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Review

Ecological Engineering and Restoration of Eroded Muddy Coasts in South East Asia: Knowledge Gaps and Recommendations

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Abstract: Ecological engineering (EE) was employed for developing strategies for stabilizing eroded muddy coasts (EMCs). However, there was a limited analysis of these EE strategies with respect to design, performance, and lessons learned. This study employed a critical review for addressing the limitations. There were four EE models designed with different restoration interventions for stabilizing EMCs. The models using active interventions have not been cost-effective in controlling erosion because the interventions failed to achieve their goals or were costly and unnecessary. Of the two passive intervention models, the one with structures constructed from onshore proved to be more cost-effective in terms of construction costs, the survival rate of transplanted seedlings, and levels of sea mud accumulation. Interventions with adequate consideration of the muddy coastal ecological processes and the ecological reasoning for the positioning of these interventions play a crucial role in stabilizing EMCs. A passive restoration model using gradually expanded interventions should be promoted in order to ensure sustainable management of EMCs in the future.

Keywords: active restoration; muddy coasts; passive restoration; sea mud accumulation; transplantation

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1. Introduction

Ecological engineering (EE) has evolved as a prominent field with global significance, particularly in the context where resources are dramatically diminished [1,2]. EE involves the application of ecological processes in combination with engineered principles in restoring substantially disturbed ecosystems to as close to their original conditions as possible, or in creating new sustainable ecosystems with human and ecological values [3–5]. EE entails a crucial principle that is ecological restoration [3]. Ecological restoration basically aims to restore a damaged ecosystem through the promotion of self-healing processes in an ecosystem that assists in gaining equilibrium or to support healthy communities with minimum human intervention [6]. Ecological restoration does not produce maximum effects until different knowledge sources, i.e., social and natural sciences, are combined [7]. Ecological restoration is needed when an ecosystem has been degraded to the extent that it has no signs of recovery [3]. Ecological restoration is undertaken through either active restoration or passive restoration [2]. While active restoration involves the use of external influence, normally by conventional engineering approaches for restoring degraded ecosystems, passive restoration seeks to remove stressors facing ecosystems so that they gradually recover themselves [2].

EE has been employed for developing management strategies in various fields; for example, promotion of sustainable agriculture development [8], control of erosion on mountainous areas [9], conservation of karst-related ecosystems [10], mangrove restoration [3], reduction of environmental impacts caused by built infrastructure, or provision of a more natural habitat for species in coastal protection [11–15]. Recently, EE has been highly likely to become an integral part of viable solutions for stabilizing eroded muddy coasts (EMCs) [16,17] because other solutions such as the construction of sea dykes, groins, and revetments cause negative effects on marine and coastal hydro-dynamics [18–21]. Managed realignment and the absence of active intervention are not popular because these two solutions require the protection of coastal areas as part of erosion control and exclude economic development from eroded areas [22–24]. Protection and exclusion are not possible because coastal lands are a center of human settlements, and important for economic development in developing countries [25].

However, there has been a limited analysis of EE solutions in term of stabilization of EMCs, although various EE cases were reported [26–31]. Control of EMCs using EE solutions was only described with limited analysis on the efficacy of the solutions [17]. Four questions remain unanswered: what the optimal EE solutions are for stabilizing EMCs; how the EE solutions work toward stabilizing EMCs; what elements (ecological processes or engineered principles) should be prioritized for designing the EE solutions; and what lessons should be learned from the use of the EE models for controlling the erosion. These questions are crucial and overdue, especially in instances where muddy coasts have been increasingly eroded with the loss of mangrove forests, particularly in developing countries [32–36]. Therefore, this paper aims to review papers reporting the use of the EE solutions for controlling EMCs to gain a thorough understanding of how EE solutions worked toward stabilizing EMCs, determine which EE elements contributed to stabilizing EMCs, and provide feasible recommendations for sustainable management of EMCs in the future.

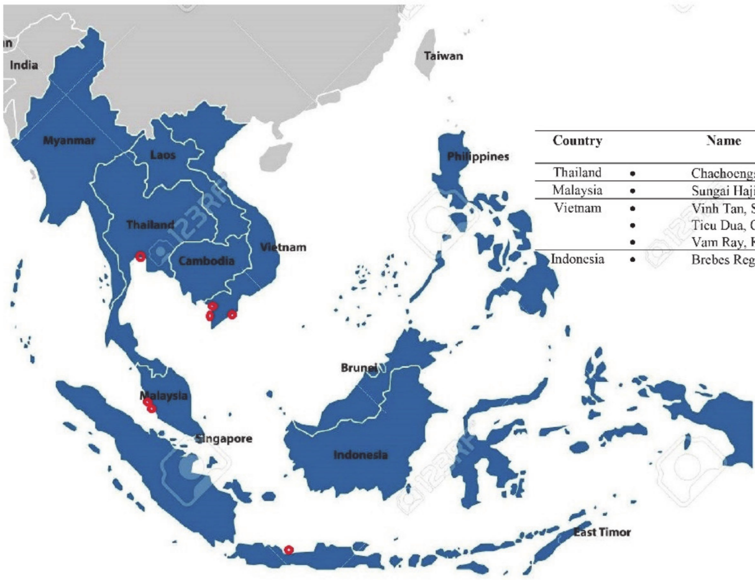
2. Methods

Web of Science was used for searching for the papers in this study. The terms "EMCs", "mangrove restoration on EMCs", "mangrove rehabilitation on EMCs", "muddy coastal protection", and "mangrove transplantation on eroded areas" were used for searching publications on Web of Science. The search was limited in time span: Web of Science—all years (1965 and 2020), Science Citation Index Expanded (SCI-EXPANDED)—1965–present, Conference Proceedings Citation Index-Science (CPCI-S)—1990–present, and Emerging Sources Citation Index (ESCI)—2015-present. The hits were refined using the filters provided by Web of Science, which include article, review, and proceedings papers. The authors admit that the use of these terms could have caused relevant publications to be missed. However, the use enabled the authors to critically review the efficacy of the EE solutions in controlling the erosion and to provide feasible recommendations for controlling EMCs in the future. The search resulted in 89 hits.

Hits that dealt with mangrove restoration on eroding coastal areas or discussed muddy coastal erosion control were selected for analysis in this review. Hits that discussed mangrove rehabilitation/transplantation/restoration on mudflats with an attempt to restore mangrove areas/reverse conversion of mangrove areas into aquaculture areas and models proposed for controlling eroded coasts, erosion monitoring systems, and erosion evaluation were not used in this review because they all did not provide practical lessons in this regard. In addition, technical reports, which the authors were involved in or familiar with, were also included in this review. As a result, thirteen hits (including three technical reports, one Master thesis, and nine scientific publications) were selected for final review. Two technical reports undertaken by GIZ in 2013 and 2018 were excluded from the final review because these two reports synthesized coastal protection in the Mekong Delta of Vietnam and shared a description of coastal erosion structures published by [26,29]. Thus, only eleven hits were further analyzed in order to develop a summary of how the EE solutions worked, comprehend what elements have contributed to stabilizing EMCs, and draw lessons (Table 1).

3. Results

The critical review resulted in four EE models (Table 1 and Figure 1), identified important elements that contributed to stabilizing EMCs, and provided recommendations in order to improve the efficacy of the EE solutions. The following sections provide the results in detail.



Country		Name	GPS Coordinates	No. of EE locations
Thailand	•	Chachoengsao	13°27'34.94"N; 100°54'3.82"E	1
Malaysia	•	Sungai Haji Doraini	3038'36.6"N; 101000'37.3"E	2
Vietnam	•	Vinh Tan, Soc Trang	9°16'30.87"N; 105°54'42.54"E	3
	•	Ticu Dua, Ca Mau	9°28'9.53"N; 104°49'46.27"E	
	•	Vam Ray, Kien Giang	10°11'51.78"N; 104°48'5.38"E	
Indonesia	•	Brebes Regency	6°49'27.03"S; 108°56'31.93"E	1

Figure 1. Locations of the places where the models were implemented (red dots indicate locations). Background is a Google map.

3.1. Four EE Models and Restoration Interventions

Four models employed different restoration interventions toward stabilizing EMCs (Figures 2 and 3). The first two models (Figure 2A,B) emphasized transplantation of local mangrove seedlings with protection to be provided by offshore structures such as bamboo fences [30,37], sand-filled geo-containers, low crested revetments, concrete pillar revetments [28,38,39], and Melaleuca fences [26,27,29,40]. The difference between these two models was the position of the interventions. While the Figure 2A model witnessed the interventions constructed offshore, the Figure 2B model encompassed gradually expanded interventions. The two remaining models highlighted the accumulation of fine-grained sediment through the construction of coastal structures as a compulsory intervention toward stabilizing EMCs (Figure 3A,B). In addition to the difference in the position of the interventions, the intentional functions of these interventions differentiated the characteristics of the two remaining models.

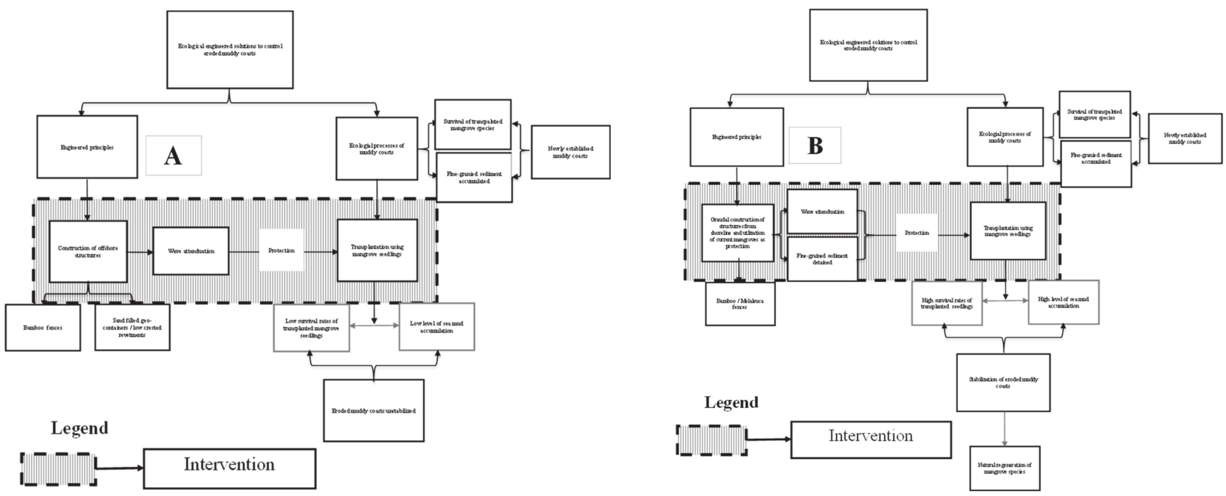


Figure 2. Models using active restoration interventions.

3.2. The EE Restoration Elements towards Stabilizing EMCs

Different restoration interventions resulted in different designs of coastal structures and the positioning of structures. The Figure 2A model was designed using offshore structures that assisted in attenuating incoming waves and trapping the sediment [28,30,37–39]. These offshore structures included bamboo fences, sand-filled geo-containers, low crested revetments, and concrete pillar revetments. The structures were constructed offshore, creating substantial gaps between the structures and the shoreline. Seedlings of mangrove species were transplanted in these gaps. Gap creation was justified using numerical models. However, this model had limited success in stabilizing EMCs. The offshore structures did not function as well as planned. The crest of the concrete pillar revetments was higher than that of the incoming waves on high tides and stopped the sediment transported onshore, resulting in a low level of sea mud accumulation [39]. In some cases, offshore structures were broken, damaging the transplanted seedlings [28,30,37,38]. The transplanted mangrove species did not survive strong waves due to either poor protection provided by the offshore bamboo fences [30,37] or insufficient support provided by the topography of restoration sites [38].

The Figure 2B model was constructed using Melaleuca fences that contained elements with the functions of breaking the energy of incoming waves and accumulating the sediment transported onshore by the incoming waves because this model emphasized the sediment accumulation and survival of transplanted mangrove seedlings as an ultimate goal. The Melaleuca fences have been effective in protecting transplanted mangrove seedlings, accumulating a high level of sediment, and facilitating the natural regeneration of mangrove species [26,27,29,40]. However, the transplantation was not necessary, as concluded by [29] and [40].

The Figure 3A model, a pilot model, employed the establishment of trapping microsites for trapping the sediment and floating seeds of mangrove species for promoting natural germination of mangrove species [41]. The trapping microsites were constructed from onshore by laying discarded, small Melaleuca sticks horizontally on the surface of the restoration site. The construction of the trapping microsites mimicked natural features by trapping the seeds of local mangrove species and sediment that were observed in the area. The model produced a high level of sea mud accumulation and natural regeneration of mangrove species [41]. The remaining model used the construction of T-shaped bamboo fences as revetments for trapping sediment [31]. There was a low level of sea mud accumulation [31].

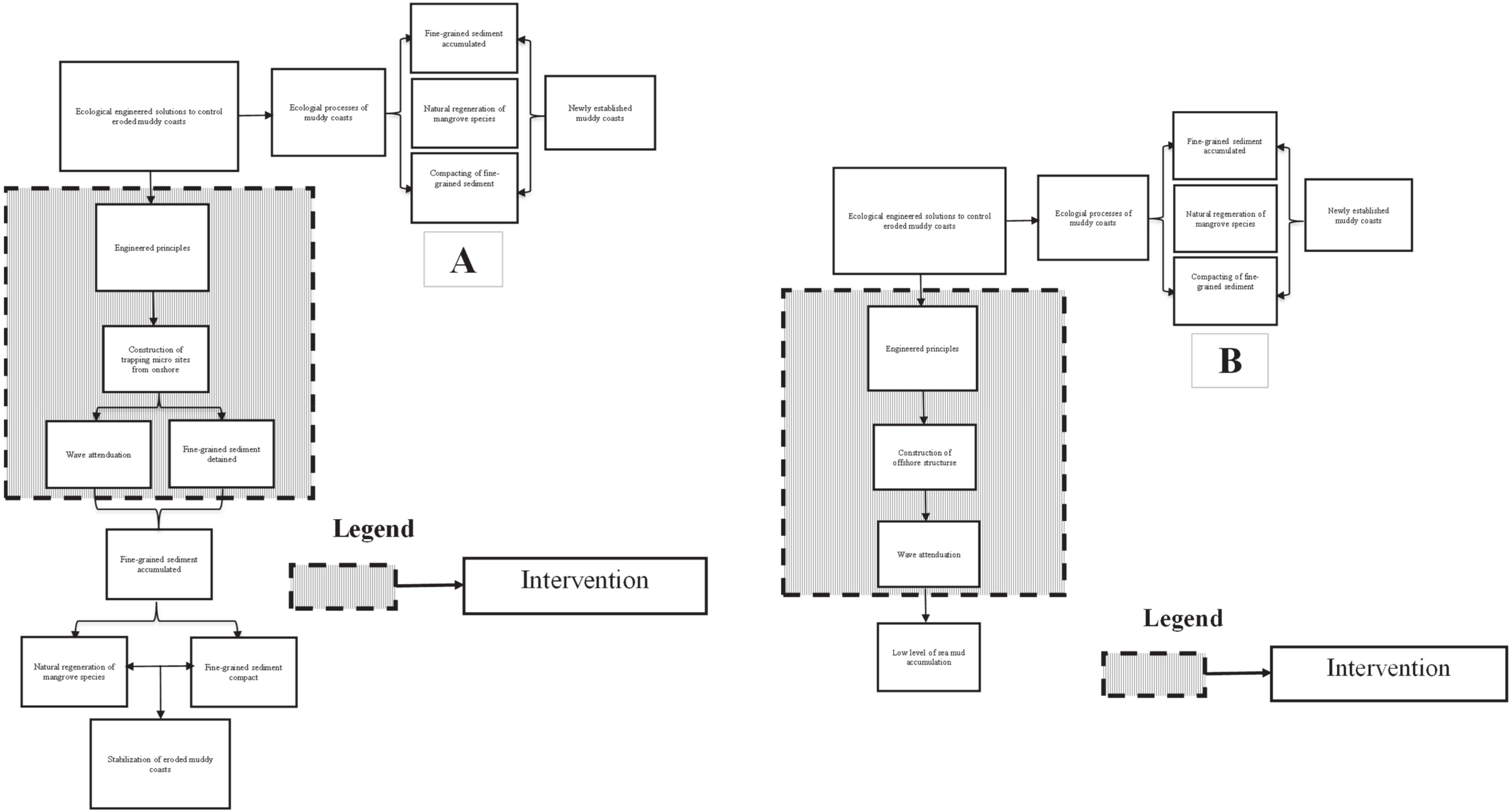


Figure 3. Models using passive restoration interventions.

Table 1. The classification of the hits.

No.	Hits	Author(s)	Publication	Types of Intervention/Model	Cost/Length/Structural Difference/Function as Reported by Publication	Coastal Status and Results as Reported by Publication
1	Coastal protection for the Mekong Delta (CPMD)	GIZ 2018	Technical report			
2	Shoreline management guidelines: Coastal Protection in the Lower Mekong Delt	GIZ 2013				
3	Basic Scientific Research for Selecting Engineered Solutions to Protect the Western Muddy Coast and to Rehabilitate Mangroves in Khanh Tien Commune, Uminh District, Ca Mau Province	[39]	Master thesis	Active intervention/ Figure 2A Model	Cost: USD 8,791,430—Length: 6318 m • Concrete pillar revetments were constructed offshore, leaving substantial gaps between the structures and the shoreline. The revetments aimed to break the energy of incoming waves and trap sediment. • Transplantation of seedlings of mangrove species in gaps.	The coast has not been completely stabilized due to • Low level of sea mud accumulation (no details were recorded). • Low survival rate of transplanted mangrove species.
4	An integrated approach to coastal rehabilitation: mangrove restoration in Sungai Haji Dorani, Malaysia	[28]	Scientific publication	Active intervention/ Figure 2A Model	Cost: USD 85,000—Length: Approximately 150 m • Low-crested breakwaters were constructed offshore, leaving substantial gaps between the structures and the shoreline. The breakwaters aimed to break the energy of the incoming waves and trap sediment. • Transplantation of seedlings of mangrove species in gaps.	The coast has not been completely stabilized due to • Low survival rate (approximately 30% of the total saplings transplanted) due to unsupportive topographical elements. • Fine-grained mud accumulated (less than 1.0 m), but not compact.
5	Strategies for mangrove rehabilitation in an eroded coastline of Selangor, peninsular Malaysia	[38]	Scientific publication	Active intervention/ Figure 2A Model	Cost: unknown; Length: Approximately 150 m • Breakwaters were constructed offshore, breaking the energy of incoming waves. • Transplantation of seedlings of mangrove species in gaps.	The coast has not been completely stabilized due to • Low survival rate. • Negligible levels of fine-grained accumulation (approximately 0.0037 cm/year).
6	Mangrove transplantation in Brebes Regency, Indonesia: Lessons and recommendations—Scientific publication	[37]	Scientific publication	Active intervention/ Figure 2A Model	Cost: unknown; length: 45 km • Offshore bamboo fences break the energy of incoming waves and protect the transplanted mangrove species. • Transplantation of seedlings of mangrove species.	The coast has not been completely stabilized due to • Broken offshore bamboo fences. • Low survival rates of transplanted mangrove species (no details were recorded).

Table 1. *Cont.*

No.	Hits	Author(s)	Publication	Types of Intervention/Model	Cost/Length/Structural Difference/Function as Reported by Publication	Coastal Status and Results as Reported by Publication
7	Erosion protection options of a muddy coastline in Thailand: stakeholders' shared responsibilities	[30]	Scientific publication	Active intervention/ Figure 2A Model	Cost: USD 16,000,000; Length: 11 km • Transplantation of seedlings of mangrove species. • Offshore revetments, gabion breakwaters, and bamboo fences break the energy of incoming waves and protect the transplanted mangrove species.	The coast has not been completely stabilized due to • Coastal structures broken. • Transplanted seedlings were uprooted due to waves.
8	Coastal Rehabilitation and Mangrove Restoration using Melaleuca Fences: Practical Experience from Kien Giang Province	[27]	Technical report	Active intervention/ Figure 2B Model	Cost: Approximately USD: 17,000; Length: 800 m • Transplantation of seedlings of mangrove species. • Melaleuca fences gradually constructed to break the energy of incoming waves, trap sediment, and protect transplanted mangrove species.	The coast has been completely stabilized due to • High levels of fine-grained sediment (more or less 45 cm high). • The sediment became compact. • High survival rates of transplanted. mangrove species • High levels of naturally regenerated mangrove species.
9	Using Melaleuca fences as soft Coastal engineering for mangrove restoration in Kien Giang, Vietnam	[26]	Scientific publication	Active intervention/ Figure 2B Model		
10	Community perspectives on an internationally funded mangrove restoration project: Kien Giang province, Vietnam	[29]		Active intervention/ Figure 2B Model		
11	Gradual expansion of mangrove areas as an ecological solution for stabilizing a severely eroded mangrove dominated muddy coast	[40]		Active intervention/ Figure 2B Model		
12	Area coastal protection and the use of bamboo breakwaters in the Mekong Delta	[31]		Passive intervention/ Figure 3B Model	Cost: USD 70,000; Length: 700 m • Construction of T-shaped bamboo fences as sediment trapping structures.	The coast has not been completely stabilized due to • Low levels of fine-grained accumulation.
13	Melaleuca entrapping microsites as a nature-based solution to coastal erosion: A pilot study in Kien Giang, Vietnam	[41]		Passive intervention/ Figure 3A Model	Cost: mainly labor days; Length: 50 m • Construction of trapping microsites using used Melaleuca poles for trapping fine-grained sediment and seeds from the mother trees of mangrove species nearby.	The coastal section has been completely stabilized due to • High levels of fine-grained sediment (approximately 25 cm high). • The sediment becoming compact. • High levels of naturally regenerated mangrove species.

4. Discussion

The four EE models applied active and passive restoration interventions toward stabilizing EMCs. The interventions are discussed in detail in the following sections.

4.1. The Model Interventions and Stabilization of EMCs

In practice, passive restoration is better than active restoration in tropical forests [42]. Theoretically, sea mud accumulation enables the establishment of intertidal mudflats and facilitates the natural regeneration of mangrove species [43,44]. In this review, the models of Figure 3A,B follow the passive restoration model and prioritized sea mud accumulation, thus being completely in accordance with the practical and theoretical experience. However, the Figure 3A model was more effective in stabilizing eroded EMCs than the Figure 3B model because the restoration site where the Figure 3A model was implemented was stabilized with a high level of sea mud accumulation and natural regeneration of mangrove species.

By contrast, the models of Figure 2A,B applied active restoration and highlighted transplantation as a compulsory intervention because it was believed that survival of the transplanted mangrove species would likely contribute to trapping sediments toward stabilizing EMCs. The Figure 2A model has had limited success in stabilizing EMCs because offshore structures of the Figure 2A model failed to perform the tasks as planned, resulting in a low survival rate of the transplanted seedlings. The Figure 2B model was more effective in stabilizing EMCs than the Figure 2A model because the Melaleuca fences of the Figure 2B model were successful in trapping sediment, protecting transplanted seedlings, and promoting the natural regeneration of mangrove species. However, a lesson drawn by the Figure 2B model is that transplantation is not necessary, and as soon as the intended restoration sites are stabilized and topographical conditions are provided, mangroves naturally regenerate [29,40]. This lesson is in tune with the conclusions made by [3,45–47].

4.2. The EE's Structural Elements and Stabilization of EMCs

Muddy coasts are influenced predominantly by waves and sedimentation [43]. Successful restoration requires full consideration of topographical elements of the intended restoration sites, as recommended by [3] and [46,47]. The Figures 2B and 3A models were obviously outputs of adequate consideration of the muddy coastal ecological processes and topographical elements because the structures constructed in these models aimed to accumulate the sediment and utilize current mangrove stands for stabilizing EMCs [26,27,29,40]. Meanwhile, the offshore structures were constructed with a single, practical function of breaking the energy of incoming waves, leading to a low level of sea mud accumulation [28,30,31].

4.3. Optimal Models for Stabilizing EMCs

This review reveals that among the four models, the Figure 3A model, although tested on a small scale, has been the most cost-effective in accumulating sediment and promoting the natural regeneration of mangrove species in terms of construction costs, levels of sea mud accumulation, and the natural regeneration of mangrove species. The Figure 2B model is highly likely to be a strong candidate if transplantation is eliminated. The Figure 3B model could be a candidate if the coastal structures are reinforced with additional structural elements to be constructed from onshore that assist in accumulating sediment.

5. Conclusions

The current EE models for stabilizing EMCs were examined using a comprehensive critical review. The review resulted in four EE models with different restoration interventions. The models employing the passive intervention proved to be cost-effective in stabilizing EMCs in terms of construction costs, the survival rate of transplanted seedlings, and levels of sea mud accumulation. Interventions with adequate consideration of the muddy coastal ecological processes and the ecological reasoning for the positioning of these interventions play a crucial role in stabilizing EMCs.

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