

**BIOPOLYMER–DRIVEN BIOFILM FORMATION
ON INDUSTRIAL–WASTE–BASED
CEMENTITIOUS COMPOSITES**

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**BIOPOLYMER–DRIVEN BIOFILM FORMATION
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CEMENTITIOUS COMPOSITES**

by

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LIST OF SYMBOLS

a	Water absorption
CO ₂ e	Carbon Dioxide Equivalent
g	Gram
MPa	Megapascal
mm	Millimetre
M _n	Number Average Molecular Weight
M _w	Weight Average Molecular Weight
N	Newton
w/v	Percent of Weight of Solution in the Total Volume of Solution
Ø	Porosity
σ_f	Flexural Pressure
σ	Compressive Pressure

LIST OF ABBREVIATIONS

ANOVA	Analysis of Variance
B/Ag	Binder-to-aggregate Ratio
CEM I	Type I OPC Cement
CFU	Colony-forming Unit
ECF	Embodied Carbon Factor
Eco-engineering	Ecological Engineering
EDX	Energy-dispersive X-ray Spectroscopy
FTIR	Fourier-transform Infrared Spectroscopy
GGBS	Ground Granulated Blast Furnace Slag
IUCN	International Union for Conservation of Nature
kV	Kilovolt
NbS	Nature-based Solutions
OPC	Ordinary Portland Cement
P(3HB)	Poly(3-Hydroxybutyrate)
PAHs	Polycyclic Aromatic Hydrocarbons
PBAT	Poly(butylene adipate-co-terephthalate)
PCoA	Principal Coordinates Analysis
PHAs	Polyhydroxyalkanoates
QD	Quarry Dust
RS	River Sand
SCMs	Supplementary Cementitious Materials
SEM	Scanning Electron Microscopy
SS	Seashells
W/B	Water-to-binder ratio

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PEMBENTUKAN BIOFILEM DIPACU BIOPOLIMER PADA KOMPOSIT SIMEN BERASASKAN SISA INDUSTRI

ABSTRAK

Perubahan iklim dan kenaikan paras laut yang semakin ketara membawa kepada penggunaan penyelesaian kejuruteraan keras seperti struktur pertahanan pantai yang diperbuat daripada konkrit. Walaupun berkesan untuk perlindungan pantai, kebergantungan tinggi terhadap konkrit menyumbang kepada pelepasan karbon yang tinggi serta kemusnahan habitat semula jadi, menyebabkan kehilangan biodiversiti dan fungsi ekologi. Pada masa yang sama, pelupusan sisa industri yang tidak terkawal telah memburukkan lagi pencemaran darat dan air, mencetuskan cabaran di persekitaran bandar. Untuk menangani isu-isu tersebut, objektif kajian ini adalah untuk mencipta konkrit mesra alam dan rendah karbon dengan menggunakan bahan buangan industri, serta meningkatkan kereaktifan bio permukaan (bioreceptivity) konkrit bagi menyokong pertumbuhan organisma hidupan air. Secara metodologi, konkrit mesra alam dihasilkan dengan menggantikan sepenuhnya agregat tradisional seperti debu kuari, kulit kerang, sanga relau letupan berbutir halus (GGBS), dan pengurangan penggunaan simen Portland. Untuk menggalakkan pertumbuhan mikrob, permukaan konkrit mesra alam tersebut disalut dengan poli(3-hidroksibutirat) [P(3HB)], sejenis polimer biodegradasi yang disintesis di makmal melalui proses pemulihan biologi. Dua kepekatan (1% dan 6% w/v) telah digunakan dan diuji dalam keadaan terkawal (*ex-situ*) serta dalam persekitaran semula jadi (*in-situ*). Hasil kajian menunjukkan bahawa konkrit mesra alam dengan gabungan 50% debu kuari dan 50% kulit kerang mencapai kekuatan setanding dengan konkrit konvensional, di samping mengurangkan jejak karbon dengan ketara. Salutan P(3HB) meningkatkan liputan biofilem sebanyak

80–100% dalam eksperimen *ex-situ*. Dalam persekitaran *in-situ*, permukaan bersalut menyokong kepelbagaian alfa mikrob yang lebih rendah tetapi pengkhususan fungsi yang lebih tinggi, termasuk takson yang mampu menguraikan P(3HB), hidrokarbon dan menyumbang kepada kitaran nitrogen. Komuniti ini memudahkan pematangan biofilem yang lebih pantas serta perekrutan pengguna sekunder dan tertier. Namun begitu, keputusan yang diperoleh tidak konsisten di semua persekitaran, menekankan pengaruh kuat faktor persekitaran. Walaubagaimanapun, pendekatan dwi ini menawarkan penyelesaian yang boleh diskalakan dan mudah disesuaikan bagi infrastruktur yang berasaskan alam semula jadi, sejajar dengan Matlamat Pembangunan Mampan (SDG) 11 (Bandar dan Komuniti Mampan), 13 (Tindakan terhadap Perubahan Iklim) dan 14 (Hidupan di Bawah Air), dalam usaha meningkatkan daya tahan pantai di rantau Asia Tenggara yang sedang pesat membangun.

BIOPOLYMER-DRIVEN BIOFILM FORMATION ON INDUSTRIAL-WASTE-BASED CEMENTITIOUS COMPOSITES

ABSTRACT

With the increasing impact of climate change and rising sea levels, the use of hard engineering solutions, such as coastal infrastructure primarily made of concrete, has expanded. While effective for coastal defence, this extensive reliance on concrete contributes to high carbon emissions and the destruction of natural habitats, leading to biodiversity loss and reduced ecological function. Simultaneously, the uncontrolled disposal of industrial waste has exacerbated land and water pollution, creating additional challenges in urban environments. To address these interconnected issues, the objectives of this research were to develop low-carbon, eco-friendly concrete using industrial waste materials and to enhance the bioreceptivity of concrete surfaces to support marine life colonization. Methodologically, eco-concrete was produced by fully replacing traditional aggregates with varying proportions of quarry dust, seashells, ground granulated blast furnace slag, and a reduction in Portland cement. To enhance microbial colonization, the surface of the optimized mix was coated with poly(3-hydroxybutyrate) [P(3HB)], a biodegradable polymer synthesized in the laboratory via biorecovery. Two concentration (1% and 6% w/v) were applied and tested under controlled *ex-situ* conditions and natural *in-situ* environments. Results showed that the optimized eco-concrete—comprising 50% quarry dust and 50% seashells—achieved comparable strength to conventional concrete while significantly lowering embodied carbon. The P(3HB) coating increased biofilm coverage by 80-100% in *ex-situ* tests. In *in-situ* settings, coated surfaces supported microbial communities with reduced alpha diversity but higher functional specialization,

including taxa capable of degrading P(3HB), hydrocarbons, and contributing to nitrogen cycling. These communities facilitated faster biofilm maturation and the recruitment of secondary and tertiary colonizers. However, the improved results did not repeatable in every environmental condition, emphasizing the strong influence of environmental factors. Nevertheless, this dual approach offers a scalable and adaptable solution for nature-inclusive infrastructure, aligning with Sustainable Development Goal targets 11 (Sustainable Cities and Communities), 13 (Climate Action), and 14 (Life Below Water) for advancing coastal resilience across rapidly urbanizing Southeast Asian regions and beyond.

CHAPTER 1

INTRODUCTION

1.1 Background on Urban Marine Ecology

Climate change, primarily attributed to human activities, constitutes the prolonged modification of Earth's climate (Gowdy, 2020). This phenomenon is characterized by the amplified presence of greenhouse gases like carbon dioxide and methane in the atmosphere (Malhi et al., 2020; Rehman et al., 2021), contributing to rising global temperatures, altered weather patterns, oceanic currents, and widespread ecosystems disruptions (Franco et al., 2020; Wang & Gu, 2021).

These environmental shifts profoundly affect coastal regions and island nations, where sea-level rise and intensified storms threaten communities with flooding, erosion, and infrastructure damage (Sinay & Carter, 2020). Altered ocean conditions disrupt marine ecosystems, shift fish stocks, and threaten livelihoods in fishing and aquaculture (Lam et al., 2020). Ocean acidification stemming from increased carbon dioxide absorption further impacts biodiversity and coral reef health, compromising natural barriers shielding against coastal erosion and wave impact (Brathwaite et al., 2021; Cornwall et al., 2021). These changes jeopardize coastal economies, food security, and community resilience.

In response, expansive coastal infrastructures—such as seawall, rock revetment and breakwaters—has been widely constructed (Nazarnia et al., 2020). However, the prevalent adoption of conventional cement-based materials contributes significantly to carbon emissions and replaces natural ecosystems with artificial 'grey' environments. These structures disrupt the natural ebb and flow of tides and sediment transport along the shoreline (Nunn et al., 2021), hindering ecosystem nourishment and biodiversity

maintenance (Sempere-Valverde et al., 2023). The repercussions of this transition alter ecological conditions by impeding the natural landward movement of rising sea levels, reducing intertidal habitat width, and ultimately diminishing biodiversity due to the trapped habitat between the sea and the structure (Aguilera et al., 2020; Siegel, 2020), disturbing feeding, breeding, and migratory patterns of marine organisms (Cáceres-Farias et al., 2022; Jackson et al., 2020).

The 'grey' infrastructure also leads to significant alterations in biotic elements by introducing new substrates for colonization that may not adequately support diverse marine life, primarily due to the distinct properties of these structures (Heery et al., 2018). The surface characteristics—like roughness, topography and chemical composition—differ notably from natural substrates, creating an ecological niche that lacks complexity found in natural coastal habitats (Grasselli & Airoidi, 2021; Sedano et al., 2020). This shift in habitat structure tends to favour certain hardy or invasive species, granting them dominance over native marine communities and causing an overall reduction in biodiversity (Bulleri & Chapman, 2010).

Beyond macro-organisms, artificial 'grey' structures influence microbial communities by creating microenvironments with altered light exposure, temperature, and nutrient availability (Marzinelli et al., 2018; Tan et al., 2015). The modifications in surface chemistry of 'grey' infrastructure affect the initial biofilms which serve as crucial foundational layers for subsequent colonization by larger organisms (Freckelton et al., 2022). Yet, the altered conditions on artificial surfaces may foster biofilms with distinct compositions and structures compared to those on natural substrates (Marzinelli et al., 2018; Tan et al., 2015). This discrepancy might disrupt the assembly of diverse microbial communities, subsequently influencing the recruitment and establishment of higher trophic-level organisms. Therefore,

understanding the nuanced role of microbial communities on artificial structures is crucial for comprehending the broader impacts of these structures on the marine biotic community as a whole.

1.2 Concrete Solutions for Global Challenges

The intersection of climate change, biodiversity loss, and urbanization presents urgent challenges for sustainable development in coastal areas. While removing artificial marine structures is impractical, developing alternatives that combine structural performance with ecological value is essential. One promising approach involves rethinking concrete formulations (Arredondo et al., 2024). By incorporating industrial by-products such as slag, it is possible to produce eco-concrete with significantly reduced embodied carbon while maintaining structural integrity (Yee et al., 2025). This upcycling of industrial waste addresses both carbon reduction and waste management.

Concrete's adaptability and scalability makes it ideal for ecological enhancement (Seddon et al., 2020). Through surface modification and the incorporation of biologically compatible additives, concrete can be conditioned to promote early colonization, encourage biodiversity, and mimic natural habitat complexity (Bone et al., 2022; Chee et al., 2021). Among these additives, biodegradable polyhydroxyalkanoates (PHAs)—particularly poly(3-hydroxybutyrate) [P(3HB)]—offer a novel direction grounded in microbial ecology. P(3HB) is a microbially synthesized polyester naturally produced under nutrient-limited conditions. Its molecular structure and biodegradability render it highly compatible with microbial metabolism, particularly for bacteria involved in biofilm formation (Tribelli & López, 2011). Since biofilms represent the foundational stage of marine colonization—where

surface-associated microbial communities regulate nutrient cycling, substrate conditioning, and subsequent ecological succession—the integration of biocompatible compounds like P(3HB) may influence early microbial attachment, succession dynamics, and community assembly (Caruso, 2020). While P(3HB) has been extensively explored in medical and packaging industries due to its stability and biodegradation behaviour in natural systems (Park et al., 2023), its potential influence on microbial ecological processes in marine infrastructure contexts remains largely underexplored.

By combining material innovation—through low-carbon, waste-based concrete—with bioactive enhancement using nature-compatible polymers, this research explores integrated, nature-based approaches to transform marine infrastructure from passive grey barriers into active ecological assets. These ecological engineering approaches not only mitigate infrastructure-induced degradation but also align with global sustainability efforts. Specifically, they advance Sustainable Development Goals (SDGs) 11 (Sustainable Cities and Communities) by promoting inclusive and sustainable urbanization; SDG 13 (Climate Action) by reducing carbon-intensive construction materials; and SDG 14 (Life Below Water) by protecting marine biodiversity and ecosystems. Together, these innovations present a comprehensive path forward in addressing the ecological challenges of coastal development in the face of climate change.

1.3 Problem Statement

In fast-developing coastal regions like Southeast Asia, grey infrastructure such as seawalls, revetments, and breakwaters has become essential for urban expansion and flood protection (Dong et al., 2024). However, the widespread use of concrete in

these structures comes at a high environmental cost. Traditional concrete production accounts for 8% of global carbon emissions and its smooth, alkaline, and biologically inert surfaces offer little support for marine life colonization (Farfan et al., 2019; Hayek et al., 2023). This leads to biodiversity loss, fragmented habitats, and weakened coastal ecosystem resilience (Hosseinzadeh et al., 2022). At the same time, industrial sectors—including iron and steel industry and seafood processing—produce large volumes of waste materials like ground granulated blast furnace slag, quarry dust, and discarded seashells, much of which is poorly managed, contributing to land and marine pollution (Fărcean et al., 2024; Yusoff et al., 2024).

Failure to address such issues will worsen marine habitat degradation, reduce the adaptive capacity of coastal cities to climate change, and derail progress toward global sustainability goals, especially in regions already facing environmental and social vulnerabilities (Bishop et al., 2017).

Although ecological engineering has been proposed to improve urban coastal ecosystems, current efforts largely focus on adding physical complexity to infrastructure (Strain et al., 2020; Vozzo et al., 2021). These strategies often overlook the importance of substrate chemistry and microbial processes that are foundational to establishing diverse, functional marine communities (Cosentino et al., 2023). In particular, the potential of integrating waste-derived eco-concrete and biodegradable surface treatments to stimulate early microbial colonization and support ecological restoration is still poorly understood.

To close this knowledge gap, interdisciplinary research is needed to explore how waste-based material compositions and bioactive surface coatings influence both the sustainability and bioreceptivity of coastal infrastructure. Such insights are critical to

designing nature-inclusive structures that not only protect urban coastlines but also regenerate ecological value in tandem.

1.4 Research Questions

In the current landscape of marine ecosystem conservation, there is a burgeoning interest in exploring innovative materials and surface treatments aimed at enhancing bioreceptivity within concrete structures, though extensive practical applications are yet to be widely implemented. This has led to an exploration of the potential of utilizing industrial-waste-based by-products along with biodegradable polyester, P(3HB), as a bioactive surface coating, which has spurred the following research question:

- (i) How does the integration of eco-friendly concrete, developed from industrial and seafood waste by-products, impact the concrete's durability, strength, and environmental sustainability in marine environments compared to traditional concrete formulations?
- (ii) How does the application of P(3HB) as a surface coating on concrete influence the growth and development of biofilms in marine environment?
- (iii) What are the correlations between variations in P(3HB) coating and the enhancement of biofilm growth on concrete surface?
- (iv) To what extent does the introduction of P(3HB) on the concrete surfaces impact the biofilm communities compared to uncoated surfaces?

By addressing these research questions, the present study is anticipated to contribute to sustainable urban coastal development, fostering a harmonious relationship between artificial infrastructure and the marine environment.

1.5 Objectives

This study aims to evaluate the mechanical performance of eco-friendly concrete while investigating the ecological enhancement achieved through biopolymer surface coatings. To achieve this, the study is guided by two key objectives:

1.5.1 Objective 1

To evaluate the influence of partial replacement of conventional aggregates and binders with selected industrial wastes and by-products on the mechanical properties, bioreceptivity, and environmental sustainability of concrete in marine conditions. This objective addressed three key facets:

(I) Assess the relationship between partial replacement levels and mechanical strength (e.g., compressive and flexural strength) to determine the optimal eco-friendly concrete formulation;

(II) Quantify the reduction in embodied carbon footprint and cost through a cradle-to-gate life cycle assessment;

(III) Examine how surface characteristics (e.g., porosity, roughness) influence the bioreceptivity of concrete in terms of initial biofilm attachment.

1.5.2 Objective 2

To investigate the application of biodegradable polyester, poly(3-hydroxybutyrate) [P(3HB)], as a bioactive surface coating to enhance biofilm formation and microbial colonization on eco-concrete in marine environments. This study utilized eco-friendly concrete developed in a preceding experiment, applying moulded P(3HB) as a bioactive compound on the concrete surface to:

(I) Determine the correlation between P(3HB) coating parameters (concentration and coating cycles) and biofilm enhancement, evaluated through biomass surface coverage quantification;

(II) Analyze the influence of P(3HB) coating on biofilm growth dynamics under both controlled and natural marine conditions;

(III) Compare the microbial community structure of biofilm developed on P(3HB)-coated concrete versus uncoated surfaces, using molecular rRNA sequencing techniques.

1.6 Hypotheses

In line with the research objectives and questions, this study aims to test the following hypotheses to examine the relationships between material composition, surface enhancement, and ecological performance of the developed concrete in marine conditions:

1.6.1 Hypothesis 1

Null hypothesis (H_{01}): Partial replacement of industrial waste materials does not significantly affect the mechanical performance of concrete.

Alternative hypothesis (H_{11}): Partial replacement of industrial waste materials significantly improves the mechanical performance of concrete.

1.6.2 Hypothesis 2

Null hypothesis (H_{02}): Partial replacement of industrial waste materials does not result in a statistically significant reduction in embodied carbon footprint or overall material cost.

Alternative hypothesis (H_{12}): Partial replacement of industrial waste materials significantly reduces the embodied carbon footprint and overall material cost of concrete production.

1.6.3 Hypothesis 3

Null hypothesis (H_{03}): Concrete with partial replacement of industrial waste materials have no significant effect on the bioreceptivity or microbial colonization potential.

Alternative hypothesis (H_{13}): Concrete with partial replacement of industrial waste materials shows significantly enhanced bioreceptivity and microbial colonization compared to standard concrete.

1.6.4 Hypothesis 4

Null hypothesis (H0₄): Variations in P(3HB) coating concentration and coating cycles have no statistically significant effect on biofilm density or coverage.

Alternative hypothesis (H1₄): Variations in P(3HB) coating concentration and coating cycles significantly influence biofilm density and coverage.

1.6.5 Hypothesis 5

Null hypothesis (H0₅): The application of poly(3-hydroxybutyrate) as surface coating does not significantly enhance microbial colonization under either controlled or nature marine conditions.

Alternative hypothesis (H1₅): The use of poly(3-hydroxybutyrate) as surface coating significantly enhances microbial colonization under both controlled and natural marine conditions.

1.6.6 Hypothesis 6

Null hypothesis (H0₆): There is no significant difference in microbial community composition between biofilms developed on P(3HB)-coated concrete and those on uncoated concrete surfaces.

Alternative hypothesis (H1₆): Biofilms developed on P(3HB)-coated concrete surfaces exhibit significantly different microbial community composition compared to those on uncoated concrete.

1.7 Rationale and Significance

The growing global emphasis on climate emergency and the United Nations sustainability goals has spurred a heightened interest in nature-based solutions for ecological rehabilitation and conservation. In response, the exploration of nature-based and hybrid coastal engineered structures utilizing nature-inspired approaches has gained traction. However, in many developing nations, including Malaysia, these interventions have been adopted without comprehensive execution or a thorough understanding of their impact.

This study aims to bridge this gap by integrated green grey infrastructure, thereby exploring the potential of multifunctional coastal engineered structures. Through the adaptation of P(3HB) as a bioactive compound to enhance these artificial structures, this research presents a novel approach. While P(3HB) has seen widespread use in various fields such as medicine and plastics manufacturing, its utilization in biofilm enhancement for ecological engineering remains unexplored.

The novelty of this study lies in its pioneering application of P(3HB) to augment the availability of food resources for marine organisms, particularly microbes, contributing to a novel aspect of ecological engineering practices. Traditionally, ecological engineering has predominantly focused on physical habitat enhancement, and this innovative approach introduces a new dimension by addressing fundamental biological elements.

Moreover, the utilization of by-products in concrete production leads to the development of environmentally friendly concrete suitable for marine environments. This innovation limits harmful leakage while demonstrating substantial underwater

performance, thereby holding significant promise for sustainable marine infrastructure.

In summary, this research transcends the constraints within prevailing ecological engineering practices by introducing pioneering applications of novel bioactive compounds and sustainable concrete solutions. Through an exploration of these factors, it endeavours to contribute to the development of more resilient urban marine ecosystems. Specifically, investigation delves into the potential of this biodegradable coating to augment bioreceptivity and foster ecological connectivity within urban coastal environments.

1.8 Thesis Outline

This thesis is organized into six chapters:

(i) Chapter 1: Introduction

Introduces the research background, outlines the problem statement, research questions, objectives, hypotheses, and significance of the study.

(ii) Chapter 2: Literature review

Provides a critical review of relevant literature on urban marine ecology, eco-concrete, ecological engineering, and polyhydroxyalkanoates (PHA). This chapter identifies key knowledge gaps and establishes the theoretical foundations for this study.

(iii) Chapter 3: Methodology

Describes the experimental design, materials, and procedures used in both quantitative and qualitative experiments. It includes details on sample preparation for eco-concrete, laboratory experiment and field deployment of P(3HB) enhanced concrete, data collection, and analysis methods.

(iv) Chapter 4: Results

Presents the mechanical performances and environmental assessment of eco-concrete formulations. Reports findings from *ex-situ* and *in-situ* studies on microbial colonization and community assembly in response to P(3HB) coating.

(v) Chapter 5: Discussions

Provides a critical analysis and interpretation of the research findings. It compares the performance of various eco-concrete formulations and evaluates the effectiveness of P(3HB) coatings in enhancing microbial colonization. The discussion integrates experimental results with existing literature to assess the environmental and ecological implications of the proposed solutions.

(vi) Chapter 6: Conclusion and recommendations

Summarizes the key findings, contributions to knowledge, research limitations, and provides suggestions for future research and practical applications in sustainable urban coastal development.

CHAPTER 2

LITERATURE REVIEW

2.1 From Hard Solutions to Nature-Based Solutions

Coastal regions are increasingly vulnerable to a myriad of threats, including rising sea levels, heightened storm surges, alterations in wind patterns, and intensified wave actions (Herrmann et al., 2020; Morim et al., 2021; Reguero et al., 2019). These factors collectively amplify the susceptibility of these regions to environmental hazards. The profound devastation wrought by hurricanes such as Katrina (2005) and Sandy (2012), as well as the 2018 Sulawesi Tsunami, vividly exemplify the destructive force inherent in coastal floods and extreme weather events (Teh & Khan, 2021).

Traditionally, the response to these challenges has been the construction of robust defence structures and infrastructure along the coastlines (Dedekorkut-Howes et al., 2020). Globally, significant portions of coastal regions have been extensively transformed through the implementation of hard engineering structures, primarily consisting of concrete. In the United States, it is estimated that approximately 14% of the coastline has been reinforced. This trend is strongly correlated with population density. Projections indicate that, if the current rates of population growth and shoreline hardening continue at an annual increase of 200 kilometres, up to one-third of the U.S. coastline could be fortified by the year 2100 (Gittman et al., 2015).

Other countries have followed similar trends. For instance, Singapore has fortified between 70% to 80% of its coastline, employing various hard wall structures, stone embankments, revetments, and other coastal defence systems to safeguard vulnerable coastal areas (Pushing Frontiers, 2024). Similarly, China has seen a significant

expansion in its artificial coastline coverage, which increased to 60% by the year 2020 (Bhullar, 2013; Li et al., 2023).

However, these structures have significant environmental consequences. The production of concrete entails high energy consumption and CO₂ emissions (Cao et al., 2021), contributing to climate change and ocean acidification. Additionally, the extraction of natural resources like sand for concrete production has led to widespread habitat destruction, ecosystem degradation, and loss of biodiversity (Rentier & Cammeraat, 2022). This is evident in coastal areas where sand mining degrades water quality by releasing sediments, altering flow patterns, and increasing turbidity. These changes negatively impact nutrient cycles, dissolved oxygen levels, and overall ecosystem health, posing direct threats to aquatic species, smothering habitats, and affecting the reproductive success of sensitive organisms (Damseth et al., 2024).

Beyond environmental impacts, these concrete structures alter coastal landscapes, disrupt natural coastal processes, and fragment habitats. For example, seawalls and other hard engineering structures disrupt tidal movements, obstructing the natural ebb and flow, interfering with nutrient cycles, and impeding the migration pathways of marine species (Bishop et al., 2017; Matsushima & Ferreira, 2022). This impediment to the movement of species, such as fishes and small crustaceans, exacerbates biodiversity loss and undermines ecosystem resilience. Additionally, the smooth, featureless surfaces of concrete structures fail to provide suitable habitats for native marine flora and fauna (Sella et al., 2022). Instead, they inadvertently facilitate the colonization of non-native, invasive species that thrive in harsh conditions, such as high wave energy and limited resources (Schaefer et al., 2024). These conditions deter the establishment of native species, leading to a loss of biodiversity and disrupting the ecological balance and functioning of coastal ecosystems.

The environmental consequences of traditional hard engineering structures have prompted the search for more sustainable solutions to mitigate coastal threats while minimizing ecological harm. In response, nature-based solutions (NbS) have emerged as an effective strategy to enhance the resilience and functionality of urban marine environments (O’Leary et al., 2023). Consequently, there has been a gradual shift from hard engineering defences on sandy shorelines to soft solutions and hybrid designs, such as mangrove afforestation, vegetated buffers, and the use of toe nourishment to protect seawalls against local scour (Gijón Mancheño et al., 2021; Slee et al., 2023). These approaches offer added benefits such as improved hazard risk reduction, ecological restoration, aesthetics enhancement, and long-term adaptability (Anderson et al., 2022).

Over the past decades, our understanding of coastal management has evolved significantly, leading to a reassessment of the conventional reliance on hard defences (Toimil et al., 2020). This shift demonstrates a heightened appreciation for more flexible and ecologically integrated shoreline strategies that recognize the value of biodiversity, habitat connectivity, and scenic qualities alongside protection.

In Malaysia, coastal environments are increasingly subjected to mounting pressures from both natural hazards and anthropogenic activities. With an extensive coastlines stretching over 8,840 kilometers, the country faces heightened vulnerability to sea-level rise, coastal erosion, flooding, and extreme weather events, particularly along low-lying areas such as the west coast of Peninsular Malaysia and parts of Sabah and Sarawak (Hamzah & Mahamud, 2023). Rapid urban expansion, intensive aquaculture, unregulated sand mining, and land reclamation have further destabilized coastal systems, leading to habitat fragmentation, mangrove loss, and reduced shoreline resilience (Sahabat Alam Malaysia, 2019). For instance, the Kuala Muda district and the west coast of Langkawi in Kedah, which are classified as having a very high physical

vulnerability index, are increasingly susceptible to tsunami, coastal erosion, and periodic flooding (Al-Qadami et al., 2024). Similarly, in Batu Pahat, Johor, chronic erosion has resulted in managed retreat from affected coastal zones, including the abandonment of adjacent coconut plantations (Mohamed Rashidi et al., 2021). In Sabak Bernam, Selangor, the degradation of mangrove belts in Sungai Haji Dorani due to land reclamation and agriculture encroachment has further weakened natural coastal buffers, increasing exposure of infrastructure to wave action and saltwater intrusion (Stanley & Lewis III, 2009).

Despite these risks, Malaysia's coastal protection strategies have long been dominated by grey infrastructure solution—such as seawalls, revetments, and groynes—primarily focused on erosion control and flood prevention (Dong et al., 2024). While effective in the short term, these hard structures often result in adverse ecological outcomes, including downstream erosion, disrupted sediment transport, and habitat loss in intertidal zone (Bishop et al., 2017). Moreover, hard infrastructure generally lacks the flexibility to adapt to long-term climate variability and typically fails to integrate ecological and biodiversity considerations (Nunn et al., 2021). The adoption of ecological engineering or nature-based solutions remains limited in Malaysia, constrained by fragmented governance structures, insufficient inter-agency coordination, and a lack of localized ecological data and long-term monitoring frameworks (Chee et al., 2021).

These challenges highlight a critical need to reassess conventional approaches and explore more sustainable, adaptive, and ecosystem-based strategies for coastal protection. Embracing NbS offers a pathway to address the dual objectives of climate resilience and ecological integrity. This shift aligns closely with Malaysia's national adaptation priorities and supports the broader objectives of global sustainability

frameworks, particularly the United Nations Sustainable Development Goals, including SDG 13 (Climate Action) and SDG 14 (Life Below Water).

2.2 Definitions and Scope of Nature-based Solutions

The International Union for Conservation of Nature (IUCN) defines Nature-based Solutions (NbS) as strategies focused on the protection, sustainable management, and restoration of natural or modified ecosystems to effectively and adaptively address societal challenges. These societal challenges include a broad range of issues such as climate change mitigation and adaptation, disaster risk reduction, economic and social development, human health, food security, water security, and combatting environmental degradation and biodiversity loss (IUCN, 2020a). The IUCN emphasizes the NbS should promote human well-being and biodiversity enhancement simultaneously. Importantly, they advocate for the application of NbS principles and criteria on a landscape level, involving evidence-based assessments of ecosystem conditions before implementation, periodic evaluations of outcomes concerning biodiversity and human well-being, and the consideration of trade-offs and risks beyond the intervention site (Cohen-Shacham et al., 2019). Specifically, five main NbS typology categories into (a) ecosystem restoration approaches, (b) issue-specific ecosystem-related approaches, (c) infrastructure-related approaches, (d) ecosystem-based management approaches, and (e) ecosystem protection approaches.

By providing specific examples and strategies for each category, the IUCN framework is recognized as the best available operational framework that facilitates the practical application and implementation of NbS (IUCN, 2020b). However, over the past decades, NbS implementation has predominantly focused on terrestrial environments, with their application in marine urban built ecosystems—such as coastal

cities, ports, and waterfronts—being underrepresented. Case studies in these areas account for less than 20% of NbS initiatives worldwide (Chausson et al., 2020; Debele et al., 2023). These areas are particularly vulnerable to climate change impacts, such as sea-level rise and increased storm intensity, making the integration of NbS critical for enhancing resilience and sustainability.

2.3 Nature-based Solutions in Marine Urban Built Ecosystems

NbS presents a valuable shift from the traditional "building in nature" approach to a more harmonious "building with nature" paradigm (Van Der Meulen et al., 2023). Traditionally, "building in nature" often involved imposing human structures on natural landscapes, which could disrupt ecosystems. In contrast, "building with nature" integrates natural processes and features into human developments. While greening and sustainability concepts have existed for some time, NbS now link these ideas with a focus on ecosystem services and broader environmental, social, and economic benefits (Wójcik-Madej & Sowińska-Świerkosz, 2022).

In marine and coastal areas, NbS interventions typically emphasize natural ecosystems, embracing ecosystem-based adaptation over engineering-based approaches. Examples include mangrove restoration, coastal dune management, and beach nourishment (Giffin et al., 2021; Vasseur, 2021). Extensive mangrove restoration projects are prominent worldwide, especially in developing regions like Africa and Southeast Asia (Beeston et al., 2023; Gerona-Daga & Salmo, 2022; Huxham et al., 2023). Notable examples include the replanting of 45,000 hectares of mangroves in Casamance and Sine Saloum estuaries of Senegal in 2011 (Livelihoods Funds, 2020), and Indonesia's National Mangrove Rehabilitation Program aiming to rehabilitate 600,000 hectares by 2024 (Sasmito et al., 2023).

The Sand Motor project in the Netherlands, initiated in 2011, added 21 million m³ of sediment to the Delfland Coast. This mega nourishment project has slowed coastal erosion and facilitated the deposition of sediment in adjacent coastlines, leading to the establishment of pioneer plants and animals on newly formed dunes (Luijendijk & Oudenhoven, 2019; Tonnon et al., 2018).

NbS take this further by promoting living shorelines to replace traditional engineering approaches. These living shorelines use natural elements like saltmarshes, oyster shell, and rock to stabilize coasts, provide habitats, and improve water quality (Smith et al., 2020), reflecting a shift in coastal protection that also focuses on restoring ecosystem services (Palmer et al., 2014).

Further emphasis on semi-natural ecosystem adaptation in marine urban environments includes multifunctional land use, such as floating islands and constructed wetlands. These features enhance urban aesthetics and cool areas while supporting biodiversity and managing stormwater (Calheiros et al., 2020; Tsatsou et al., 2023). Floating islands (also known as floating wetlands or floating gardens, though not to be confused with floating vegetable gardens in Bangladesh used for cultivate crops on flooded agricultural land) are platforms that support emergent vegetation for purposes such as water treatment and landscape enhancement, effectively mimicking natural wetland ecosystems (Qin et al., 2023). This approach is gaining popularity in highly urbanized areas like Portugal and developing regions such as Vietnam (Calheiros et al., 2020; Vo et al., 2023). In South Korea, 54 constructed wetlands have been installed since 2011 to treat stormwater runoff and pollutants (Choi et al., 2021).

In marine urban built environments, where engineering considerations are critical due to hydrodynamic impact and space constraints, environmental restoration may not

be an immediate concern. Consequently, there is a shift towards infrastructure-related NbS. This approach emphasizes integrating natural elements with engineered solutions to effectively address urban challenges. Such hybrid NbS, have garnered significant attention and are increasingly becoming the focus of research and implementation efforts in marine urban built ecosystems (Evans et al., 2019; Ruckelshaus et al., 2016).

2.4 Ecological Engineering of Marine Infrastructures

There is growing recognition of the crucial role of green infrastructure in mitigating the impacts of climate change, particularly in addressing issues like coastal erosion and flooding (Kuwae & Crooks, 2021; Rodrigues et al., 2023). This recognition has spurred increased investment and policy support for nature-based solutions. In addition, the demonstrated effectiveness and cost-efficiency of green infrastructure projects in providing immediate and multiple environmental, economic, and social benefits, such as flood protection, water filtration, and carbon sequestration, have contributed to their popularity (Kabisch et al., 2016; Ruskule et al., 2023). Furthermore, the integration of green infrastructure into urban planning and development processes has become more mainstream, driven by initiatives promoting sustainable and resilient cities (Zuniga-Teran et al., 2020).

These approaches entail the integration of natural elements into built infrastructure projects to bolster their resilience and sustainability. They encompass a variety of nature-based coastal defences focus on providing effective coastal protection against erosion, flooding, and inundation while simultaneously conserving, restoring, or creating habitats. These habitats not only strengthen the protective functions but also offer regulating and supporting ecosystem services (Kindeberg et al., 2023). Such approaches are also known by various names, including "ecological engineering" (eco-

engineering), "engineering with nature", "living seawall", "living shorelines", "blue-green infrastructure", or "integrated green-grey infrastructure" (Firth, 2023; Gittman et al., 2016; Naylor et al., 2017, 2023; O'Shaughnessy et al., 2020; Suedel et al., 2022).

Soft engineering approaches resemble living shorelines and involve removing artificial structures to allow natural processes, such as tidal flow and species recruitment, to resume (Bilkovic et al., 2017). Coastal vegetated ecosystems, like coral reefs, kelp forests, seagrass beds, mangroves, and oyster reefs, act as natural infrastructures against wave action, stabilize sediments, and support ecological and socio-economic benefits (Burke & Spalding, 2022).

Eco-engineering stands apart from soft approach by maintaining artificial infrastructure as a central element of the landscape. These structures, whether newly built or retrofitted, are designed to enhance ecological functions in addition to serving as coastal defences (Chapman & Underwood, 2011). This approach is particularly relevant in urban settings where the structural integrity of coastal defences like seawalls and breakwaters is crucial (Sawyer et al., 2020). Enhancements such as adding substrate complexity—using artificial rock pools or ecologically-designed concrete panels—can create new habitats for foliose algae and sessile invertebrates, thereby supporting biodiversity and improving interaction of these coastal defence structures with the environment (Evans et al., 2019; Ushiamo et al., 2019).

In marine environments, enhancing marine urban infrastructures has primarily focused on increasing habitat complexity to support biodiversity and restore ecological functions. This is often achieved through habitat enhancement, a conservation and ecological engineering approach that modifies hard substrates—such as seawalls, breakwaters, and pilings—to improve their ecological value (Bishop et al., 2022; Strain

et al., 2018). The goal is to mimic natural habitat features, increase surface area, and create microhabitats that provide shelter, feeding grounds, and breeding spaces for marine organisms, thereby increasing species diversity and ecosystem resilience (Firth et al., 2014). These enhancements range from micro-scale alterations to large-scale structural modifications, using both additive and subtractive methods.

Additive approaches involve attaching structures such as textured tiles, habitat complexity panels, or water-retaining features. Examples include “BioGeo Ecotile” and “Eco-engineered Tiles”, which incorporate holes, grooves, crevices, and rough surfaces (Kosová et al., 2023), and the “Living Seawalls Panels” that feature designs mimicking tidal pools, ridges, and weathered rock patterns (Bishop et al., 2022; Bradford et al., 2020). Additionally, “Flowerpot” and “Vertipool” are protruding containers that retain water during low tide, to support marine biodiversity (A. E. Hall et al., 2019; Morris et al., 2017). These can also include seeding with habitat-forming taxa like bivalves or corals (Kikuzawa et al., 2021; Vozzo et al., 2021). Subtractive methods create depressions by removing substrate from structures, such as “Drill-cored Rock Pools” to create artificial tidal pools on otherwise dry rock revetments (Evans et al., 2016). These strategies, whether additive or subtractive, offer diverse avenues for enhancing ecological biodiversity and functionality of urban coastal infrastructure.

In Malaysia, coastal management has long been dominated by hard engineering solutions—such as seawalls, revetments, and groynes—primarily aimed at controlling erosion and adapting to sea-level rise (Mohamed Rashidi et al., 2021). While effective in short term, these structures often result in downstream erosion, ecological disruption, and lack adaptability to future climate scenarios. In recent years, there has been a gradual shift towards hybrid approaches that combine grey infrastructure with elements of natural systems (Table 2.1). While hybrid engineering is generally considered part of

the broader NbS framework, its application in Malaysia has limited in scope of facilitating mangrove rehabilitation and shoreline stabilization, rather than embodying the full ecological integration and multifunctionality characteristics of true NbS approaches (Samsuddin Sah et al., 2025).

To date, most coastal initiatives in Malaysia have focused on ecosystem protection and conservation rather than ecosystem integration (Chee et al., 2021). These include the designation of Marine Protected Areas (MPAs), RAMSAR wetlands, and national parks aimed at preserving biodiversity and critical habitats. While these efforts are essential, they do not address the ecological void created by heavily urbanized and engineered shorelines, particularly in cities and ports where natural habitats have been extensively replaced by concrete infrastructure.

The application of ecological engineering principles in marine infrastructure remains relatively nascent and is underexplored within the Malaysian context. Only in recent years have local initiatives begun to incorporate ecological elements into engineered coastal systems (Table 2.1). Notable examples include the installation of drill-cored rock pools on rock revetment that mimic natural tidal pools during low tide (Chee et al., 2020), the use of octa-hexagonal concrete pots as artificial habitats on breakwaters to create intertidal refuges, and textured surface panels installed on seawalls to increase habitat complexity (Chee et al., 2021). These pilot efforts, adapted from temperate regions, signal a growing awareness of ecological enhancement, yet remain isolated and exploratory.

Unlike traditional conservation or hybrid engineering, ecological engineering aims to embed ecological functions directly into the design and materiality of built infrastructure (O'Shaughnessy et al., 2020). Rather than merely protecting existing