KEY FACTORS INFLUENCING ECOLOGICAL ENGINEERING IMPLEMENTATION IN COASTAL CONSTRUCTION PROJECTS IN MALAYSIA AND RECOMMENDATIONS

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Abstract: In Malaysia, the pressures of climate change and rapid urbanisation are accelerating coastal development, often referred to as ocean sprawl. The lack of integration of natural elements in construction practices increases risks for both communities and the environment, particularly since much of the population resides near coastal areas. Eco-engineering offers a promising solution by incorporating natural elements into conventional infrastructure and has seen widespread adoption in many developed countries. However, its implementation in Malaysian coastal construction remains limited. This study explores key factors influencing the implementation of eco-engineering in coastal construction projects and provides recommendations for improvement. Data were collected through interviews with project participants and on-site observations of three case studies in Penang: The Andaman, The Light, and the Queens Waterfront. A validation process was conducted via a mini-focus group discussion with eco-engineering experts and interviews with relevant government departments. Analysis using NVivo software identified four main influencing factors: Government enforcement, regulations, standards, and initiatives, cost considerations, knowledge and awareness of eco-engineering approaches, and engineering inspection, monitoring, and maintenance. The study concludes with recommendations aimed at enhancing the implementation of eco-engineering in Malaysian coastal construction, contributing to sustainable coastal development, habitat conservation, and ecological restoration.

Keywords: Coastal construction, eco-engineering, implementation, restoration, sustainability.

Introduction

According to the United Nations (2017), the global population is estimated to increase by over 80 million people each year. This rapid population growth is a catalyst for economic growth, particularly within the maritime industry (Saha, 2023). With the oceans covering approximately 71% of the Earth's surface (Visbeck, 2018), coastal areas are not only the most densely populated and economically active regions (Cosby *et al*., 2024) but also habitats for highly valuable ecosystems (Carrasco De La Cruz, 2021). This is particularly relevant in Malaysia, where approximately 60% of the population of over 33 million live along or near the coast (Ariffin *et al*., 2023). However, these coastal zones are already experiencing the adverse impacts of climate change, prompting the use of artificial structures as adaptation solutions (Rashidi *et al*., 2021), thus, degrading the coastal natural environment.

Coastal development is expected to rise with population growth, posing increasing threats to coastal and marine habitats globally. Rapid development and population growth in Malaysia have driven large-scale land reclamation and artificial island construction (Chee *et al*., 2023), often protected by hard structures such as seawalls and rock revetments. Similar pressures in the Bay of Bengal, including urbanisation, industrial expansion, and overfishing have led to coastal habitat degradation (Saengsupavanich *et al*., 2024). Human-induced shoreline instability such as jetty construction along the Gulf of Thailand disrupts sediment transport and

contributes to erosion (Saengsupavanich *et al*., 2022a). Climate change further exacerbates these issues, accelerating coastal erosion and reshaping shorelines across Southeast Asia (Wan *et al*., 2024). These challenges highlight the urgent need for sustainable coastal management to mitigate environmental degradation.

While sustainable coastal development is increasingly important, many mega projects continue to be constructed with minimal consideration for the natural environment (Firth *et al*., 2020). Developing countries often prioritise hard engineering solutions like revetments or seawalls because they provide immediate protection against the coastal threats of erosion, sea level rise, and extreme weather events. When properly designed, these coastal structures not only safeguard the coastline but also enhance the livelihoods of local communities (Saengsupavanich, 2022b; Saengsupavanich & Pranzini, 2023), contributing to sustainable coastal development in terms of preserving coastlines and community benefits. However, traditional hard structures can be made more environmentally friendly if integrated with ecological engineering approaches.

As a result, a novel field of ecological engineering (eco-engineering) has recently emerged as a new conservation strategy for the greening of hard infrastructure that cannot be replaced with green solutions (Naylor *et al*., 2017; Firth *et al*., 2020). Numerous eco-engineering trials have been conducted in coastal regions in Europe, the United States, Australia, China, Singapore, Malaysia, and South Africa (Chee *et al*., 2020; 2021a; Accola *et al*., 2022a; 2022b; Bishop *et al*., 2022; Clifton *et al*., 2022; Dauvin *et al*., 2022; Lapinski *et al*., 2022; Sun *et al*., 2022; Hartanto *et al*., 2022; Gauff *et al*., 2023; Kosová *et al*., 2023; Hofstede & Koningsveld, 2024; Teong *et al*., 2024; Schaefer *et al*., 2024; Herbert *et al*., 2025; Seath *et al*., 2025). It is a promising approach for enhancing biodiversity and providing environmental benefits while maintaining infrastructure functionality. These multifunctional infrastructures align with the United Nations Sustainable Development Goal

(UN SDG) 14: Life below water, which aims to conserve and sustainably manage ocean and marine resources (Firth *et al*., 2024).

Despite the rapid advancements in this field, knowledge and implementation are mostly limited to academic sectors and developed nations (Firth *et al*., 2024). In Malaysia, the adoption of eco-engineering is limited, with artificial infrastructures still the preferred option in most coastal construction projects. Although previous research has provided a way forward for enhancing Nature-based Solutions (NbS) (Chee *et al*., 2021b), efforts to specifically enhance the implementation of eco-engineering are still lacking. This is particularly important in developing countries like Malaysia, where hard infrastructures are constructed for development and coastal protection but often degrade marine ecosystems. Therefore, this article aims to identify key factors influencing eco-engineering implementation and propose recommendations to enhance eco-engineering implementation in coastal construction projects in Malaysia.

Literature Review

This section presents the factors influencing the implementation of eco-engineering in coastal construction projects based on previous studies.

Knowledge and Awareness of the Eco-engineering Available Options

According to Morris *et al*. (2019), one major barrier to implementing eco-engineering is the lack of information among local, state, and national governments. Similarly, Rahman *et al*. (2023) found that knowledge gaps hinder nature-based coastal adaptation efforts. While eco-engineered coastline research is led by countries such as Australia, Europe, and the United States, many regional governments remain unaware of its concept, rationale, and potential benefits (Morris *et al*., 2019). Significant knowledge deficiencies exist at the local level and across sectors regarding the effectiveness of nature-based solutions (Rahman *et al*., 2023).

Public awareness is another challenge. Strain *et al*. (2019) highlighted that public understanding of eco-engineering is poor, particularly in Europe and Asia, where artificial coastal structures have caused significant environmental degradation. Public education is essential to foster informed decision-making and garner support for small-scale trials, which can lead to large-scale eco-engineering projects (Dafforn *et al*., 2015a; Morris *et al*., 2019).

Moreover, Naylor *et al*. (2017) argued that the lack of implementation may stem less from the absence of eco-engineering options and more from insufficient motivation and uncertainty about potential returns. Chee *et al*. (2021b) supported this, noting that policymakers and practitioners hesitate to adopt new technologies, preferring affordable, familiar, and low-risk approaches.

In Malaysia, stakeholders' lack of awareness and knowledge is a major barrier to sustainable construction (Durdyev *et al*., 2018a). Demonstration projects have been proposed as effective tools for building awareness and knowledge in this field. Additionally, online repositories documenting NbS, including successes and failures can facilitate knowledge sharing (Chee *et al*., 2021b). Morris *et al*. (2019) suggested establishing an international eco-engineering organisation and educational website to showcase projects and promote awareness globally. Evans *et al*. (2019) further recommended an evolving catalogue of eco-engineering options to help decision-makers understand available solutions and facilitate knowledge transfer.

Engagement and Communication with Multiple Stakeholders

Townhill *et al*. (2021) highlight that collaboration and communication barriers arise due to the complexity of stakeholder networks. With multiple stakeholders holding diverse priorities, active cooperation and coordination are essential (Seddon *et al*., 2020). Effective engagement of architects, engineers, ecologists, and socioeconomic scientists fosters collaboration, aligning expertise toward a shared goal (Morris *et al*., 2019). Given the cross-disciplinary nature of artificial structure management, strong communication ensures that ecological enhancements are integrated and tested scientifically (Dafforn *et al*., 2015a).

However, a lack of integration between engineers and ecologists creates challenges in balancing ecological and technical considerations (Pioch *et al*., 2018). Non-biologists designing habitats may yield ineffective results and misaligned objectives can further hinder communication (Dafforn *et al*., 2015a). Strengthening communication and collaboration among local communities, governments, non-governmental organisations, the private sector, and academia is crucial (Chee *et al*., 2021b). Given that NbS span multiple disciplines and institutions, aligning resources, interests, and responsibilities is essential (Seddon *et al*., 2021; Rahman *et al*., 2023). Without high-level coordination, isolated efforts risk being undermined by ongoing environmental degradation (Cohen-Shacham *et al*., 2019).

Each stakeholder group brings unique technical expertise, financial capacity, and local knowledge, fostering trust and ecosystem stewardship (Waris *et al*., 2019; Chee *et al*., 2021b). Including diverse stakeholders helps assess risks, guides engineers in designing effective solutions (Mickovski & Thomson, 2018), and ensures that developers and engineers consult ecologists and oceanographers for feasibility studies (O'Shaughnessy *et al*., 2020).

Ultimately, effective communication and engagement are critical for integrating eco-engineering into coastal development. A lack of coordination can lead to negative outcomes, whereas collaborative problem-solving enhances NbS implementation (Nelson *et al*., 2020). Building trust and understanding among stakeholders ensures that coastal infrastructure meets engineering, ecological, and social objectives (Evans *et al*., 2017).

Government Policies

Most countries lack specific policies for integrating eco-engineering into coastal construction (Morris *et al*., 2019). However, eco-engineering can support policy objectives related to sustainable development and biodiversity enhancement (Dafforn *et al*., 2015b). For instance, the UN Sustainable Development Goals (SDGs) provide a framework for environmental protection, where eco-engineering can serve as a key approach for sustainable coastal development.

Some countries have regulations that facilitate the implementation of eco-engineering. In the United States, strict mitigation measures for coastal and marine development encourage investment in ocean-friendly infrastructure (Sachdev, 2019). In Europe, policy solutions such as the Green Infrastructure Strategy, the European Union Strategy on Adaptation to Climate Change, and the Floods Directive support the implementation of NbS (Moraes *et al*., 2022). Additionally, policy coherence can help scale up small interventions into broader, more impactful initiatives (Cohen-Shacham *et al*., 2019). In Malaysia, jurisdictional conflicts between state and federal governments hinder the implementation of NbS (Chee *et al*., 2021b). For small island developing states without formal adaptation planning requirements, coordinating adaptation across sectors is challenging (Townhill *et al*., 2021). The lack of relevant regulations further impedes NbS adoption (Versini *et al*., 2023) while conflicting policies between existing regulatory frameworks and environmental management create additional barriers (Seddon *et al*., 2020; Gain *et al*., 2022).

Sustainable coastal development is vital for Malaysia's progress, but overlapping regulations and poor coordination hinder biodiversity conservation (Tong, 2020). Figure 1 outlines key national policies for environmental protection and sustainable development. Despite multiple agencies overseeing sustainable development, project approval is primarily based on legal compliance (Department of Environment [DOE], 2016), traditional hard infrastructure remains dominant, indicating inadequate regulatory support for marine and coastal biodiversity. To address this, governments must strengthen policies and regulations to establish urban ocean green standards, similar to land-based sustainability frameworks (Airoldi *et al*., 2021).
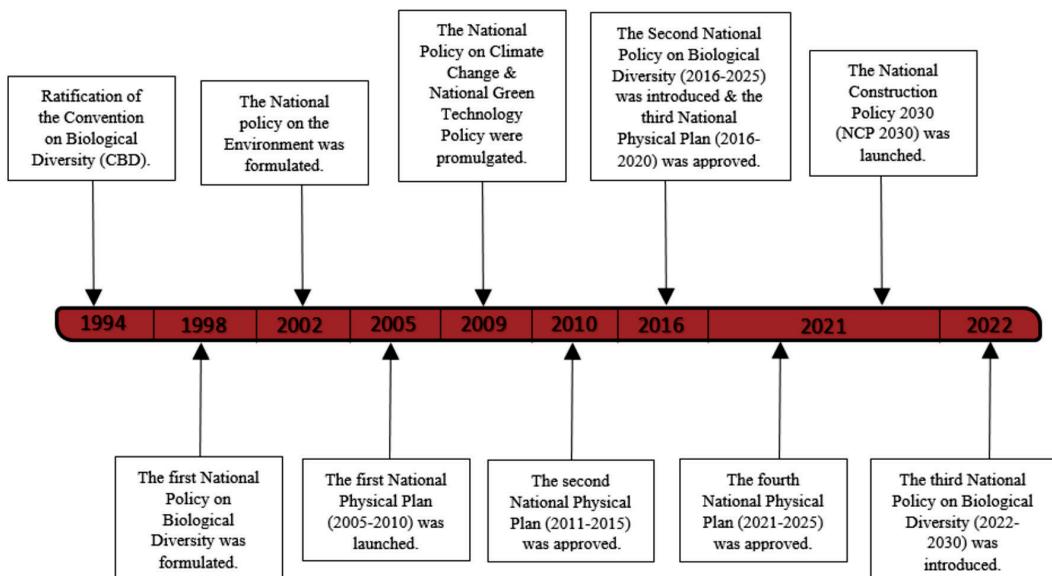

Figure 1: National policies and plans relevant to environment protection and sustainable development transition in Malaysia

Science-based Evidence

Eco-engineered coastlines present temporal challenges that are more complex than those associated with traditional engineering materials (Morris *et al*., 2019). For instance, material fatigue, a well-understood phenomenon in traditional engineering, can be predicted and planned for during the design stage. However, the living components of eco-engineering structures introduce greater variability, making their long-term performance less predictable (Bouma *et al*., 2014). This highlights a knowledge gap in the effectiveness, implementation, and design of NbS (Nelson *et al*., 2020).

Despite growing evidence of the efficacy of eco-engineering, full-scale implementation remains limited (Evans *et al*., 2017; 2019). Many trial experiments have been conducted only once, in single locations, which restricts confidence in their transferability to different projects and environmental conditions (Evans *et al*., 2019; O'Shaughnessy *et al*., 2020). Stakeholders, including developers, engineers, and decision-makers seek a clear balance between costs and benefits, requiring greater assurance that predicted outcomes will be realised (Evans *et al*., 2019).

To address these challenges, expanding the evidence base for NbS is essential, with a focus on explicitly designed, measurable biodiversity benefits (Chee *et al*., 2021b; Seddon *et al*., 2021). Additionally, a key concern among developers and regulators remains: "How much enhancement is sufficient?" (Evans *et al*., 2019). Understanding density-dependent effects across various structures is critical to ensuring that enhancements are proportionate to the scale of development and effectively integrated into coastal projects.

Cost

Many eco-engineering projects are limited to small-scale trials due to insufficient financial support, posing a significant challenge for scaling up adaptation efforts (Morris *et al*., 2019; Griggs & Reguero, 2021). One of the primary barriers to adopting eco-engineering is uncertainty over economic costs (Naylor *et al*., 2017). Eco-engineering measures are often excluded from projects because they are seen as additional assets requiring maintenance, with no allocated budget to cover ongoing costs. As a result, financial constraints are recognised as a major barrier to implementing NbS globally (Seddon *et al*., 2020), especially in developing countries, where high costs, lack of incentives, and long payback periods further limit sustainable practices (Chan *et al*., 2017; Durdyev *et al*., 2018a; 2018b).

Funding limitations also hinder coastal naturalisation efforts, despite their proven effectiveness for coastal protection (Rahman *et al*., 2021). Traditional funding sources are typically allocated to disaster risk management, water and waste management, and land use leaving limited financial resources for the implementation of NbS (Whelchel *et al*., 2018; Griggs & Reguero, 2021). This challenge is evident in Malaysia, where specific funding opportunities for NbS remain scarce (Chee *et al*., 2021b). A key reason for this underfunding is that the benefits of mitigation and adaptation strategies are not immediately realised, leading to a lack of financial urgency (Townhill *et al*., 2021).

Despite financial concerns, studies suggest that integrating eco-engineering into construction plans requires only minor modifications at minimal cost while yielding significant economic, social, and environmental benefits (Naylor *et al*., 2017; 2018; Burt & Bartholomew, 2019). However, most eco-engineering enhancements have only been tested in small-scale pilot projects, making it difficult to compare the costs and benefits of large-scale implementation (Evans *et al*., 2019). Additionally, flawed appraisal methods often undervalue the long-term economic benefits of working with nature, leading to underinvestment in NbS (Seddon *et al*., 2020; Gain *et al*., 2022). Moreover, a major challenge is the lack of comprehensive cost-benefit analyses explicitly comparing NbS to traditional hard engineering

solutions (Nelson *et al*., 2020). The difficulty in monetising ecosystem services, adaptation costs, and socioeconomic impacts makes it challenging to accurately estimate the financial returns of NbS investments (Griggs & Reguero, 2021).

Expertise

A key factor for successful NbS implementation is the careful selection of site and timing (Chee *et al*., 2021b). Adequate expertise is essential to ensure proper governance and execution of these projects. However, leadership gaps can reduce the ability and willingness of coastal managers to adopt adaptation measures (Townhill *et al*., 2021). A lack of professional training and expertise in sustainability poses a challenge to sustainable construction in developing countries (Durdyev *et al*., 2018a).

Additionally, site characteristics must be considered when implementing NbS, particularly in heavily developed coastal areas like Penang Island, where space limitations, reduced connectivity, and species dispersal present challenges (Chee *et al*., 2017; Sarabi *et al*., 2020). However, local organisational capacity is often constrained by shortages in expertise, leading to frequent outsourcing to consulting engineers (Rahman *et al*., 2023). A critical issue is that civil engineers may lack awareness of ecological considerations when designing coastal projects (Pioch *et al*., 2018), highlighting the need for interdisciplinary collaboration between engineers and ecologists.

Engineering Performance, Inspection, and Maintenance

A key barrier to the wider adoption of eco-engineering is uncertainty about its impact on engineering performance, inspection, and maintenance (Naylor *et al*., 2017). Limited data on how green solutions affect grey infrastructure raises concerns about long-term performance, with potential negative, neutral, or positive effects. Additionally, maintenance requirements may increase due to the self-regenerative nature of plants, which may necessitate the

removal of undesirable species (Rahman *et al*., 2021). The lack of structured maintenance and prolonged government and business inaction further hinders nature-based coastal adaptation (Rahman *et al*., 2021).

Another challenge is identifying appropriate indicators and metrics to measure the social-ecological effectiveness of interventions (Seddon *et al*., 2020). Maintenance and repair capacity is also a critical issue, particularly in developing regions where adaptation projects are often built by external parties, leaving local stakeholders with limited expertise to sustain these measures over time (Griggs & Reguero, 2021). While NbS can self-maintain, their dynamic nature requires careful consideration of the safety, functionality, and upkeep of the project (Airoldi *et al*., 2021). Consequently, NbS may not be widely adopted until they are subjected to the same performance standards as traditional infrastructure (Nelson *et al*., 2020).

Although Naylor *et al*. (2017) reassured stakeholders about eco-engineering's feasibility through independent expert reviews, the actual impact on structural integrity remains untested. It is still unclear how much modification different structures can support without risk (Evans *et al*., 2019). A well-designed eco-engineering project must be durable and withstand extreme weather, yet a limited understanding of natural processes continues to reinforce reliance on traditional hard engineering approaches (Rahman *et al*., 2021). As a result, practitioners require greater confidence and certainty in the risk reduction capacity of natural infrastructure (Whelchel *et al*., 2018; Nelson *et al*., 2020).

Systematic Management with Long-term Monitoring

To maximise the lifespan of eco-engineering projects, maintenance and long-term monitoring programmes should be integrated into approved plans. This integration ensures comparability with standard engineering practices while enhancing stakeholder confidence (Whelchel *et al*., 2018). Monitoring is essential to assess how newly created habitats contribute to local

ecology (Dafforn *et al*., 2015a). However, the long-term efficacy of ecological enhancement schemes is often poorly monitored, even when included in development mitigation strategies (Naylor *et al*., 2017). This oversight may be due to post-implementation monitoring costs, which are necessary to evaluate coastal protection performance and ecological restoration capacity (Rahman *et al*., 2023).

Exceptions exist where eco-engineering innovations become part of third-party research collaborations such as those conducted with the education sector (Naylor *et al*., 2017). Additionally, long-term monitoring and emergency planning often depend on research interests and local community motivation, particularly in cases where funding is limited (Mickovski & Thomson, 2018).

A lack of systematic management further hampers NbS implementation (Chee *et al*., 2021b). Establishing robust management protocols is especially crucial when using non-indigenous species, which may tolerate environmental stressors but also pose risks to native ecosystems (Airoldi *et al*., 2021). Adaptive management and long-term monitoring are essential to ensure positive ecological outcomes and build a strong evidence base for future interventions. However, the effectiveness of NbS depends on the capacity of managers to assess outcomes and adjust strategies accordingly (Cohen-Shacham *et al*., 2019). Thus, institutionalising monitoring programmes within stakeholder groups is crucial to securing both social and environmental benefits and ensuring the long-term success of NbS initiatives.

Methodology

This study employs a qualitative approach with three stages. In the first stage, existing research was reviewed to identify factors influencing eco-engineering implementation in coastal construction. The systematic literature review informed the development of semi-structured interview questions (Appendix A), refined through a pilot study to ensure clarity.

In the second stage, data was collected through interviews with project team members from three purposively selected Penang projects: Andaman, The Light, and Queens Waterfront. Finally, findings were validated through interviews with government representatives and a mini Focus Group Discussion (FGD) with eco-engineering experts, using a validation study form (Appendix B).

To enhance reliability, this study employed triangulation by integrating multiple data collection methods, including literature review, case studies with onsite observation and first-round interviews, as well as a validation study with FGD and second-round interviews. This approach mitigated the weaknesses of individual methods while strengthening overall findings. Cross-verification improved result validity and accuracy, reinforcing the interpretation and providing a comprehensive discussion, particularly within the Malaysian context.

Interviews with project team members, conducted in person or online, consisted of two parts: The first gathered background information and understanding of eco-engineering while the second explored key factors and recommendations. In contrast, the validation study, which included in-person interviews with government representatives and an online mini-focus group discussion with eco-engineering experts, only collected background information in the first part, with the second part focused on validating key factors and recommendations. Participants were invited via email or phone, with the study's purpose and interview or FGD process outlined. To ensure confidentiality, respondent identities remain anonymous. All sessions were recorded with consent, transcribed, and analysed using thematic analysis in NVivo.

Stage 1 - Systematic Literature Review

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method, adapted from Shaffril *et al*. (2018) was applied to the systematic literature review. The review focused on Scopus and ScienceDirect, leading platforms for interdisciplinary research.

Its goal was to identify factors influencing the implementation of eco-engineering, NbS, or adaptive approaches in coastal construction, which would inform the design of the semi-structured interview questions.

The process involved three phases. First, relevant keywords related to constraints, barriers, challenges, eco-engineering, sustainable coastal development, NbS, and climate change adaptation were used to search for pertinent journal articles. Table 1 shows the search string applied during the systematic review process.

Second, articles were screened based on eligibility criteria, including research and review articles in English (2014 - 2023) within environmental science, social sciences, earth and planetary sciences, agriculture, biology, and engineering. The objective of this review was to focus on the challenges to eco-engineering, NbS, or the implementation of adaptive approaches; thus, only articles with related content were selected. Table 2 shows the inclusion and exclusion criteria used in this systematic review.

Third, full-text assessments were conducted, followed by content analysis. As a result, 19 articles met the inclusion criteria, identifying factors that influence the implementation of eco-engineering, NbS, or adaptive approaches in coastal construction, as presented in Table 3.

Stage 2 - Case Studies

The case studies were conducted on several coastal development projects on Penang Island (Figure 2), including Andaman Island (Figure 3), The Light (Figure 5), and Queens Waterfront (Figure 8), located at latitudes 5.2632°N, 5.3624°N, and 5.3338°N and longitudes 100.4846°E, 100.3157°E, and 100.3107°E, respectively. Penang was chosen for its rapid growth, which is accompanied by significant land reclamation projects and the anticipated expansion of artificial coastlines.

The study aims to identify factors influencing the implementation of eco-engineering in coastal construction. Purposive sampling was employed, focusing on recently completed land reclamation projects featuring artificial coastlines. After evaluating potential developments, three coastal projects—Andaman P1, The Light, and Queens Waterfront—were selected. Figure 2 illustrates their locations on Penang Island.

Table 1: The search string was applied for the systematic review process

Resources	Keywords Used
Scopus	"constraint" OR "barrier" OR "challenge" AND "eco-engineering" OR "ecological" AND "engineering" OR "nature-based" AND "solution" OR "NbS" OR "climate" AND "change" AND "adapt*" OR "mitigate*" OR "sustain*" AND "coast*" AND "develop*" OR "manage*"
Science Direct	"constraint" AND "barrier" AND "challenge" AND "sustainable coastal development" AND "eco-engineering" AND "nature-based solution" AND "climate change adaptation"

Table 2: The inclusion and exclusion criteria for articles included in this study

Criterion	Inclusion	Exclusion
Document types	Review and research articles	Book chapters, book, report, and thesis
Language	English	Non-English
Timeline	2014 to 2023	< 2014
Subject areas	Environmental science, social sciences, earth and planetary sciences, agricultural and biological sciences, and engineering	Energy, business, management and accounting, economics, econometrics, and finance
Content of the study	Challenges, barriers, or constraints to eco-engineering/NbS/adaptive approaches implementation	Not focusing on challenges, barriers, or constraints to eco-engineering/NbS/adaptive approaches implementation

Table 3: Factors identified from the previous studies

| Factors	References
Knowledge and awareness of the available options for eco-engineering	Dafforn *et al.* (2015a); Evans *et al.* (2019); Morris *et al.* (2019); Strain *et al.* (2019); Chee *et al.* (2021b); Rahman *et al.* (2023)
Engagement and communication with multiple stakeholders	Dafforn *et al.* (2015a); Evans *et al.* (2017); Cohen-Shacham *et al.* (2019); Morris *et al.* (2019); Mickovski & Thomson (2018); Nelson *et al.* (2020); Seddon *et al.* (2020); Townhill *et al.* (2021); Chee *et al.* (2021b); Rahman *et al.* (2023)
Government policies/initiative	Dafforn *et al.* (2015b); Naylor *et al.* (2017a); Cohen-Shacham *et al.* (2019); Morris *et al.* (2019); Gain *et al.* (2022); Seddon *et al.* (2020); Townhill *et al.* (2021); Airoldi *et al.* (2021); Chee *et al.* (2021b); Versini *et al.* (2023)
Science-based evidence	Evans *et al.* (2017; 2019); Morris *et al.* (2019); Nelson *et al.* (2020); Chee *et al.* (2021b)
Cost	Naylor *et al.* (2017a); Whelchel *et al.* (2018); Morris *et al.* (2019); Evans *et al.* (2019); Griggs & Reguero (2021); Chee *et al.* (2021b); Gain *et al.* (2022); Nelson *et al.* (2020); Seddon *et al.* (2020); Townhill *et al.* (2021); Rahman *et al.* (2021)
Expertise	Rahman *et al.* (2023); Townhill *et al.* (2021)
Engineering performance, inspection, and maintenance	Airoldi *et al.* (2021); Evans *et al.* (2019); Griggs & Reguero (2021); Naylor *et al.* (2017a); Nelson *et al.* (2020); Rahman *et al.* (2021); Seddon *et al.* (2020); Whelchel *et al.* (2018)
Systematic management with long-term monitoring	Airoldi *et al.* (2021); Chee *et al.* (2021b); Cohen-Shacham *et al.* (2019); Dafforn *et al.* (2015a); Mickovski & Thomson (2018); Naylor *et al.* (2017a); Rahman *et al.* (2023); Whelchel *et al.* (2018)
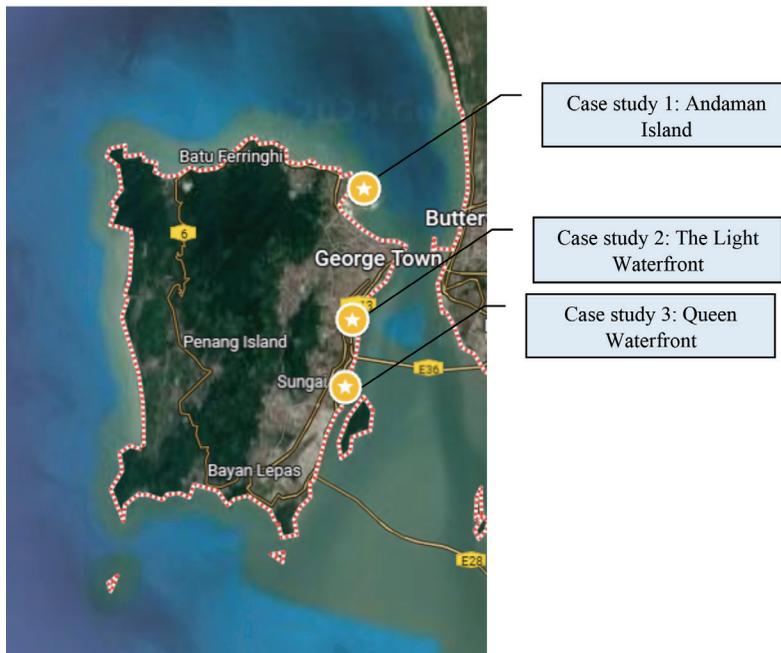
Figure 2: Case study locations on Penang Island

Case Study 1: Andaman Island

Andaman Island is a 760-acre urban island development, with Phase 1 (253 acres) fully reclaimed by 2019 and Phase 2 (507 acres) set for completion by 2028. Designed to balance island tranquillity with urban vibrancy, it embraces a green living concept. Over 90 acres are dedicated to public greens, parks, exercise walkways, playgrounds, and beaches. A seafront promenade encourages pedestrian and cyclist movement, promoting a healthy lifestyle. Figure 3 illustrates a 3D representation of Andaman Island.

Convenient access is ensured via two strategically placed bridges linking Andaman to Penang Island: One connects directly to Gurney Bay (under construction) and another to Seri Tanjung Pinang (STP), which is already completed. Several residential projects, including The Meg, Arica, and The Lume are currently under construction in Phase 1. Developed by Eastern & Oriental Berhad (E&O), a leading Penang developer, Andaman is part of STP Phase 2, which began in 2016. E&O previously developed STP Phase 1, a mixed-use project completed in 2006 that included land reclamation and is now fully developed.

Based on onsite observation, Andaman Island is surrounded by artificial infrastructure such as rock revetments, with coastlines built using traditional methods without integrating natural elements (Figure 4).

Figure 3: A 3D illustration of Andaman Island

Figure 4: On-site observation of Andaman Island's coastline

Case Study 2: The Light

The Light Waterfront Penang, launched in 2009, spans three phases of seafront development. Phase 1 (43 acres) comprises completed residential projects: The Light Point, The Light Collection, and The Light Linear. Phase 2 (103 acres) features mixed-use developments while Phase 3 (7 acres) is dedicated to a seafront park. As of writing, Phase 2 is underway, including the Waterside Residence and Light City, which encompasses retail spaces, the Penang Waterfront Convention Centre, commercial and office towers, a hotel, and luxury residences.

The project is a joint venture between IJM Corporation Berhad and Perennial Holdings Private Limited. IJM is a diversified global conglomerate with interests in construction, property development, and infrastructure while Perennial is a Singapore-based real estate and healthcare company. This large-scale mixed-use development on George Town's eastern coast is one of Penang's most prominent projects, integrating eco-friendly initiatives such as green spaces, sustainable building materials, and water- and energy-saving technologies. Figure 5 presents The Light's master plan.

On-site observation (Figure 6) reveals that the Light's coastline is reinforced with artificial hard infrastructure, including rock revetments,
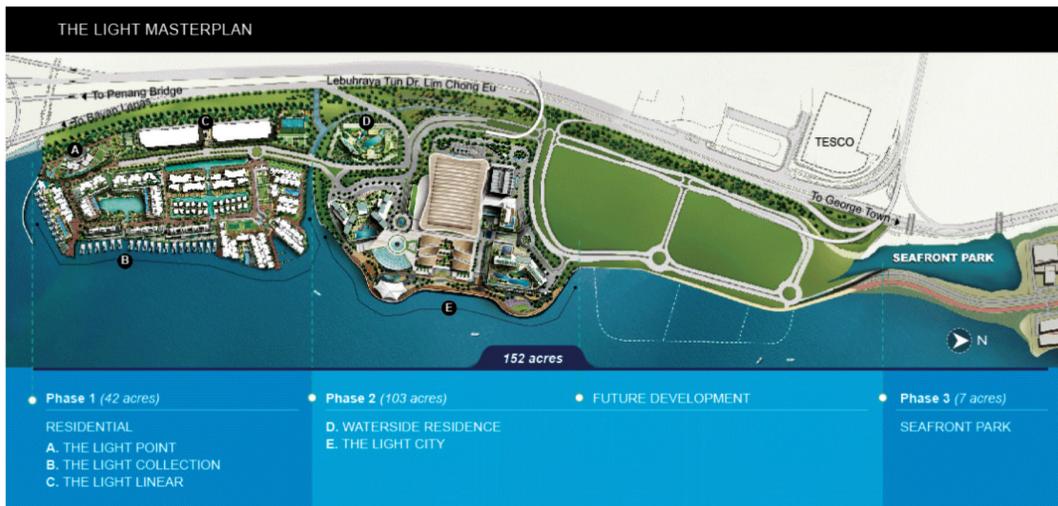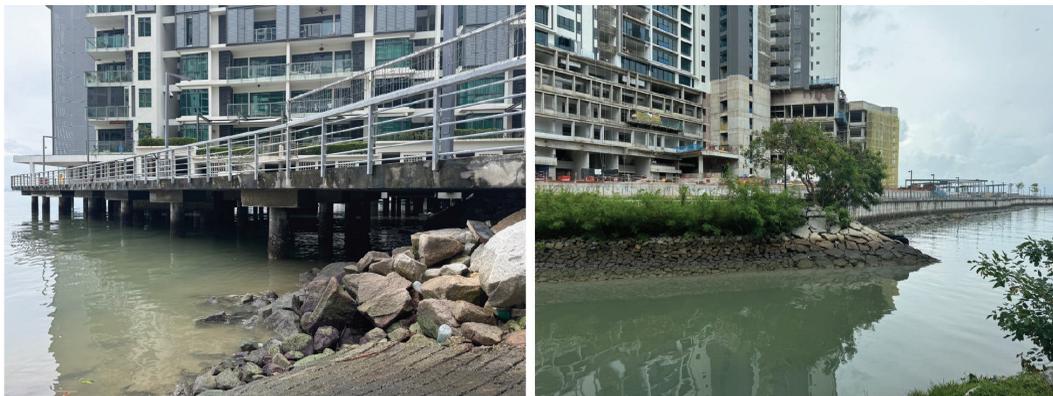

Figure 5: The Light Master Plan

Figure 6: On-site observation of the Light's coastline

a seawall, and a marine platform. Constructed using conventional methods, the seawall also features textured tiles (Figure 7) as part of a small-scale eco-engineering initiative. This collaboration with an educational institution under a Corporate Social Responsibility (CSR) programme makes the Light a relevant case study.

Case Study 3: Queens Waterfront

Queens Waterfront is a 36.53-acre mixed-use development by Ideal Property Group, featuring 24.79 acres of reclaimed land. The project includes Queens Residences, Queens Sports Centre, and an international school. Queens Residences comprises four condominium towers: Q1 (21 storeys) and Q2 (24 storeys), both completed in 2022, with Q3 and Q4 currently under construction. Amenities include a 6.1-acre marina and a waterfront promenade with marine life themes, a sculpture park, and a beach habitat. The ground and first floors house upscale restaurants. Figure 8 illustrates the 3D rendering of Queens Waterfront.

Ideal Property Group, a leading Malaysian developer has an extensive portfolio that includes high-rise, landed residential, commercial, and mixed-use projects. Queens Waterfront is their inaugural coastal reclamation venture, enhancing their reputation in Penang's property development sector. Strategically located in southern Penang Island between Queensbay Mall and Pulau Jerejak, the development offers stunning sea views. Observations (Figure 9) reveal that Queens Waterfront's coastline employs traditional artificial structures such as rock revetments and marine platforms, which lack natural elements.

Figure 7: Textured tiles attached to the seawall in the Light City

Figure 8: A 3D illustration of Queens Waterfront

Figure 9: On-site observation of Queens Waterfront's coastline

Selection of Interviewees for Case Studies

Respondents were selected through purposive sampling based on their experience and qualifications in coastal construction in Penang. Given the rarity of such projects in Malaysia, it was crucial to gather insights from knowledgeable professionals. All respondents were project team members from the Andaman, The Light, and Queens Waterfront projects, identified through nominations by project developers, appointed consultant firms, awarded contractor firms, and LinkedIn searches.

Out of 15 invitations, 10 respondents agreed to participate in the interviews, including three from the Andaman project, three from The Light project, and four from the Queens Waterfront project. These respondents represented diverse professional roles and experience levels, contributing to a broad range of perspectives. The interviews provided comprehensive insights into eco-engineering implementation in coastal construction projects in Penang. The respondents' varied backgrounds enriched the research by offering diverse viewpoints and justifications, enhancing the validity of the findings. The basic profiles of the interviewees are summarised in Table 4.

Stage 3 - Validation Study

The validation study involved FGDs with eco-engineering experts to confirm the identified factors and recommendations, thereby strengthening the credibility of the findings. Given the rigorous nature of government-related departments, second-round interviews were conducted to validate primary data related to the government sector and ensure the accuracy of the results.

Selection of Participants for Validation Study

Malaysia's artificial coastlines primarily rely on hard infrastructure and there is a limited pool of experts with extensive eco-engineering experience. Consequently, the validation study employed purposive sampling to recruit FGD participants with significant expertise in eco-engineering. Potential FGD participants were identified through coastal development projects involving habitat restoration.

Due to conflicts of interest, only two experts agreed to participate in the FGD. Despite the small number, they represented a broad spectrum of the eco-engineering field. Both were consultants specialising in eco-engineering integration, actively engaged in academia and

Table 4: Background information of interviewees

No.	Position of Interviewee	Type of Stakeholder	Involvement in Coastal Construction Project	Years of Working Experience	Years of Coastal Working Experience	Type of Interview
I1	Assistant Project Manager	Contractor	Andaman	> 5 years	> 5 years	Face to face
I2	Quantity Surveyor	Contractor	Queens Waterfront	> 15 years	> 5 years	Face to face
I3	Site Engineer	Contractor	Queens Waterfront	> 10 years	> 10 years	Face to face
I4	Environment Officer	Developer	The Light	> 5 years	> 5 years	Face to face
I5	Assistant Environment Officer	Contractor	Andaman	> 5 years	> 5 years	Online platform
I6	Assistant Project Manager	Developer	Andaman	> 5 years	> 5 years	Online platform
I7	Contract Manager	Contractor	Queens Waterfront	> 20 years	> 15 years	Face to face
I8	Construction Manager	Developer	Queens Waterfront	> 10 years	> 10 years	Face to face
I9	Contract Manager	Developer	The Light	> 10 years	> 10 years	Face to face
I10	Engineer	Consultant	The Light	> 10 years	> 10 years	Online platform

collaborating with government agencies on Environmental Impact Assessments (EIA) and ecosystem restoration. Their extensive experience—35 and 46 years in marine and coastal areas—provided a holistic perspective. Table 5 presents their background information.

After consulting PLANMalaysia Pulau Pinang, the Department of Engineering, and the City Council of Penang Island (MBPP), it was recommended to approach the Department of Irrigation and Drainage (DID) and the DOE. These agencies play critical roles in coastal management, pollution control, and environmental improvement. Table 6 presents details of the interviewees from the relevant government departments.

Table 5: Background information of the FGD participants

No.	Position	Organisation	Years of Experience in Coastal Areas	Advanced Degree
P1	Marine and Coastal Ecologist	Consultant/academic institution	35	Doctoral Degree
P2	Marine and Coastal Environmental Consultant	Consultant/academic institution	46	Doctoral Degree

Analysis and Results

This section presents the data collected from the case studies and validation study.

Perception of Eco-engineering by Interviewees from Case Studies

In this study, it was essential to investigate the interviewees' basic understanding of the concept of eco-engineering in relation to coastal construction projects. Therefore, the first section of the interview included a question that allowed the respondents to describe their understanding of eco-engineering and assess their awareness, perception, and knowledge of how eco-engineering can be integrated into coastal constructions.

Based on the data, the findings revealed that the understanding of eco-engineering among respondents was varied. The majority described eco-engineering in simple terms, with literal explanations indicating a general understanding of the concept. Only a limited number of participants provided detailed descriptions. Several key concepts and terms emerged from their explanations of eco-engineering, including novel approaches for sustainable construction, incorporating ecology into built structures, integrating ecosystems into structures, restoring and managing ecosystems within the built environment, and ensuring benefits for both humans and the environment. The respondents' interpretations of eco-engineering are presented in Table 7.

Table 6: Profile of the interviewees from government sectors

No.	Position	Department	Years of Experience in the Government Sector
P3	Assistant Director of Rivers and Coasts	DID	> 10
P4	Environment Control Officer	DOE	> 10

Table 7: Interpretation of the term "eco-engineering" by the interviewees

Definition Classification	Interpretation by the Interviewees
Construction innovation	*"...is a novel approach…"* (I2) *"...is something very new in coastal construction in Malaysia…"* (I8)
Integration of ecology and engineering	*"...integrates ecology with engineering..."* (I2) *"It restores the environment by integrating the ecology principle with engineering concepts..."* (I3) *"It is bringing ecology to the built structure..."* (I4) *"It is the integration of the ecosystem into the structure..."* (I5) *"...that merges ecology with structure..."* (I8) *"...is building artificial ecosystems into the structure..." (I*9) *"...combines the concept of ecology with engineering..."* (I10)
Ecosystem restoration	*"...is the design of ecosystems…"* (I1) *"...to restore our natural environment."* (I4, I8) *"It is the design, restoration, and management of ecosystems…"* (I6) *"It is restoring and managing the ecosystem in the built environment…"* (I7)
Sustainable development	*"...to benefit both humans and nature."* (I1) *"...for sustainable construction."* (I2, I5) *"...for the benefit of human society and the built environment."* (I3) *"...to achieve environmental sustainability."* (I6) *"...to minimise the adverse impacts of construction."* (I7) *"...for the benefit of humans and the environment."* (I9) *"...to conserve the environment from the negative impacts of construction."* (I10)

Most interviewees in this study defined eco-engineering as the integration of ecology and engineering. As the terms "ecological" and "engineering" are embedded in the terminology, they clearly reflect the concept of eco-engineering. Despite slight variations in terminology, these definitions are consistent with those provided by previous research. Essentially, eco-engineering is an emerging field that integrates engineering and ecological principles to mitigate environmental impacts from the built environment (Dafforn *et al*., 2015a; Chee *et al*., 2017).

Generally, the participants perceived eco-engineering as an innovative approach that encompasses concepts such as sustainable construction, ecosystem integration, and ecosystem restoration. This suggests a broader understanding of eco-engineering as the restoration of the natural environment for sustainable coastal development, rather than a narrow focus on coastline reinforcements.

However, the findings of this study indicate that eco-engineering is not being applied to coastal infrastructure projects in Penang. Most of the artificial coastlines have been constructed using traditional methods such as rock revetment, which aligns with the findings by Chee *et al*. (2017). In summary, eco-engineering approaches are not commonly integrated into coastal construction projects, resulting in most project team members in Malaysia possessing a basic and limited understanding of eco-engineering.

Factors Influencing the Eco-engineering Implementation in Coastal Construction Projects in Malaysia

All the interviewees were optimistic that eco-engineering would contribute to more sustainable coastal developments and several factors were identified. It is important to note that the interviewees regarded these factors as temporary challenges that could be resolved over time.

This section outlines the factors influencing the implementation of eco-engineering in coastal construction projects, as described by the interviewees and identified by the researcher through NVivo.

Based on the results from NVivo, the factors are: (1) Cost considerations, (2) knowledge and awareness of the importance of coastal ecosystem protection, (3) knowledge and awareness of the available eco-engineering options, (4) expertise, (5) government enforcement, regulations, standards, and initiatives, (6) impacts of engineering performance, (7) science-based evidence of eco-engineering, (8) engagement and communication with stakeholders, (9) impacts of inspection, monitoring, and maintenance, (10) the culture of the construction industry, (11) availability of materials, (12) aesthetic appeal, and (13) coastal dynamics. All factors that influence the implementation of eco-engineering are included in Table 8.

Table 8: Factors influencing the eco-engineering implementation in coastal construction projects in Malaysia

Factors	Explanations
(1) Cost considerations	
➤ Longer project duration	➤ Extended time required to complete the project due to the complexities of eco-engineering integration compared to conventional method.
➤ Emphasis on profit margin	➤ Project owners are reluctant to adopt if eco-engineering increases costs without a proportional increase in revenue or long-term financial benefits.
➤ Incur additional expenses	➤ Integration of eco-engineering requires extra costs due to additional stakeholder involvement, changes in traditional project scope, and resource availability.

(2)	Knowledge and awareness of the importance of coastal ecosystem protection		
	➢	Lack of environmental awareness for protecting nature	➢ Stakeholders do not fully recognise the importance of nature conservation.
	➢	Lack of knowledge of the value of coastal ecosystems	➢ Stakeholders focus more on terrestrial ecosystems and undervalue coastal ecosystems due to limited knowledge of services provided by coastal ecosystems such as coastal protection, enhancing biodiversity, water filtration, and carbon sequestration.
(3)	Knowledge and awareness of eco-engineering approaches		
	➢	Lack of knowledge and awareness of eco-engineering available options	➢ Stakeholders are unaware of eco-friendly alternatives to traditional infrastructure solutions.
	➢	Lack of knowledge and awareness of ecosystem services provided by eco-engineering	➢ Stakeholders are unaware of this valuable measure that is able to restore the coastal environment.
(4)	Expertise		
	➢	Limited experience, skilled, and competent project team members	➢ Traditional hard infrastructure continues to dominate coastal development, restricting the availability, and advancement of eco-engineering expertise.
	➢	Lack of opportunity for employment	➢ As eco-engineering is a relatively novel approach to habitat restoration, the limited availability of job opportunities within this field further discourages workforce development and skill specialisation.
(5)	Government enforcement, regulations, standards and initiatives		
	➢	Lack of enforcement	➢ Coastal ecosystem protection-related policies are not strictly imposed.
	➢	Insufficient government initiatives	➢ Lack of funding or incentives from the authorities to encourage the adoption of eco-engineering in coastal construction.
	➢	Insufficient government rules, regulations, and standards	➢ Inadequate legal frameworks governing the integration of eco-engineering in coastal construction.
(6)	Engineering performance		
	➢	Concern about the integrity of coastal infrastructures	➢ Stakeholders have limited confidence in the infrastructure's performance if integrating eco-engineering solutions due to the unpredictable natural elements.

(7) Science-based evidence of eco-engineering		
	➤ Limited cost-benefit analysis	➤ The long-term economic, environmental, and social benefits of eco-engineering compared to traditional hard infrastructure are unclear.
	➤ Lack of evidence for the effectiveness of eco-engineering	➤ Most eco-engineering trials have been conducted in Western countries, lack of empirical data proving its success in Asia.
(8) Engagement and communication with stakeholders		
	➤ Limited opportunity for collaborating with stakeholders	➤ Conventional hard infrastructure is still the leading option in coastal construction, leading to limited joint efforts among key stakeholders for integrating eco-engineering in coastal construction.
	➤ Insufficient collaboration between biologists and ecologists with engineers	➤ Engineers prefer the conventional method with expected outcomes, leading to key parties of ecologists and engineers not effectively working together and challenges in knowledge sharing.
(9) Engineering inspection, monitoring, and maintenance		
	➤ Concern about the future maintenance and inspection fees	➤ Eco-engineering integration requires regular inspection and maintenance to sustain the positive impact of natural elements. However, these activities incur additional costs and most stakeholders prioritise revenue over long-term upkeep.
	➤ Concern about the responsibility of future work	➤ Eco-engineering requires regular inspection and maintenance after project completion; however, most stakeholders prioritise the shortest possible project duration.
(10) Culture of the construction industry		
	➤ Concern about the future maintenance and inspection fees	➤ The project team views eco-engineering as an "extra" since authorities do not mandate its integration into coastal construction.
	➤ Emphasis on personal responsibility and reputation	➤ Engineers are reluctant to integrate eco-engineering due to concerns that invasive species may weaken coastal infrastructure, increasing the risk of structural failure.
	➤ Insufficient proper discussion between project team members	➤ The project team usually focuses on their tasks; each of the entities works separately and individually.
	➤ Attitude and behaviour of project team members	➤ The project team typically conducts inspections and maintenance only when required by authorities, visible ecosystem damage occurs or high suspended solid levels.
(11) Availability of the materials		
	➤ Lack of suppliers in developing eco-engineering products	➤ A shortage of manufacturers that supply materials or components necessary for eco-engineering measures within the country.

(12) Aesthetic appeal	
➤ The aesthetic of artificial infrastructures	➤ Most projects prioritise aesthetics, natural elements such as barnacles above sea level are perceived as less visually appealing.
(13) Coastal dynamics	
➤ Poor ecosystems in the coastal areas	➤ Many perceive muddy coastlines as having little ecological value, assuming the ecosystem was already damaged before coastal construction began..
➤ Geographical conditions	➤ Geographical conditions, including topography, type of soil and climate influence the suitability of integrating eco-engineering into coastal infrastructure.
➤ Limited data availability on coastal ecosystems	➤ There is a lack of recorded data on existing coastal ecosystems due to the difficulty of accessing coastal ecosystems compared to terrestrial ones.

Main Factors Influencing the Eco-engineering Implementation in Coastal Construction Projects in Malaysia and Recommendations

This section presents the main factors influencing the implementation of eco-engineering, as indicated by the interviewees. After all the factors were described, the interviewees were asked to specify the most significant ones. Table 9 shows the key factors that influence the implementation of eco-engineering, as selected by the interviewees.

Table 9: Selection of main factors influencing the eco-engineering implementation by interviewees

Main Factor	Interviewee Selection	Total Selection (No.)
Government enforcement, regulations, standards, and initiatives	(I1, I2, I3, I5, I6, and I10)	6
Knowledge and awareness of eco-engineering approaches	(I4 and I9)	2
Cost considerations	(I7 and I8)	2
Second Factor	**Interviewee Selection**	**Total Selection (No.)**
Cost considerations	(I2, I3, I5, I6, and I10)	5
Government enforcement, regulations, standards, and initiatives	(I4, I7, I8, and I9)	4
Knowledge and awareness of eco-engineering approaches	(I1)	1
Third Factor	**Interviewee Selection**	**Total Selection (No.)**
Engineering inspection, monitoring, and maintenance	(I2, I3, I5, I7, I8, and I10)	6
Cost considerations	(I1, I4, and I9)	3
Knowledge and awareness of eco-engineering approaches	(I6)	1

The findings highlighted that the key factors influencing the implementation of eco-engineering, as identified by the interviewees are consistent. The main factors are (1) government enforcement, regulations, standards, and initiatives; (2) cost considerations; (3) knowledge and awareness of eco-engineering approaches; and (4) engineering inspection, monitoring, and maintenance. Figure 10 illustrates the main factors influencing the implementation of eco-engineering in coastal construction projects, along with recommendations from the interviewees.

Validation of the Main Factors and Recommendations

Conducting the validation study was essential to clearly demonstrate the factors influencing eco-engineering implementation and to provide recommendations for improving it. Participants were asked to validate the identified factors and recommendations. Table 10 summarises the participants' comments on the key factors affecting eco-engineering implementation while Table 11 presents their feedback on the recommendations for enhancing it.

According to Table 10, all participants agreed on the primary factors. Participant P1 noted that these factors are interrelated, suggesting a cyclical system. This implies that if the main factors are effectively addressed, the remaining factors will fall into place.

Based on Table 11, all the participants agreed on the identified recommendations; however, some suggestions were made for revising or rephrasing the sentences of the recommendations to better convey their exact meanings.

Discussion

The following section synthesises the case studies with the findings from the validation study, offering a comprehensive discussion.

Main Factor of Government Enforcement, Regulations, Standards, and Initiatives

The findings indicate that existing regulations prioritise land development and construction-friendly practices such as pollution control, over integrating nature into engineering. This is consistent with the study by Airoldi *et al.* (2021), which found that the practice of restoration in the ocean is less advanced than it is on land. Despite Malaysia's national policies on environmental protection and biodiversity management, governance remains fragmented. The results show shortcomings in coastal biodiversity conservation, aligning with Tong (2020). Similarly, China faces legal deficiencies, with coastal restoration projects managed by overlapping departments, leading to the risk of conflicts and inconsistencies (Zhang *et al.*, 2024).

Malaysia's EIA guidelines require projects to meet legal and policy requirements (DOE, 2016). However, the findings reveal that the DOE prioritised conventional guidelines and standards for construction projects, as reflected in all the coastal infrastructures that have been developed using conventional methods. Therefore, the lack of standards and guidelines limits broader implementation of eco-engineering (Whelchel *et al.*, 2018). The findings also indicate that sustainability is not a top priority for stakeholders, as project plans are primarily concerned with obtaining approval from the authorities.

Integrating eco-engineering requires substantial resources; however, the study found that government initiatives for sustainable coastal development are inadequate, with limited funding or incentives for eco-engineering integration in coastal infrastructure. This finding is supported by Chee *et al.* (2021b), whose research stated that the lack of awareness and initiative to explore and engage in new technologies among policymakers and practitioners has hindered the implementation
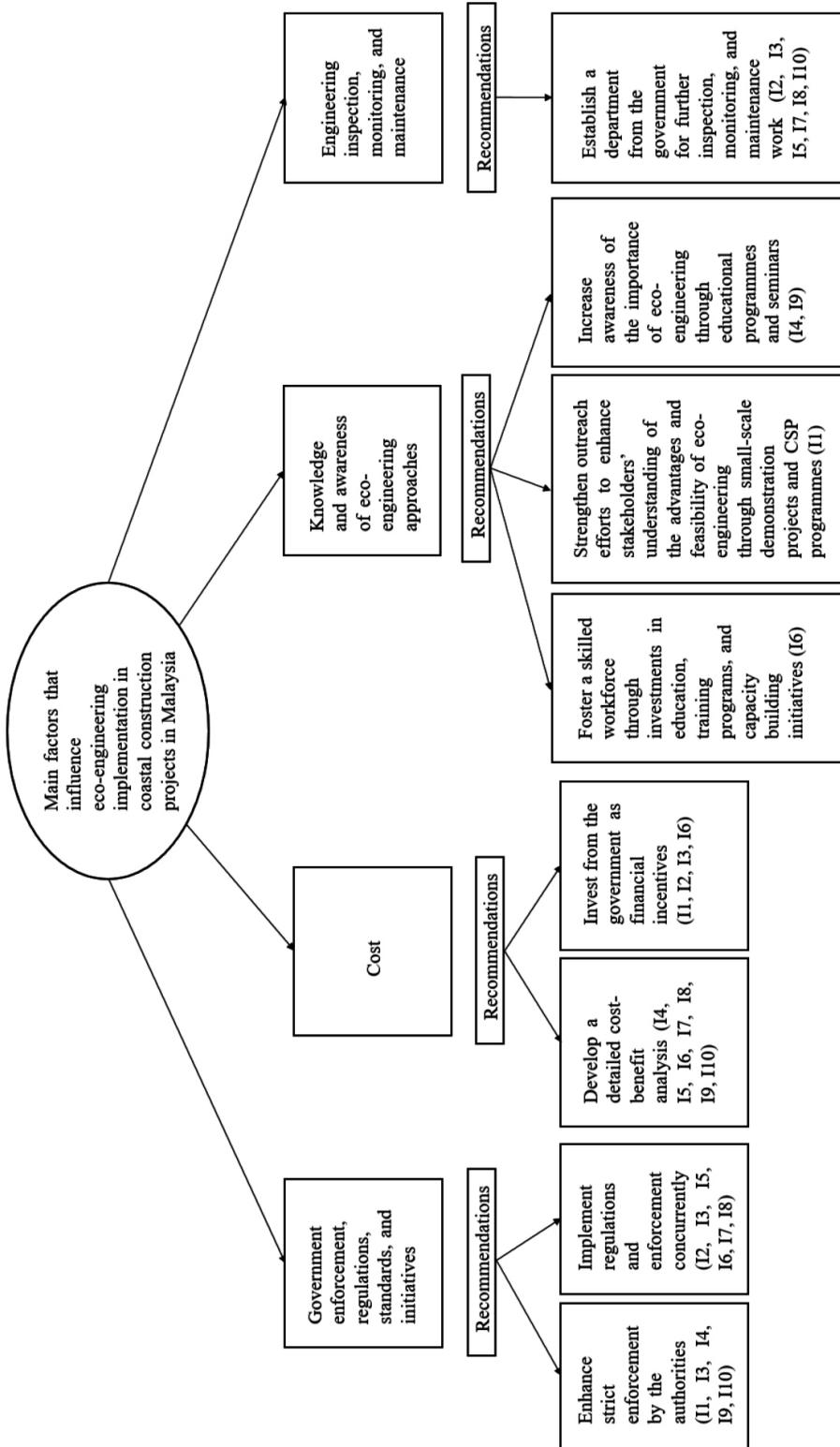
Figure 10: Main factors that influence the eco-engineering implementation in coastal construction projects and recommendations

Table 10: Summary of the participants' comments on the main factors influencing eco-engineering implementation

Main Factors Influencing Eco-engineering Implementation in Coastal Construction Projects in Malaysia	Comments by Participants

(1) Government enforcement, regulations, standards, and initiatives
  ➤ Lack of enforcement
  ➤ Insufficient government initiatives
  ➤ Insufficient government rules, regulations, and standards
	All the participants strongly agreed this factor influences eco-engineering implementation. The participants presented as follows:
	
	(1) *"We don't have any specific regulation and enforcement* (for eco-engineering integration) *in this country at the moment."* (P1)
	(2) *"There is no regulation and guideline for eco-engineering integration, then, it is not under enforcement."* (P3)
	(3) *"If there is regulation, only then will follow the rules and guidelines."* (P3)
	(4) *"They* (DID) *have guidelines on coastal protection, but they have no law."* (P4)

(2) Cost considerations
  ➤ Longer project duration
  ➤ Emphasis on profit margin
  ➤ Incur additional expenses
	All the participants strongly agreed that cost is one of the main factors influencing eco-engineering implementation. The participants stated as follows:
	
	(1) *"Developers want to do it as cheaply as possible."* (P2)
	(2) *"Developers want a storyline that says that whatever you ask me to do must make money, at least it must make sure it does not lose money."* (P2)
	(3) *"If the government does not insist on it, why should they (developers) do it? That means it is an additional cost but who is the beneficiary of this integration?"* (P2)
	(4) *"Every developer wants to save money, if they don't have to, they will not do it."* (P1)
	(5) *"The moment you said that the developer has to do it as it going to be better ecology throughout the world, the developers won't care about it."* (P2)
	(6) *"Cost and benefits are very important, the main things would be these two things, the cost and the benefit for the developer."* (P1)
	(7) *"The integration of eco-engineering needs extra costs, it is one of our main concerns."* (P3)
	(8) *"Limited manufacturers for producing eco-engineering products in Malaysia, will need additional costs for importing the products."* (P3)
	(9) *"The consultant has the expertise and they will suggest to the developers the sustainable approaches, but the developer will say it's costly."* (P4)
	(10) *"On our part, when the developer has to disturb this area, they will need to have the control equipment to avoid pollution, in reality, when we go to the site for inspection, the suggested control measure is 10 equipment for example, but they only installed 5 to 6 equipment on site, so, the main thing is cost."* (P4)

(3) Knowledge and awareness of eco-engineering approaches
  ➤ Lack of knowledge and awareness of the available options of eco-engineering
  ➤ Lack of knowledge and awareness of ecosystem services provided by eco-engineering
	All the participants agreed with this factor that influences the eco-engineering implementation. The participants expressed as follows:
	
	(1) *"Eco-engineering is quite new here (in Malaysia)."* (P1 & P2)
	(2) *"We are not familiar with eco-engineering."* (P3)
	(3) *"I am not used to hear the term eco-engineering, most of Penang's manmade coastlines are constructed with armour rock."* (P4)

(4) Engineering inspection, monitoring, and maintenance
  ➤ Concern about the future maintenance and inspection fees
  ➤ Concern about the responsibility of future works
	All the participants agreed with this factor that influences the eco-engineering implementation. It is discussed as follows:
	
	(1) *"This factor is related to the factor of government enforcement, regulations, standards, and initiatives. If there is no regulation, nobody will do the monitoring."* (P1)
	(2) *"Just like the EIA, there is a requirement by the DOE, that's why people do the monitoring."* (P2)
	(3) *"It is one of the main factors as eco-engineering requires regular inspection and maintenance, which lead to extra time and cost."* (P4)

Table 11: Summary of the participants' comments on the recommendations for enhancing eco-engineering implementation

Main Factors Influencing Eco-engineering Implementation	Recommendations for Enhancing Eco-engineering Implementation	Comments by Participants
(1) Government enforcement, regulations, standards, and initiatives	✓ Enhance strict enforcement by the authorities ✓ Implement regulation and enforcement concurrently	All participants agreed with the recommendations and two participants provided some minor suggestions. (1) Participant (P3) stated that it should revise the second recommendation from "implement regulation and enforcement concurrently" to "develop regulation and implement enforcement concurrently" as there is no regulation and guideline for the eco-engineering integration at the moment. (2) Participant (P4) highlighted that the first recommendation "enhance strict enforcement by the authorities" should be revised to "enhance strict enforcement by the local authorities" due to local authorities being able to establish local environmental regulations and policies.

(2) Cost considerations	✓ Develop a detailed cost-benefit analysis ✓ Invest a substantial amount of money from the government as financial incentives	All participants agreed with the recommendations and one participant provided suggestions to rephrase the second recommendation. (1) Participant (P1) expressed that the sentence "invest from the government" from the second recommendation should be revised because it is deemed inappropriate. The participant stated: (1) *"The thing is that the government is not going to invest in any private developer or any private project. To do any eco-engineering, the government is not going to put any money, the money has to come from the developer or the project proponent."* (P1) (2) *"The second recommendation should be rephrased such as advocating for more financial incentives from the government, to make it more concise."* (P1)
(3) Knowledge and awareness of eco-engineering approaches	✓ Foster a skilled workforce through investments in education, training programmes, and capacity-building initiatives ✓ Increase outreach efforts to enhance stakeholders' understanding of the advantages and feasibility of eco-engineering through small-scale demonstration projects and CSR programmes ✓ Increase awareness of the importance of eco-engineering through educational programmes and seminars	All participants agreed with the recommendations.
(4) Engineering inspection, monitoring, and maintenance	✓ Establish a department from the government for further inspection, monitoring, and maintenance work	All participants agreed with the recommendations and one participant provided a minor suggestion. (1) Participant (P4) suggested revising "establish a department from the government for further inspection, monitoring, and maintenance work" to "establish a department from the local government for further inspection, monitoring, and maintenance work" as the local government has the responsibilities and authorities to manage the city more sustainably and in line with the State's and Nation's development policies.

of NbS. Hence, Shiiba *et al*. (2022) suggest that innovative financial mechanisms such as blue bonds and debt-for-nature swaps can support ocean conservation while promoting economic growth.

Strict policies have successfully promoted ocean-friendly infrastructure in the United States (Sachdev, 2019) and Europe (Moraes *et al*., 2022), but Malaysian authorities do not mandate eco-engineering. According to Airoldi *et al*. (2021), there has been a passive regulatory approach to the ocean, with existing development prioritising economic growth or poverty alleviation instead of climate change adaptation (Townhill *et al*., 2021). The findings from previous studies indicate the same in Malaysia, highlighting a notable lack of enforcement for protecting marine biodiversity in the country.

While the National Construction Policy 2030 emphasises a sustainable built environment, it primarily focuses on eco-friendly construction materials for carbon reduction and waste management (Construction Industry Development Board, 2022). Although environmental sustainability is one of the dimensions involved in the Twelfth Malaysia Plan, this plan mainly focuses on socioeconomic development towards a more prosperous society. There is a lack of a specific framework for eco-engineering integration in coastal infrastructure, a gap also noted by Morris *et al*. (2019) in global policies.

This study aligns with Shumway *et al*. (2021), who found that poor planning, coordination, and funding lead to fragmented restoration efforts in Australia. Similarly, developing countries like Vietnam, Indonesia, and Bangladesh struggle with limited funds, weak enforcement, and ineffective legal frameworks (Rahman, 2022; Suhardi *et al*., 2024; Giang & Khanal, 2024). Therefore, stronger enforcement and a dedicated policy for integrating eco-engineering by local authorities are essential for advancing sustainable coastal construction.

Main Factor of Cost Considerations

Eco-engineering is still a relatively new approach in Malaysia's coastal construction sector, with many projects continuing to rely on conventional engineering methods. Research indicates that eco-engineering tends to extend project durations due to its multi-stage integration process. The World Bank (2017) highlights the necessity of non-traditional engineering frameworks for both standalone Nature-based Solutions (NbS) projects and their integration into traditional infrastructure. Given Malaysia's dependence on hard infrastructure, adopting innovative eco-engineering methods requires additional time for feasibility assessments, skilled labour and material sourcing, construction, and long-term maintenance, ultimately leading to increased costs.

These additional costs—comprising direct, indirect, and resource-related expenses—have restricted the implementation of eco-engineering in Malaysia. This is consistent with findings by Naylor *et al*. (2017), who identified financial constraints as a significant barrier to the adoption of eco-engineering. Similarly, Chan *et al*. (2017) and Durdyev *et al*. (2018a; 2018b) found that high costs impede sustainable practices in developing countries. While some studies propose that minor modifications could allow for more affordable integration of eco-engineering (Naylor *et al*., 2017; 2018; Burt & Bartholomew, 2019), this study found otherwise. The findings revealed that integrating eco-engineering necessitates larger budgets, which developers often transfer to end-users through higher prices.

Profit margins frequently take precedence over sustainability, making traditional hard methods the preferred option. The increase in reclamation projects for urbanisation highlights this focus on profitability. Findings suggest that depending on the project's objectives, coastal developments might diverge from traditional designs to attract tourists or support broader economic functions. This observation aligns with the Marine and Coastal Management Working Group (2020), which noted that

economic activities along Malaysia's coasts often overshadow conservation efforts. Respondents also raised concerns about long-term maintenance and inspection costs. While the ecological benefits of restoration are acknowledged, the additional financial burden often leads decision-makers to favour cost-effective, conventional approaches over environmentally sustainable alternatives.

Consequently, securing adequate funding and resources from government programmes, public-private partnerships, international cooperation initiatives, and innovative financing mechanisms for coastal restoration is critical in Small Island Developing States (Hernández-Delgado, 2024). In contrast, cost is not the primary determinant in regions such as Europe and China, where government funding supports NbS initiatives. However, these studies also advocate for funding through diversified stakeholder collaborations to strengthen and expand such efforts (Moraes *et al*., 2022; Liu & Ma, 2024). Acknowledging these financial challenges, there is a growing consensus advocating for a fundamental shift in funding strategies and research programmes to better support the development, implementation, and global application of eco-engineering (Firth *et al*., 2024).

Cost remains a significant barrier to the implementation of eco-engineering due to the substantial resource investment required. To promote wider adoption, it is crucial to quantify the economic benefits, including long-term environmental and societal gains (Strain *et al*., 2018). However, findings indicate that few cost-benefit analyses effectively communicate these advantages to stakeholders, as supported by Morris *et al*. (2018). Therefore, a comprehensive cost-benefit analysis is recommended to demonstrate the economic viability of eco-engineering. Additionally, increased government financial incentives could help mitigate high initial costs and encourage adoption, particularly in Malaysia, where cost-saving remains a priority over sustainability.

Main Factor of Knowledge and Awareness of Eco-engineering Approaches

The findings indicate that most respondents possess only a basic understanding of eco-engineering, primarily viewing it as the integration of nature with artificial infrastructure. This limited awareness may be attributed to Malaysia's focus on national economic development and the infrequent application of eco-engineering in coastal projects. The preference for traditional artificial coastlines further entrenches this gap, leaving project team members unfamiliar with eco-engineering approaches. Additionally, some stakeholders depend on environmental officers for guidance on environmental protection. These findings are consistent with Durdyev *et al*. (2018a), who identified a lack of awareness and knowledge of sustainable practices among stakeholders as a barrier to sustainable construction in Malaysia.

This study highlights that collaboration between developers and educational institutions can enhance small-scale demonstration projects, CSR programmes, and the long-term efficacy of eco-engineering through regular monitoring. Such collaboration also increases project visibility and accessibility, showcasing eco-engineering strategies to the public. However, insufficient exposure and support from educational institutions, non-governmental organisations, and government sectors contribute to this knowledge gap. Limited outreach efforts to educate stakeholders about the potential of eco-engineering have inadvertently led to a preference for conventional hard solutions over eco-engineering. This finding aligns with Seddon *et al*. (2020), who noted that reliance on grey infrastructure persists due to a lack of awareness regarding the ecosystem services provided by NbS.

In contrast to developed countries, knowledge and awareness of eco-engineering are not the primary challenges to its implementation. In these regions, eco-engineering is widely acknowledged as essential for restoring ecosystem services. Angnuureng *et al*. (2025)

observe that the use of coastal grey infrastructure is declining, with NbS and eco-engineering gaining traction. The Sydney Living Seawall in Australia exemplifies how scientific principles are being applied with empirical data (Vozzo *et al*., 2021; Bishop *et al*., 2022), successfully raising global awareness of eco-friendly infrastructure. However, a recent review by Firth *et al*. (2024) highlights that advancements in eco-engineering are more pronounced in the academic sectors of developed nations.

The results underscore that a lack of knowledge and awareness remains a critical factor, aligning with Rahman *et al*. (2023). Given that project team members have limited familiarity with eco-engineering, it is likely that public understanding is also minimal. Therefore, substantial efforts are needed to educate key stakeholders through educational programmes and environmental seminars that emphasise the importance and benefits of eco-engineering, as well as small-scale demonstration projects and CSR programmes. Additionally, fostering a skilled workforce through investments in education, training programmes, and capacity-building initiatives for engineers and practitioners is essential. These findings resonate with Chee *et al*. (2021b), who emphasised the need for formal and informal educational initiatives to build confidence in eco-engineering solutions and promote the adoption of nature-based strategies.

Main Factor of Engineering Inspection, Monitoring, and Maintenance

Most research highlights concerns regarding engineering performance and maintenance as obstacles to the adoption of eco-engineering (Naylor *et al*., 2017; Whelchel *et al*., 2018; Morris *et al*., 2019). However, this study found that engineering inspection, monitoring, and maintenance are key factors influencing its implementation. A significant reason for these concerns is that developers prioritise cost savings over conservation. Short project timelines and cost-cutting measures often result in inadequate long-term monitoring and maintenance planning, leaving future

responsibilities uncertain. Consequently, respondents expressed deep concerns about who will oversee monitoring and upkeep once the projects are completed. This contrasts with previous studies, which emphasised the lack of performance and maintenance data as barriers to the adoption of eco-engineering.

The Seattle Seawall project in the United States serves as a successful example of research translated into practice, providing an aspirational benchmark for multifunctional infrastructure globally (Firth *et al*., 2024). Although the integration of eco-engineering increased total construction costs by an estimated 2% (Sawyer *et al*., 2020; Accola *et al*., 2022b), the long-term maintenance costs remain unknown. Furthermore, the limited number of "real-world" large-scale eco-engineering projects highlights another significant challenge: Understanding how such interventions will perform under climate change pressures (Firth *et al*., 2024). In contrast, this study indicates that uncertainty regarding long-term monitoring and maintenance plays a more immediate role in influencing eco-engineering implementation.

Naylor *et al*. (2017) also pointed out that ecological enhancement schemes often lack proper long-term monitoring, even when this is crucial for development mitigation. This aligns with findings from Penang's Go Green Project, where the Entopia butterfly farm failed to maintain its ecological facade and switched to an artificial design due to inadequate upkeep.

To address this issue, it is recommended that a dedicated department or delegation be established within agencies like the Marine Department or the Department of Environment for ongoing monitoring and maintenance. Inspired by Malaysia's Public Works Department, which oversees public infrastructure maintenance, a similar approach could enhance eco-engineering implementation and sustainability. These findings are supported by Naylor *et al*. (2017), who suggested that third-party research collaborations such as those with universities can effectively monitor the long-term efficacy of eco-engineering. Establishing a

dedicated entity or involving third parties is vital for enhancing implementation and ensuring the sustained success of eco-engineering in developing countries.

Conclusions

Enhancing eco-engineering integration in coastal infrastructure requires a clear understanding of the influencing factors and actionable recommendations. With the rise of hard infrastructure and reclamation projects along the coast of Penang, this study identifies four key factors shaping eco-engineering implementation: (1) Government enforcement, regulations, standards, and initiatives; (2) cost considerations; (3) knowledge and awareness of eco-engineering approaches; and (4) engineering inspection, monitoring, and maintenance. To address these, several targeted actions are recommended:

(1) Develop regulations alongside strong enforcement mechanisms.

(2) Strengthen enforcement by local authorities.

(3) Conduct comprehensive cost-benefit analyses.

(4) Provide financial incentives through government support.

(5) Promote awareness through outreach efforts, small-scale demonstration projects, and CSR initiatives.

(6) Increase education on eco-engineering via programmes and seminars.

(7) Invest in developing a skilled workforce through training and capacity-building.

(8) Establish a dedicated local government department for continuous inspection, monitoring, and maintenance.

Rather than focusing on general factors, priority must be given to examining specific local conditions and contexts. By addressing the primary influencing factors through these recommendations, secondary challenges can be mitigated, ultimately supporting more effective eco-engineering implementation in Malaysia's coastal construction projects.

Acknowledgements

Conflict of Interest Statement

The authors declare that they have no conflict of interest.

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Appendix A

Interview

**Moving Towards Sustainable Coastal Development in Malaysia:
Integration of Ecological Engineering in Coastal Construction Project**

Dear Mr./Mrs./Ms.
This research aims to identify the factors influencing ecological engineering (eco-engineering) uptake in coastal construction projects in Malaysia and investigate how eco-engineering can be integrated into coastal construction projects. Urbanisation and population growth are leading to ocean sprawl and ocean squeeze. Therefore, working with nature such as eco-engineering is increasingly gaining concern around the world to save our oceans and seas. However, there is a poor uptake of eco-engineering in the Malaysian construction industry. We would appreciate and be grateful if you could participate in this interview. All responses are strictly confidential and will be used for academic purposes only. Thank you.

<u>Section A: Respondents' background information</u>

1. Name of company:

   _____

2. Email address:

   _____

3. Working's position:

   _____

4. Years of working experience:
   □ ≥ 5 years
   □ ≥ 10 years
   □ ≥ 15 years
   □ ≥ 20 years

5. Years of coastal working experience:

    □ ≥ 5 years

    □ ≥ 10 years

    □ ≥ 15 years

    □ ≥ 20 years

6. Type of stakeholder:

    _____

7. Involvement in coastal construction project:

    _____

8. What is eco-engineering?

    _____

Section B: Factors influencing the eco-engineering uptake in coastal construction projects in Malaysia

1. What is your opinion towards the factor of **knowledge and awareness of the available options**?

    _____

    _____

    _____

    _____

    _____

2. What is your opinion towards the factor of **engagement and communication with multiple stakeholders**?

    _____

    _____

    _____

    _____

    _____

3. What is your opinion towards the factor of **government policies/initiatives**?

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4. What is your opinion towards the factor of **science-based evidence**?

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5. What is your opinion towards the factor of **cost**?

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6. What is your opinion towards the factor of **expertise**?

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7. What is your opinion towards the factor of **engineering performance, inspection, and maintenance**?

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8. What is your opinion towards the factor of **systematic management with long-term monitoring**?

_____

_____

_____

_____

_____

9. What are the other factors that influence the integration of eco-engineering in coastal construction projects in Malaysia?

_____

_____

_____

_____

_____

10. What are the main factors that influence the eco-engineering uptake in coastal construction projects in Malaysia?

_____

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_____

Appendix B

Validation Study

**Moving Towards Sustainable Coastal Development in Malaysia:
Integration of Ecological Engineering in Coastal Construction Project**

(Kong Shih Shan, P-RD0133/21(R))

Dear Mr./Mrs./Ms.

Urbanisation and population growth have contributed to ocean sprawl and ocean squeeze, placing immense pressure on coastal ecosystems. In response, ecological engineering (eco-engineering) is increasingly recognised worldwide as a vital strategy for sustainable coastal management.

Despite this growing awareness, the uptake of eco-engineering in the Malaysian construction industry remains limited. This study aims to identify the key factors influencing the uptake of eco-engineering and to propose recommendations to enhance its implementation for sustainable coastal development in Malaysia.

The research is conducted in two stages:
1. Stage one involves identifying relevant variables through an extensive literature review and first-round interviews.
2. Stage two includes second-round interviews and a mini-focus group discussion to validate the identified factors and recommendations.

We kindly invite you to participate in the second stage of the validation process. Your insights and professional experience are highly valuable to this research. Please note that all responses will be kept strictly confidential and will be used for academic purposes only. Thank you for your time and consideration.

<u>**Section A: Respondents' background information**</u>

1. Organisation/Department:

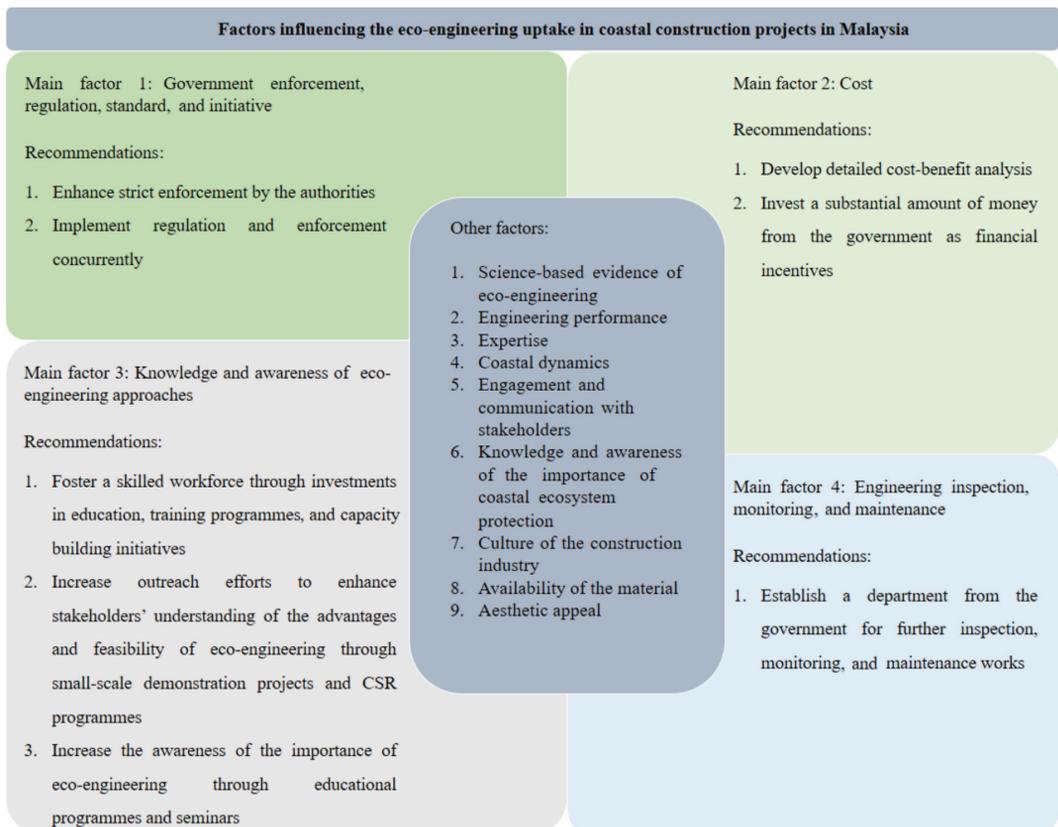   _____

2. Email address:

   _____

3. Working's position:

   _____

4. Years of working experience in the coastal areas/government sectors:

_____

Section B: Factors influencing the eco-engineering uptake in coastal construction projects in Malaysia and recommendations

1. Kindly validate the identified factors influencing the uptake of eco-engineering in coastal construction projects, along with the associated recommendations for the main factors. The list of sub-factors is provided on the following page.

Factors influencing the eco-engineering uptake in coastal construction projects in Malaysia

Main factor 1: Government enforcement, regulation, standard, and initiative

Recommendations:

1. Enhance strict enforcement by the authorities
2. Implement regulation and enforcement concurrently

Main factor 3: Knowledge and awareness of eco-engineering approaches

Recommendations:

1. Foster a skilled workforce through investments in education, training programmes, and capacity building initiatives
2. Increase outreach efforts to enhance stakeholders' understanding of the advantages and feasibility of eco-engineering through small-scale demonstration projects and CSR programmes
3. Increase the awareness of the importance of eco-engineering through educational programmes and seminars

Other factors:

1. Science-based evidence of eco-engineering
2. Engineering performance
3. Expertise
4. Coastal dynamics
5. Engagement and communication with stakeholders
6. Knowledge and awareness of the importance of coastal ecosystem protection
7. Culture of the construction industry
8. Availability of the material
9. Aesthetic appeal

Main factor 2: Cost

Recommendations:

1. Develop detailed cost-benefit analysis
2. Invest a substantial amount of money from the government as financial incentives

Main factor 4: Engineering inspection, monitoring, and maintenance

Recommendations:

1. Establish a department from the government for further inspection, monitoring, and maintenance works

Factors Influencing Ecological Engineering Uptake in Coastal Construction Projects in Malaysia

1. Cost
   ➢ Longer project duration
   ➢ Emphasis on profit margin
   ➢ Incur additional expenses

2. Knowledge and awareness of the importance of coastal ecosystem protection
   ➢ Lack of environmental awareness for protecting nature
   ➢ Lack of knowledge of the value of coastal ecosystem

3. Knowledge and awareness of eco-engineering approaches
   ➢ Lack of knowledge and awareness of eco-engineering available options
   ➢ Lack of knowledge and awareness of ecosystem services provided by eco-engineering

4. Expertise
   ➢ Limited experience, skilled, and competent project team members
   ➢ Lack of opportunity for employment

5. Government enforcement, regulation, standard, and initiative
   ➢ Lack of enforcement
   ➢ Insufficient government initiatives
   ➢ Insufficient government rules, regulations, and standards

6. Impacts of engineering performance
   ➢ Concern about the integrity of coastal infrastructure

7. Science-based evidence of eco-engineering
   ➢ Limited cost-benefit analysis
   ➢ Lack of evidence for the effectiveness of eco-engineering

8. Engagement and communication with stakeholders
   ➢ Limited opportunity for collaborating with stakeholders
   ➢ Insufficient collaboration between biologists and ecologists with engineers

9. Impacts of inspection, monitoring, and maintenance
   ➢ Concern about the future maintenance and inspection fees
   ➢ Concern about the responsibility of future works

10. Culture of the construction industry
   ➢ Perception of the project team members
   ➢ Emphasis on personal responsibility and reputation
   ➢ Insufficient proper discussion between project team members
   ➢ Attitude and behaviour of project team members

11. Availability of the material
   ➢ Lack of suppliers in developing eco-engineering products

12. Aesthetic appeal
   ➢ The aesthetic of the artificial infrastructure

13. Coastal dynamics
   ➢ Poor ecosystems in the coastal area
   ➢ Geographical condition
   ➢ Poor available data for the record of coastal ecosystems