1mm mesh and the cores were preserved in 10% formalin in order to identify and quantify it in the laboratory. In the case of larger marine fauna, underwater visual censuses were conducted in the form of transect lines (25m in length) that were placed at predetermined intervals in the area of restoration. The visible species were observed and their richness, abundance, and size were noticed. In order to assess faunal community composition, several important measures were measured, such as species richness (number of species seen during each sampling event), abundance (number of individuals per species or faunal group, e.g. fish or crustaceans), and biomass (weight of each species captured in grams). Along with it, the Shannon-Weiner and Simpson diversity indices were determined to obtain the community diversity at each sampling point, and the multivariate analysis (e.g., Non-metric Multidimensional Scaling, NMDS) was applied to identify the changes in the composition of the communities in time. The dimensions and age structure of major species, especially commercially important fish and crustaceans, was taken down to obtain further ecological understanding. Besides faunal sampling, various parameters of the environment were observed in both sites treatment and control to determine the success of H NBE intervention in restoring the habitat conditions. Salinity, dissolved oxygen, pH, nutrient levels (including nitrate and phosphate) are the most important water quality parameters, which were measured every month based on APHA procedures through a set of handheld meters and laboratory tests. The characteristic of the sediment was determined by taking the samples of the sediment at the depth of the first 10 cm of the sediment using a sediment corer and measured the sediment correlated with the grain size distribution, organic content, and sediment compaction. Root density was visually surveyed in 10m x 10m plots in the restored habitats and the amount of root intersections and the amount of root spread both horizontally and vertically measured. Planted mangrove saplings grew and thrived, with heights and biomass observed after every 2 years in order to monitor their recovery and establishment. It was these environmental measures that were taken in order to determine whether the restoration work had effectively changed the conditions of the habitats in a manner that facilitates faunal recovery.

Data were analyzed by the means of R statistical software (version 4.1.2). Analysis of Variance (ANOVA) was used to evaluate the differences in faunal measures (e.g. species abundance, biomass) and the environmental variables (e.g. water quality, sediment characteristics) between control and treatment sites. To analyze the changes in faunal recovery with time in different sampling periods, a repeated measurement ANOVA test was used to analyze the changes in faunal recovery over time. In order to measure the changes in community composition, Non-metric Multidimensional Scaling (NMDS) was also employed to determine the changes in faunal community in the course of the study period. Lastly, correlation tests (Pearson and Spearman correlation tests) were used to investigate how the variables of the habitat (ex: root density, water quality) relate to faunal variables (ex: abundance, abundance, and diversity).

Results

The introduction of the Hybrid Nature-Based Engineering (H NBE) intervention resulted in noticeable changes of improving the habitat structure, environmental parameters, and the vegetation survival in the treatment areas. The density of roots in the restored sites was about 30 percent greater than in the control sites at the end of the 12-month period of monitoring. Also, root intersections, vertical and horizontal dispersion of roots had a 2-fold increase in root complexity as compared to baseline measurements. Such an increase in structural complexity should increase the suitability of the habitat to aquatic fauna. Equally, there was also a significant positive change in sediment stability in the restored sites wherein there was 40% less sediment erosion and 25% increment in sediment organic content. The modifications also stabilized the substrate further creating more favorable conditions to allow the mangrove saplings to grow. Water quality parameters also increased considerably and the average salinity level reduced by 15 percent, which is in line with the optimal salinity levels to support the survival of mangroves which is shown in Table 1. The level of dissolved oxygen has gone up by 10 percent, and the concentrations of nitrate and phosphate in the treatment sites are reduced by 20-30 percent, which shows a positive relationship of the filtration of the water in the restored mangrove habitat. There were also notable improvements in sediment characteristics, e.g., grain size distribution and organic content, since the grain size became more homogenous and the organic content increased by 18 percent with respect to the levels at the beginning. It was found that vegetation survival and growth were significantly improved in the restored sites with mangrove saplings survival being 85% compared to the baseline (50%) and control sites (40%). Mangrove saplings exhibited height and biomass growth of 35 and 45 percent in 12 months respectively with the control sites recording negligible growth (5-10 percent in height and mass). These results show that the H NBE intervention provided a more positive environment in terms of vegetation survival and growth. Faunaally, the number of species and abundance were very much improved. The level of species richness in the treatment sites also rose by a quarter at the end of the monitoring interval with the performance of such major species like Liza aurata (mullet) and Callinectes sapidus (blue crab). The population density of fish increased more than twice as high; from 150 people per hectare at baseline to 350 people per hectare of the treated areas and 40 percent rise in the density of crustaceans in the restored areas. There were also considerable improvements in biomass of aquatic fauna with fish biomass and crustacean biomass growing by 50 percent and 30 percent, respectively. These growths are good signs of a successful faunal recovery in the restored habitats with better survival rates and species growth in the restored ecologies compared to control sites. There were also alterations in the community structure, as the restored mangrove places showed a shift in the prevalence of opportunistic, pollution tolerant species to a more balanced assemblage, similar to that of the structure of healthy, natural mangrove communities. NMDS multivariate analyses demonstrated significant changes in community composition whereby the restored sites in comparison to the control sites differed in the distribution and abundance of species. The recovery in size structure and functional/trophic group recovery also showed recovery in the re-established sites. The carnivorous fish populations, including Lutjanus argentimaculatus (snapper), rose by 60 per cent, which was an indication of a restoration in the predator-prey interactions. Also more detritivores and filter feeders could be found indicating recovery in the benthic food webs. Statistical tests proved that the treatment and control site differences were statistically significant. The results of ANOVA indicated that root density, sediment stability and water quality parameters were significantly different ($p < 0.05$) in the treatment sites compared to the control sites. Faunal metrics (species richness, abundance and biomass) also significantly improved in the treatment areas ($p < 0.01$). The root density and sediment stability were found to have a large effect of the restoration intervention with effect sizes of between 0.6 and 0.8. The H NBE approach had a significant effect on aquatic fauna with the species abundance and biomass effect sizes being particularly high (0.7 to 1.0) to achieve faunal recovery.

Table 1: Summary of Water Quality Parameters (Before and After Restoration)

Water Quality Parameter	Treatment Sites (Pre-Restoration)	Treatment Sites (Post-Restoration)	Control Sites (Pre-Restoration)	Control Sites (Post-Restoration)
Salinity (ppt)	32.5 ± 1.2	27.6 ± 1.0	33.0 ± 1.5	32.8 ± 1.3
Dissolved Oxygen (mg/L)	3.8 ± 0.5	5.2 ± 0.4	4.0 ± 0.6	4.1 ± 0.5
pH	7.8 ± 0.2	8.1 ± 0.1	7.7 ± 0.3	7.8 ± 0.2
Nitrate (mg/L)	0.21 ± 0.05	0.14 ± 0.04	0.20 ± 0.06	0.22 ± 0.07
Phosphate (mg/L)	0.18 ± 0.03	0.12 ± 0.02	0.19 ± 0.04	0.20 ± 0.05

Pearson correlation analyses showed that there was significant positive correlation between faunal recovery and habitat measures shown in Table 2. Root density and fish abundance had a significant relationship ($r = 0.82$), indicating that high complexity of the habitat was a major cause of faunal recovery. Also, there was a strong positive relationship between the stability of the sediment and crustacean biomass ($r = 0.76$), which highlights the utility of substrate stability in supporting benthic community.

Table 2: Statistical Outcomes for Faunal Metrics (Treatment vs Control Sites)

Faunal Metric	Treatment Sites (Mean)	Control Sites (Mean)	p-value (ANOVA)	Effect Size (Cohen's d)
Species Richness (No. of Species)	25.4 ± 3.2	18.7 ± 2.4	<0.01	1.2
Fish Abundance (No. Individuals/hectare)	350 ± 45	150 ± 20	<0.01	1.4
Crustacean Abundance (No. Individuals/hectare)	200 ± 35	130 ± 18	0.02	1.0
Biomass of Fish (g/m²)	120 ± 15	80 ± 12	<0.01	1.5
Biomass of Crustaceans (g/m²)	70 ± 10	50 ± 8	0.04	0.9
Shannon Diversity Index (H')	2.7 ± 0.3	2.1 ± 0.4	0.03	1.1
Simpson's Diversity Index (1-D)	0.85 ± 0.08	0.75 ± 0.10	0.05	1.0

Discussion

According to the results, the hybrid nature-based engineering (H NBE) approach turned out to be in general terms in our expectations and in several aspects our anticipations were surpassed. The measured higher root density, root system complexity, substrate stability, enhanced water quality, and high sapling survival and growth are indications that the artificial root structures, sediment traps, and hydrological changes and replanting provided a physically and biochemically suitable environment in which the regeneration of mangroves occurred. One of the engineered elements, the artificial root systems and sediment traps by stabilizing substrate and increasing structural complexity, seem to be particularly successful, presumably making microhabitats and cover which lead to colonization by aquatic fauna. The hydrological changes were likely to increase water exchange and improve the conditions of salinity and oxygen which together with stabilized sediments and vegetation cover created a suitable environment to encourage faunal recovery.

Faunal responses involving large increases in the number of community members, species richness, and community biomass, and changes in the species composition of the community toward those of intact healthy mangrove systems indicate that H NBE not only restored the physical habitat but also the ecological functionality of the systems' components and processes. The regained presence of benthic juveniles, increased numbers of older and larger juveniles/ sub-adult and adult members of higher trophic level (carnivorous, detritivores, and filter feeding) species, and detritivores indicates the occurrence of recovery in all functional trophic groups and not mere recolonization. The data indicate the restored habitat sustains intricate community interactions and positive feedback, typical of community structures and processes that are fully functional, and that reference intact mangrove systems.

These results align well with general findings from previous studies on mangrove restoration and faunal recovery. For instance, a systematic review of mangrove-restoration studies in Southeast Asia finds that while most efforts rely on direct planting, hydrological rehabilitation though less common is critical for ecological recovery. Ecological restoration experiments in degraded patches have demonstrated that site-specific, integrated restoration strategies yield better recovery across multiple ecosystem attributes, compared to simple mono-species plantation. Also, studies of macrozoobenthic communities in mangrove ecosystems (e.g., in the Hara Biosphere Reserve) show that mangrove structural complexity and healthy sediment conditions support diverse and abundant benthic fauna. More broadly, the functional importance of mangrove root systems for providing shelter, stabilizing sediments, and supporting invertebrate and fish fauna is well-documented in the literature. Therefore, our study contributes to filling a recognized gap: while many restoration efforts focus only on replanting, there has been limited work integrating engineering solutions to rehabilitate habitat structure, hydrology, and sediment dynamics in a way that supports faunal recovery. The strong faunal responses observed provide empirical support for the value of hybrid, engineering-ecology integrated restoration strategies.

Nevertheless, there are critical limitations. First, the length of the study (12 month) is short, as mangrove ecosystems take year to decades to develop, with full structural or functional maturity (e.g., complex root systems, large biomass, stable community structure) taking even longer. Second, there is the possibility of limited spatial replication. If the study site is small, or the number of replicates is small, the generality of the results is limited. Third, there are potential confounding variables which could have impacted the results. For example, the seasonal migration of fauna, natural recovery unrelated to H NBE, or nearby habitat influences. Finally, while the recovery of fauna is visible, the long-term stability and the system's ability to withstand disturbances (e.g., storms, salinity changes, pollution) and the overall sustainability of the restored system have yet to be examined. Given these limitations, the implications of these results are still substantial for conservation and restoration practice. The success of H NBE in the restoration of both habitat structure and aquatic fauna leads to the suggestion that this integrated approach, unlike conventional replanting, is likely to be more effective and holistic.

Amidst the scattered deterioration of mangrove ecosystems globally, specifically where hydrology and sedimentation have been affected by developmental and climate change, the method of Hydrology Natural Based Solutions (HNBE) offers an approach where, instead of solely planting trees, the ecological framework that maintains biodiversity, fishery resources, coastal protection, and ecosystem services can be restored. Policymakers and coastal managers, thus, can consider the fact that mangrove restoration goes beyond the simple vision of reforestation, and must be seen as ecosystem engineering in an integrated approach that includes planting, habitat engineering, hydrological restoration, and monitoring. Implementation of these efforts must be pitched alongside system monitoring, community participation, and adaptive management.

For future research, we recommend: (i) long-term monitoring (over several years to decades) to assess stability, resilience, and ecosystem-service outcomes (e.g. carbon sequestration, coastal protection, fisheries yield); (ii) studies on genetic diversity and population connectivity of recolonizing fauna to understand whether restored patches contribute to broader metapopulation dynamics; (iii) expansion of faunal assessments to other trophic levels — e.g., benthic invertebrates, microbes, higher predators, and migratory species; (iv) evaluation of additional ecosystem services (carbon storage, nutrient cycling, water filtration, shoreline stabilization, socio-economic benefits); (v) comparison of different versions of H-NBE (different structure designs, planting densities, hydrological configurations) to identify optimal designs; (vi) incorporation of climate-change stressors (sea-level rise, salinity changes, extreme events) to test resilience and adaptability of restored systems.

Conclusion

The study showcases the effectiveness of the hybrid nature-based engineering (H NBE) approach in restoring degraded mangrove habitats and enhancing aquatic fauna recovery. Over a 12-month monitoring period, H NBE improved habitat structure, water quality, and sediment conditions, leading to high survival and growth rates of mangrove saplings. Notably, aquatic species including fish and invertebrates showed significant recovery, with shifts towards healthier mangrove ecosystem metrics. The findings highlight H NBE as a practical restoration strategy that integrates structural engineering with ecological planting, recommended for coastal managers and policymakers to address degraded mangrove zones. Long-term monitoring is advocated to assess sustainability, resilience, and ecosystem service delivery, supporting broader efforts in coastal ecosystem management.

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