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IMPLEMENTATION FRAMEWORK FOR ECO-ENGINEERING, NATURE-BASED SOLUTIONS AND ADAPTIVE APPROACHES IN COASTAL DEVELOPMENT: A SYSTEMATIC REVIEW

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ABSTRACT

The rapid expansion of coastal infrastructure due to urbanisation and climate change has intensified the degradation of marine ecosystems, a phenomenon known as "ocean sprawl". While eco-engineering and Nature-based Solutions (NbS) have emerged as promising strategies to reconcile development with ecological sustainability, their integration into coastal development remains limited and fragmented. This study conducts a systematic review of 24 peer-reviewed articles published between 2014 and 2023 to identify and synthesise implementation frameworks related to eco-engineering, NbS, and adaptive approaches in coastal settings. Using the PRISMA methodology, the review identifies five core implementation stages: Inception, planning, design, implementation, and monitoring and evaluation, comprising 41 specific processes. The findings reveal a significant gap in the early-stage integration of ecological principles, particularly within the inception and planning phases, where critical decisions are made. The study proposes a comprehensive, process-based framework to guide the systematic incorporation of eco-engineering throughout the project lifecycle. This framework provides actionable guidance for practitioners and policymakers seeking to embed sustainability and biodiversity considerations into coastal infrastructure projects. By addressing key implementation barriers, the study contributes to advancing ecologically sensitive development and supports the achievement of Sustainable Development Goal 14: Life Below Water.

Introduction

Climate change and rapid urbanisation are accelerating the 'artificialisation' of the world's coastlines, fundamentally reshaping marine and coastal ecosystems (Firth *et al*., 2020). Coastal zones are of immense ecological and socio-economic significance, providing a wide array of valuable ecosystem services such as coastal protection, fisheries, carbon sequestration, and recreational opportunities (Lu *et al*., 2018). However, the expansion of coastal development and the pressures brought about by increasing human populations are leading to substantial transformations in coastal landscapes and habitats (Loke *et al*., 2018). Approximately 50% of the global population lives within 100 km of the coastline, making these areas the most populous and dynamic regions globally (Wu *et al*., 2018).

One of the most visible outcomes of urban coastal expansion is the proliferation of artificial structures, often referred to as 'ocean sprawl' (Firth *et al*., 2016a; Bishop *et al*., 2017; Evans *et al*., 2019). This phenomenon is now recognised as one of the most pressing threats to marine biodiversity and ecological integrity

(Dafforn *et al*., 2015; Firth *et al*., 2016b). In parallel, climate change is intensifying coastal hazards such as sea level rise, storm surges, and flooding, further challenging the resilience of coastal communities and ecosystems (Griggs & Reguero, 2021). Traditionally, societies have relied on hard coastal infrastructure, also referred to as grey infrastructure, to defend against these threats, using structures like seawalls, breakwaters, and revetments to reduce erosion and protect assets (Mamo *et al*., 2022).

While effective in offering short-term protection, these hard-engineered solutions can have long-lasting negative consequences for coastal and marine environments. Such infrastructure often leads to habitat degradation, disrupts natural shoreline dynamics, and undermines the ecosystem services that human communities depend on (Waryszak *et al*., 2021). As a result, there is growing recognition of the need for sustainable and multifunctional coastal protection strategies that can simultaneously support human development and safeguard coastal biodiversity.

The widespread construction of artificial structures in the coastal and marine realm calls for the urgent integration of ecologically sensitive designs into hard infrastructure (Evans *et al*., 2019). Without careful consideration, the hardening of coastlines can disrupt ecological processes, with cascading impacts on the well-being and livelihoods of coastal populations (Eddy *et al*., 2021; Porri *et al*., 2022). Urban coastal development has often overlooked the potential of built structures to function as habitats, leading to biodiversity loss through habitat homogenisation (Mayer-Pinto *et al*., 2017; Bishop *et al*., 2022). These featureless, uniform surfaces tend to favour non-native and opportunistic species over native ones, further altering ecological balances (Firth *et al*., 2016a). In this context, eco-engineering has emerged as a promising field that reconciles infrastructure development with ecological functionality.

Eco-engineering involves modifying artificial structures to support ecological goals by incorporating design features that enhance habitat complexity and ecological resilience. Research has demonstrated that even small-scale interventions such as adding microhabitats or textured surfaces, can significantly improve biodiversity outcomes on built structures (Firth *et al*., 2016b). Given the projected increase in the use of artificial infrastructure for coastal defence (Nawarat *et al*., 2024), integrating eco-engineering principles from the outset or retrofitting them into existing coastal infrastructure can help restore the coastal environment while maintaining protective functions.

Although grey infrastructure continues to be the primary approach to coastal protection worldwide, its negative impacts have prompted a shift towards more eco-friendly solutions. Eco-engineering is increasingly applied as part of broader nature-based solutions (NbS), aiming to balance development and conservation (Strain *et al*., 2019). As a restorative component under the NbS umbrella, eco-engineering merges ecological science with engineering practices to reduce the environmental footprint of infrastructure (Dafforn *et al*., 2015; Chee *et al*., 2017; Cohen-Shacham *et al*., 2016; 2019). While eco-engineering falls under the broader umbrella of NbS, the two are not entirely interchangeable. This is because NbS are sometimes referred to as fully green solutions when they are implemented in a way that is entirely nature-based such as the restoration of mangroves or wetlands, whereas eco-engineering serves as an alternative in situations where fully green solutions are not feasible. Therefore, the integration of eco-engineering is vital to achieving long-term sustainability and resilience, especially in highly urbanised or wave-exposed coastlines.

In recent years, eco-engineering has gained traction through numerous trials and demonstration projects across Europe, the United States, Australia, China, and South Africa (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; Gauff *et al*., 2023; Kosová *et al*., 2023;

Hofstede & Koningsveld, 2024; Schaefer *et al*., 2024; Herbert *et al*., 2025; Seath *et al*., 2025), as well as in Singapore and Malaysia, highlighting the potential for these approaches in tropical climate contexts (Chee *et al*., 2020; Chee *et al*., 2021; Hartanto *et al*., 2022; Teong *et al*., 2024). These "proof-of-concept" studies have laid the groundwork for integrating eco-engineering into a variety of coastal infrastructure types, offering insights into the practical design and implementation of sustainable interventions (Firth *et al*., 2016a; Naylor *et al*., 2017; O'Shaughnessy *et al*., 2020).

Nevertheless, significant gaps and barriers hinder the widespread adoption of eco-engineering in practice. A key issue is the limited application of ecological principles during the initial stages of infrastructure planning and design, particularly by civil engineers who are unfamiliar with ecological concepts (Pioch *et al*., 2018). The potential to extend ecological principles to new coastal developments at the planning and design stages remains in its infancy (Dafforn *et al*., 2015). Eco-engineering is mainly being considered after the design of coastal infrastructure (Pioch *et al*., 2018). Thus, a comprehensive eco-engineering framework for sustainable coastal development is crucial. Such a framework could serve as a guide for planners, engineers, and policymakers, enabling them to consider ecological principles from the earliest stages of project design. Moreover, it would provide practical processes for incorporating biodiversity considerations into the engineering of artificial coastlines, thereby restoring the coastal environment.

However, there is a lack of eco-engineering integration throughout the project lifecycle. While various frameworks for sustainable coastal development have been proposed, systematic reviews of these frameworks remain scarce. This study applies a systematic review methodology to address this gap. By using explicit and structured methods to identify, select, appraise, and synthesise relevant literature (Saffril *et al*., 2018), this review examines past implementation frameworks related to eco-engineering, NbS, and adaptive management. The inclusion of NbS and adaptive approaches is justified by their close alignment with eco-engineering principles, particularly in promoting multifunctional solutions that prioritise ecosystem services as a foundation for addressing both societal and ecological challenges (Chávez *et al*., 2021). Additionally, both approaches provide valuable insights into the planning, design, implementation, and monitoring and evaluation stages, where information is often limited or lacking in the eco-engineering literature.

By analysing the processes and components of these existing frameworks, this paper aims to identify critical processes across five main phases as a foundation for a forward-looking eco-engineering framework to support countries where traditional artificial infrastructure remains dominant and eco-engineering practices face implementation challenges. These multifunctional infrastructures seek to balance immediate protection needs with preserving natural ecosystems for future generations. This approach aligns with the United Nations Sustainable Development Goal (UN SDG) 14: Life below water, which promotes the conservation and sustainable use of ocean and marine resources (Firth *et al*., 2024).

Methodology

This section explains how the PRISMA method was used to retrieve articles related to the implementation framework for sustainable coastal development. The section is further divided into five sub-sections: PRISMA, resources (Scopus and ScienceDirect), inclusion and exclusion criteria, the systematic review process, and data analysis.

PRISMA

The main principles of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) Statement review method were applied in this review. According to Shaffril *et al*. (2018) and Sierra-Correa & Cantera Kintz

(2015), the PRISMA method highlights several ways of conducting a systematic review. These comprise (1) Defining clear research questions and conducting a systematic search; (2) Explicitly identifying inclusion and exclusion criteria; (3) Assessing the substantial amount of relevant and available scientific literature within a defined timeframe; and (4) Using statistics to enhance rigor, all of which were appropriate and useful for this study.

The method also facilitates a rigorous search for terms related to the implementation frameworks for sustainable coastal development and codes information for future reviews. Furthermore, the methodology can be applied to monitor improvements in the implementation of sustainable coastal development. All of these factors contributed to the decision to apply the PRISMA Statement in this study.

Resources

The systematic review focused on two types of resources, namely Scopus and ScienceDirect. Scopus is a database that provides a comprehensive overview of global interdisciplinary scientific information, allowing searches across many disciplines and sources. ScienceDirect is the second resource used in this review; it is the leading platform for research material, offering access to a vast database of publications. This platform covers a significant portion of the world's full-text scientific, technical, and medical literature (Mohapatra & Wexler, 2009).

Inclusion and Exclusion Criteria

In this study, several inclusion and exclusion criteria were determined and applied during the review. Firstly, the collation and assessment were limited to review and research articles. Secondly, the review was restricted to articles published in English. Thirdly, in recent years, numerous guidelines have integrated natural processes into the design and implementation of solutions to address coastal problems (Chávez *et al*., 2021). Therefore, for this study, a period of ten years (from 2014 to 2023) was selected as the timeframe for capturing the current and updated implementation frameworks of sustainable coastal development. Fourthly, as the systematic review focused on the common phases of the implementation framework for eco-engineering, NbS and adaptive approaches, the subject areas of environmental science, social sciences, earth and planetary sciences, agricultural and biological sciences, and engineering were selected for this study. Lastly, the objective of this review was to concentrate on the implementation frameworks for sustainable coastal development; therefore, only articles with relevant frameworks or models were selected. Table 1 displays the inclusion and exclusion criteria used in this systematic review.

Table 1: The inclusion and exclusion criteria for journals included in this study

Criterion	Inclusion	Exclusion
Article type	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
Framework and model	Articles with a framework or model available	Articles without a framework or model available

Systematic Review Process

The systematic review process primarily involved three stages. In the first stage, keywords were identified to search for relevant articles. Keywords related to the implementation framework, sustainable coastal development, eco-engineering, nature-based solutions, and climate change adaptation were used. Table 2 presents the search string applied during the systematic review process. Following this, careful screening was conducted to determine which articles were eligible for review and which were to be removed.

The second stage involved a comprehensive assessment of articles for eligibility. Following a meticulous examination, 2,187 articles were excluded as they did not concentrate on sustainable coastal development, the implementation of eco-engineering, nature-based solutions (NbS), or adaptive solutions, and did not provide a framework or model for the available implementation practices.

The final stage of the process resulted in the inclusion of a total of 24 articles in the qualitative analysis, as they met the criteria established for the systematic review process. Figure 1 illustrates the flow diagram of this process.

Data Analysis

After completing the systematic review process, the remaining articles that met the inclusion criteria underwent an assessment and analysis procedure. The analysis focused on the specific studies that addressed the formulated questions. Firstly, data was extracted by reading through the articles' abstracts and then the content to identify the implementation framework, or model, for sustainable coastal development mentioned in the articles. Next, qualitative analysis was conducted using content analysis to identify the main stages of the implementation frameworks. These main stages further detail the processes needed to achieve sustainable coastal development. The results of the analysis were then incorporated into future frameworks to better integrate eco-engineering principles into coastal infrastructure projects in Malaysia.

Results

As ocean sprawl burgeons and climate change worsens, threatening marine and coastal ecosystems globally, sustainable coastal development must be implemented to minimise potential threats and seize opportunities. Thus, this review provides a holistic analysis of the current eco-engineering, NbS, and adaptive solution frameworks for implementing sustainable coastal development.

A rigorous review of the two resources identified 24 articles related to the implementation frameworks for sustainable coastal development. The review resulted in a total of 10 journals based on the eco-engineering framework (Poff *et al*., 2015; Mayer-Pinto *et al*., 2017; Vojinovic *et al*., 2017; Whelchel *et al*., 2018; Evans *et al*., 2019; 2021; Ostrow *et al*., 2022; Suedel *et al*., 2022; Temmink *et al*., 2023; Viehman *et al*., 2023; eight journals based

Table 2: The search string used for the systematic review process

Resources	Keywords Used
Scopus	"climate" AND "change" AND "adapt*" OR "mitigate*" AND "sustain*" AND "coastal" AND "develop*" OR "manage*" AND "eco-engineering" OR "ecological" AND "engineering" OR "green-grey" AND "infrastructure" OR "IGGI" OR "nature-based" AND "solution" OR "NbS" AND "ecological" AND "integrate*" OR "restore*" AND "implement*" OR "decision-making" AND "framework" OR "model"
Science Direct	"integration" AND "ecological engineering" AND "framework" AND "coastal sustainable development" AND "green-grey infrastructure" AND "nature-based solution" AND "green infrastructure" AND "climate change adaptation"

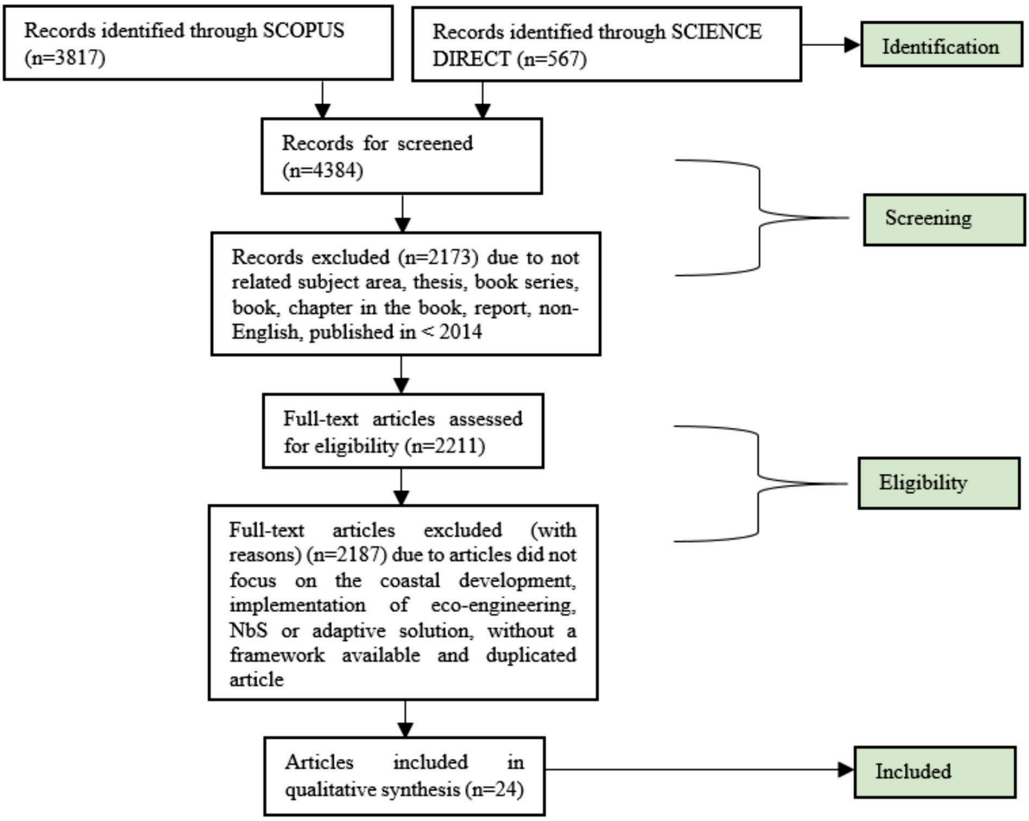

Figure 1: The flow diagram of the review process (Adapted from Shaffril *et al*., 2018)

on the NbS framework (Calliari *et al*., 2019; Kumar *et al*., 2020, 2021; Albert *et al*., 2021; Dunlop *et al*., 2023; Gonzalez-Ollauri *et al*., 2023; Hinkelman *et al*., 2023; Perricone *et al*., 2023), and another six journals based on the adaptive solution framework (Wise *et al*., 2014; Gray *et al*., 2014; Brown *et al*., 2015; Nazarnia *et al*., 2020; Chávez *et al*., 2021; Mamo *et al*., 2022). Table 3 presents the findings from the systematic review.

Regarding the timeline criteria, six articles were published in 2023, while four and three articles were published in 2021 and 2022, respectively. Two articles were published each year in 2020, 2019, 2017, 2015, and 2014, while only one article was published in 2018. Figure 2 illustrates the timeline criteria of the included journals.

Implementation Frameworks for Sustainable Coastal Development

Table 4 shows the findings of the main stages and processes from previous implementation frameworks of eco-engineering, NbS, and adaptive solutions. Most of the reviewed articles highlighted and discussed the main stages and processes in the implementation frameworks for sustainable coastal development. However, one article, in particular, identified the necessary steps for effective implementation through engineering intervention, using an evidence-based catalogue (Evans *et al*., 2019). The study focused on strengthening the evidence base by testing existing enhancement designs and exploring new enhancements through cost-benefit evaluation, to develop an evidence-based catalogue of ‘‘products’’ that encouraged the implementation of eco-engineering.

Table 3: The findings from the systematic review

Focus Stages	Total No of Studies	References	No of Studies	Type of Framework	Aim of The Framework
Inception to Monitoring and Evaluation Stages	15	(Mayer-Pinto *et al*., 2017; Ostrow *et al*., 2022; Suedel *et al*., 2022; Viehman *et al*., 2023; Whelchel *et al*., 2018)	5	Eco-engineering framework	Focused on step-by-step guidelines for implementation.
		(Albert *et al*., 2021; Calliari *et al*., 2019; Dunlop *et al*., 2023; Kumar *et al*., 2020, 2021)	5	NbS framework	
		(Brown *et al*., 2015; Chávez *et al*., 2021; Mamo *et al*., 2022; Nazarnia *et al*., 2020; Wise *et al*., 2014)	5	Adaptive solution framework	
Inception to Planning Stages	6	(Poff *et al*., 2015; Temmink *et al*., 2023; Vojinovic *et al*., 2017)	3	Eco-engineering framework	Focused on identifying problems and selecting approaches
		(Gonzalez-Ollauri *et al*., 2023; Hinkelman *et al*., 2023; Perricone *et al*., 2023)	3	NbS framework	
Inception Stage	1	(Gray *et al*., 2014)	1	Adaptive solution framework	Focus on identifying problems
Planning Stage	1	(Evans *et al*., 2019)	1	Eco-engineering framework	Focused on generating an evidence-based catalogue.
Design Stage	1	(Evans *et al*., 2021)	1	Eco-engineering framework	Focused on designing eco-engineering habitats.

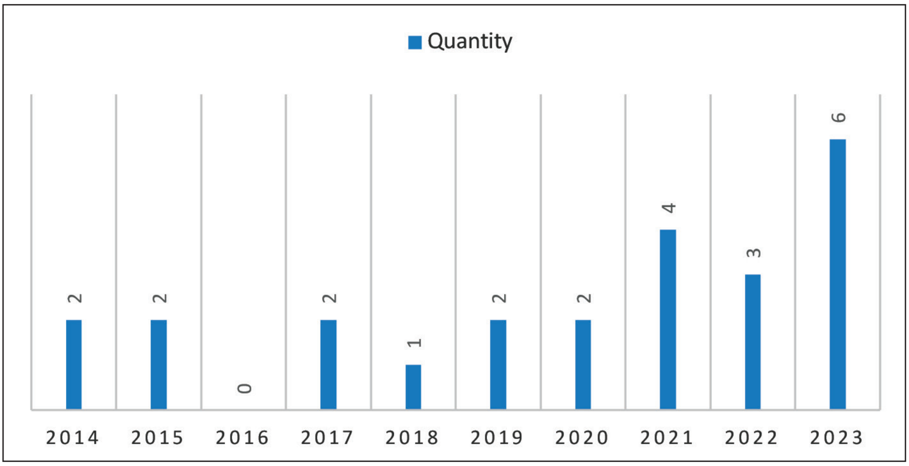

Figure 2: Timeline criteria of the included journals

Table 4: The findings of the main stages and processes from previous implementation frameworks of eco-engineering, NbS, and adaptive solutions

Stages	Processes	References
Inception	1. Problem identification	(Chávez *et al*., 2021; Dunlop *et al*., 2023; Gonzalez-Ollauri *et al*., 2023; Gray *et al*., 2014; Kumar *et al*., 2020, 2021; Mamo *et al*., 2022; Perricone *et al*., 2023; Suedel *et al*., 2022; Temmink *et al*., 2023; Whelchel *et al*., 2018)
	2. Appraisal of experts and authorities	(Gonzalez-Ollauri *et al*., 2023)
	3. Site investigation	(Gonzalez-Ollauri *et al*., 2023)
	4. Risk/hazard assessment	(Gonzalez-Ollauri *et al*., 2023; Kumar *et al*., 2020; Whelchel *et al*., 2018; Wise *et al*., 2014)
	5. Establish an action group	(Gonzalez-Ollauri *et al*., 2023; Gray *et al*., 2014; Kumar *et al*., 2020, 2021; Suedel *et al*., 2022)
	6. Define the baseline and set objectives	(Calliari *et al*., 2019; Dunlop *et al*., 2023; Evans *et al*., 2021; Kumar *et al*., 2020, 2021; Mayer-Pinto *et al*., 2017; Ostrow *et al*., 2022; Suedel *et al*., 2022)
	7. Define the scope, institutional and legal contexts	(Dunlop *et al*., 2023)
	8. Establish funding strategies	(Dunlop *et al*., 2023)
	9. Enabling and constraining external factors	(Calliari *et al*.,2019)
	10. Co-define setting	(Albert *et al*., 2021)
	11. Define challenges/issues	(Albert *et al*., 2021; Brown *et al*., 2015; Hinkelman *et al*., 2023)
	12. Gather/use information	(Gray *et al*., 2014)
	13. Ecosystem services identification and valuation	(Brown *et al*., 2015; Vojinovic *et al*., 2017)
	14. Define goals and success criteria	(Hinkelman *et al*., 2023; Poff *et al*., 2015; Viehman *et al*., 2023i; Wise *et al*., 2014)
Planning	1. Stakeholders mapping	(Gonzalez-Ollauri *et al*., 2023; Kumar *et al*., 2020)
	2. Co-creation strategy	(Gonzalez-Ollauri *et al*., 2023)
	3. Shortlist for solutions	(Gonzalez-Ollauri *et al*., 2023)
	4. Identify/develop, assess/ analyse, evaluate and select the alternative measures	(Brown *et al*., 2015; Calliari *et al*., 2019; Dunlop *et al*., 2023; Hinkelman *et al*., 2023; Kumar *et al*., 2020, 2021; Mamo *et al*., 2022; Nazarnia *et al*., 2020; Ostrow *et al*., 2022; Poff *et al*., 2015; Perricone *et al*., 2023; Suedel *et al*., 2022; Temmink *et al*., 2023; Vojinovic *et al*., 2017; Viehman *et al*., 2023; Whelchel *et al*., 2018; Wise *et al*., 2014)

	5. Test climate-proof alternatives	(Calliari *et al*., 2019; Kumar *et al*., 2020)
	6. Map the effects of alternatives	(Calliari *et al*., 2019)
	7. Identify opportunities for coordination	(Nazarnia *et al*., 2020)
	8. Information acquisition	(Mayer-Pinto *et al*., 2017)
	9. Investigate the suitability of the intervention	(Mayer-Pinto *et al*., 2017)
	10. Identify and procure funding	(Suedel *et al*., 2022; Kumar *et al*., 2020)
	11. Develop initial cost estimation	(Suedel *et al*., 2022)
	12. Investigate the site environment	(Chavez *et al*., 2021; Suedel *et al*., 2022)
	13. Evaluate cost-benefit	(Albert *et al*., 2021; Brown *et al*., 2015; Dunlop *et al*., 2023; Kumar *et al*., 2021; Vojinovic *et al*., 2017)
	14. Develop an action plan	(Kumar *et al*., 2021)
	15. Define the restoration plan	(Dunlop *et al*., 2023)
	16. Risk assessment	(Brown *et al*., 2015; Chávez *et al*., 2021; Dunlop *et al*., 2023, Suedel *et al*., 2022)
	17. Create visions and scenarios	(Albert *et al*., 2021; Brown *et al*., 2015; Ostrow *et al*., 2022)
	18. Model simulations	(Poff *et al*., 2015; Vojinovic *et al*., 2017; Viehman *et al*., 2023)
	19. Multi-criteria assessment	(Brown *et al*., 2015; Temmink *et al*., 2023)
	20. Biologize function and context	(Hinkelman *et al*., 2023; Temmink *et al*., 2023)
	21. Identify biological strategies	(Hinkelman *et al*., 2023; Perricone *et al*., 2023)
	22. Abstract functional mechanisms	(Hinkelman *et al*., 2023; Perricone *et al*., 2023)
	23. Emulate nature's lessons	(Hinkelman *et al*., 2023; Perricone *et al*., 2023)
	24. Evaluate fit and function	(Hinkelman *et al*., 2023; Perricone *et al*., 2023)
	25. Morphological analysis	(Ostrow *et al*., 2022; Temmink *et al*., 2023)
	26. Prototype trait mimic	(Temmink *et al*., 2023)
	27. Lab and field testing	(Temmink *et al*., 2023)
	28. Conduct vulnerability analysis	(Poff *et al*., 2015)

Design	1. Select the preferred measures	(Brown *et al*., 2015; Dunlop *et al*., 2023; Suedel *et al*., 2022; Vojinovic *et al*., 2017; Viehman *et al*., 2023)
	2. Design the preferred measures	(Kumar *et al*., 2020; Mayer-Pinto *et al*., 2017)
	3. Identify biological selection	(Evans *et al*., 2021)
	4. Identify topographic selection	(Evans *et al*., 2021)
	5. Identify engineering selection	(Evans *et al*., 2021)
	6. Manufacturing the enhancement design	(Evans *et al*., 2021)
	7. Apply technical specification and engineering science to design the selected measure	(Dunlop *et al*., 2023; Kumar *et al*., 2020)
	8. Design implementation processes	(Albert *et al*., 2021)
	9. Confirm the project cost estimation	(Dunlop *et al*., 2023)
	10. Develop the conceptual landscape layout plan	(Vojinovic *et al*., 2017)
Implementation	1. Implementation and construction	(Albert *et al*., 2021; Brown *et al*., 2015; Chávez *et al*., 2021; Calliari *et al*., 2019; Dunlop *et al*., 2023; Kumar *et al*., 2021; Suedel *et al*., 2022; Viehman *et al*., 2023; Whelchel *et al*., 2018; Wise *et al*., 2014)
	2. Obtain approval (biodiversity-enhanced design, specification, materials and construction schedule) and licensing	(Dunlop *et al*., 2023; Suedel *et al*., 2022)
	3. Develop and approve the adaptive management plan	(Suedel *et al*., 2022; Nazarnia *et al*., 2020)
	4. Site assessment and material collection	(Dunlop *et al*., 2023)
	5. Apply for courses and training	(Kumar *et al*., 2020)
	6. Prepare implementation manuals, guidelines, protocols, quality criteria and operating procedures	(Kumar *et al*., 2020)
	7. Develop environmentally friendly construction practices	(Mamo *et al*., 2022)

Monitoring and Evaluation	1. Monitor, assess and evaluate the implemented measure	(Albert *et al*., 2021; Brown *et al*., 2015; Calliari *et al*., 2019; Chávez *et al*., 2021; Dunlop *et al*., 2023; Kumar *et al*., 2020, 2021; Mamo *et al*., 2022; Mayer-Pinto *et al*., 2017; Nazarnia *et al*., 2020; Suedel *et al*., 2022; Viehman *et al*., 2023; Whelchel *et al*., 2018; Wise *et al*., 2014)
	2. Apply adaptation management	(Albert *et al*., 2021; Calliari *et al*., 2019; Dunlop *et al*., 2023; Mamo *et al*., 2022; Mayer-Pinto *et al*., 2017; Nazarnia *et al*., 2020; Ostrow *et al*., 2022; Suedel *et al*., 2022; Viehman *et al*., 2023; Whelchel *et al*., 2018)
	3. Report findings and lessons learned	(Dunlop *et al*., 2023; Kumar *et al*., 2021; Mamo *et al*., 2022; Mayer-Pinto *et al*., 2017; Suedel *et al*., 2022)

The review and analysis identified several stages and numerous activities from different implementation frameworks for sustainable coastal development. These can be classified into five main stages and 62 processes. The five main stages were inception (14 processes), planning (28 processes), design (10 processes), implementation (7 processes), and monitoring and evaluation (3 processes).

It is worth noting that the stages were organised to progress sequentially, in line with most frameworks, which were established to be iterative and managed adaptively (Wise *et al*., 2014; Brown *et al*., 2015; Poff *et al*., 2015; Mayer-Pinto *et al*., 2017; Calliari *et al*., 2019; Nazarnia *et al*., 2020; Kumar *et al*., 2020, 2021; Ostrow *et al*., 2022; Suedel *et al*., 2022; Mamo *et al*., 2022; Dunlop *et al*., 2023; Hinkelman *et al*., 2023; Viehman *et al*., 2023; Perricone *et al*., 2023). However, some of the identified processes overlapped due to different terms being used to describe similar activities. Therefore, the following section of the discussion will provide a comprehensive overview of the essential processes in each stage.

Numerous articles highlighted the need for interdisciplinary groups (e.g., stakeholders, engineers, ecologists, and community groups) to be involved throughout all the stages because the problems that need to be addressed are often multidimensional and complex (Gray *et al*., 2014; Brown *et al*., 2015; Poff *et al*., 2015; Pinto *et al*., 2017; Vojinovic *et al*., 2017; Calliari *et al*., 2019; Evans *et al*., 2019; Kumar *et al*., 2020, 2021; Chávez *et al*., 2021; Mamo *et al*., 2022; Suedel *et al*., 2022; Mayer-Ostrow *et al*., 2022; Temmink *et al*., 2023; Viehman *et al*., 2023; Dunlop *et al*., 2023; Gonzalez-Ollauri *et al*., 2023; Hinkelman *et al*., 2023; Perricone *et al*., 2023).

Inception Stage

A total of 22 out of 24 studies focused on the inception stage for the integration of natural elements into sustainable coastal development (Gray *et al*., 2014; Wise *et al*., 2014; Poff *et al*., 2015; Brown *et al*., 2015; Vojinovic *et al*., 2017; Mayer-Pinto *et al*., 2017; Whelchel *et al*., 2018; Calliari *et al*., 2019; Nazarnia *et al*., 2020; Kumar *et al*., 2020, 2021; Albert *et al*., 2021; Chávez *et al*., 2021; Ostrow *et al*., 2022; Mamo *et al*., 2022; Suedel *et al*., 2022; Dunlop *et al*., 2023; Gonzalez-Ollauri *et al*., 2023; Hinkelman *et al*., 2023; Perricone *et al*., 2023; Temmink *et al*., 2023; Viehman *et al*., 2023).

The most common process in the inception stage was problem identification (Gray *et al*., 2014; Whelchel *et al*., 2018; Kumar *et al*., 2020, 2021; Chávez *et al*., 2021; Mamo *et al*., 2022; Suedel *et al*., 2022; Perricone *et al*., 2023; Temmink *et al*., 2023; Dunlop *et al*., 2023; Gonzalez-Ollauri *et al*., 2023).

Other studies focused on defining the baseline and setting the project objectives (Mayer-Pinto *et al*., 2017; Calliari *et al*., 2019; Evans *et al*., 2021; Kumar *et al*., 2020, 2021; Ostrow *et al*., 2022; Suedel *et al*., 2022; Dunlop *et al*., 2023), identifying challenges/issues (Gray *et al*., 2014; Brown *et al*., 2015; Albert *et al*., 2021; Hinkelman *et al*., 2023), defining goals and success criteria (Wise *et al*., 2014; Poff *et al*., 2015; Hinkelman *et al*., 2023; Viehman *et al*., 2023, highlighting the processes of risk/hazard assessment (Wise *et al*., 2014; Whelchel *et al*., 2018; Kumar *et al*., 2020; Gonzalez-Ollauri *et al*., 2023), ecosystem services identification and valuation (Brown *et al*., 2015; Vojinovic *et al*., 2017), and establishing an action group (Gray *et al*., 2014; Kumar *et al*., 2020, 2021; Suedel *et al*., 2022; Gonzalez-Ollauri *et al*., 2023).

However, one study further included the appraisal of experts and authorities, site investigation (Gonzalez-Ollauri *et al*., 2023), scope definition, institutional and legal context, the establishment of funding strategies (Dunlop *et al*., 2023), enabling and constraining external factors (Calliari *et al*., 2019), co-definition of settings (Albert *et al*., 2021), and information gathering (Gray *et al*., 2014).

Identifying the problems, defining the challenges and baseline of the coastal area, and setting the project objectives are the main processes of the inception stage. Almost all of the implementation frameworks reviewed and analysed contain these processes. The process of defining goals and success criteria was another similar activity. As the challenges that needed to be addressed were multidimensional and complex, involving marine and coastal ecosystems situated within dynamic and diverse societal contexts (O'Leary *et al*., 2023), these processes are considered the most critical steps when designing urban coastal developments (Mayer-Pinto *et al*., 2017).

A study by Gonzalez-Ollauri *et al*. (2023) reported that in most cases, an identified problem will undergo appraisal by academic experts and local authorities if it is flagged by local communities. The study also included the process of site investigation in its current stage to better understand and gain insights within the context of the frameworks and coastal hazards. This process is akin to gathering information to define the problem through identifying the context and assessing the vulnerabilities. Furthermore, several reviewed frameworks indicated that the next step after problem identification was to understand and assess risks and hazards (Wise *et al*., 2014; Whelchel *et al*., 2018; Kumar *et al*., 2020; Gonzalez-Ollauri *et al*., 2023). Some of the reviewed frameworks employed another process such as the identification and valuation of ecosystem services (Brown *et al*., 2015; Vojinovic *et al*., 2017). Regardless of the process used, the nature of the activities is similar, which characterises the ecosystem to better define the dynamics of a problem.

As mentioned earlier, numerous reviewed articles have indicated that multidisciplinary teams are required throughout all stages. Furthermore, several other journals also highlighted the need to create action groups to incorporate their expectations, expertise, and knowledge relating to local coastal ecology, social-ecological systems, and hydrodynamics in the inception stage (Gray *et al*., 2014; Kumar *et al*., 2020, 2021; Suedel *et al*., 2022; Gonzalez-Ollauri *et al*., 2023). It is worth noting that research by Calliari *et al*. (2019) mentioned that the process of enabling and constraining external factors should be considered and included in the inception stage, as it can affect the system being worked on. This process can also assist in overcoming budget constraints through the development and implementation of a financing strategy.

A study by Albert *et al*. (2021) further noted that several processes such as co-defining the setting and understanding challenges, should be included in this stage. This is a slightly different approach from other implementation frameworks, as most usually only involve problem identification as the primary process. Co-defining a project's setting includes deciding on a project's kick-off and clarifying the context, societal challenges, aims, and processes of the project. On the other hand, understanding challenges is assessed in terms of defining what the existing problems are, as well as discovering opportunities across spatial and temporal levels.

Planning Stage

The review resulted in the highest number of processes in the planning stage. A total of 17 articles included the processes of developing/identifying, analysing/assessing, and evaluating alternative adaptive measures (Wise *et al*., 2014; Brown *et al*., 2015; Poff *et al*., 2015; Vojinovic *et al*., 2017; Whelchel *et al*., 2018; Calliari *et al*., 2019; Nazarnia *et al*., 2020; Kumar *et al*., 2020, 2021; Mamo *et al*., 2022; Ostrow *et al*., 2022; Suedel *et al*., 2022; Perricone *et al*., 2023; Temmink *et al*., 2023; Dunlop *et al*., 2023; Hinkelman *et al*., 2023; Viehman *et al*., 2023). Five and four additional journals included evaluating the costs and benefits (Brown *et al*., 2015; Vojinovic *et al*., 2017; Albert *et al*., 2021; Kumar *et al*., 2021; Dunlop *et al*., 2023), and assessing the risks involved (Brown *et al*., 2015; Chávez *et al*., 2021; Suedel *et al*., 2022; Dunlop *et al*., 2023), respectively.

Moreover, three other journals also included creating visions and scenarios (Brown *et al*., 2015; Albert *et al*., 2021; Ostrow *et al*., 2022) and model simulations (Poff *et al*., 2015; Vojinovic *et al*., 2017; Viehman *et al*., 2023). Additionally, the processes of stakeholder mapping (Kumar *et al*., 2020; Gonzalez-Ollauri *et al*., 2023), testing climate-proof alternatives (Calliari *et al*., 2019; Kumar *et al*., 2020), identifying and procuring funding (Kumar *et al*., 2020; Suedel *et al*., 2022), and investigating the site environment (Chávez *et al*., 2021; Suedel *et al*., 2022) were identified in two other studies.

Finally, one study mentioned the following processes: Co-creation strategy, shortlisting solutions (Gonzalez-Ollauri *et al*., 2023), mapping the effects of alternatives (Calliari *et al*., 2019), identifying opportunities for coordination (Nazarnia *et al*., 2020), information acquisition, investigating the suitability of the intervention (Mayer-Pinto *et al*., 2017), developing initial cost estimation (Suedel *et al*., 2022), developing an action plan (Kumar *et al*., 2021), defining the restoration plan (Dunlop *et al*., 2023), and conducting vulnerability analysis (Poff *et al*., 2015).

This review also identified a few studies focused on the biomimicry approach (Hinkelman *et al*., 2023; Perricone *et al*., 2023). These studies identified natural functions and strategies and transferred them into design applications through several processes. These processes involve biologising function and context, identifying biological strategies, abstracting functional mechanisms, emulating nature's lessons, and evaluating fit and function. Moreover, another study developed steps for designing a trait-based restoration approach (Temmink *et al*., 2023).

This solution is almost similar to the biomimicry approach, which emphasises species-specific emergent traits in mimicry approaches to restore ecosystems. The five steps consist of function identification, morphological analysis, multi-criteria analysis, prototyping trait mimicry, and lab and field testing.

In addition, the morphological analysis was also identified in the framework developed by Ostrow *et al*., (2022). The study included field measurements of vegetation morphology for the quantification of wave attenuation performance to derive the parameters needed from the natural elements for wave attenuation.

From the review, the next critical step in the inception stage was to identify and determine all the alternative adaptive measures that may address the identified problems under the planning stage. All the multiple direct and indirect costs and benefits of the alternative solutions were to be identified and compared to ensure the project objectives were satisfactorily met.

The study by Gonzalez-Ollauri *et al*. (2023) described the NbS identification and selection process in detail. To find effective and acceptable solutions, it aimed to map and classify the relevant stakeholders into three different groups: Primary, secondary, and tertiary. This classification would allow for better engagement and input collection through the co-creation process, which was intended for developing selection criteria and shortlisting solutions for implementation.

Furthermore, the research by Calliari *et al.* (2019) indicated that after the alternatives are identified and developed, it is necessary to test their climate resilience, due to climate change's impact on the ecosystem, to ensure long-term viability. The test will map the expected effects of the alternatives and break down the possible performances of each one. This is to provide a comprehensive baseline on which the alternatives can be further assessed for selection. The climate-proof testing is related to vulnerability analysis, which is used to evaluate the system's response to changes in climate (Poff *et al.*, 2015).

In addition, a step-by-step eco-engineering practices framework proposed by Mayer-Pinto *et al.* (2017) involves the processes of information acquisition and assessing the suitability of the intervention for the planning stage. The study revealed that collecting relevant information was crucial in avoiding wasted resources and identifying knowledge gaps. The gathered data was then applied to design strategic interventions that help achieve an eco-engineering project's objective. To ensure successful intervention, the benefits of a planned process and its long-term self-sustainability should be evaluated. NbS selection not only depends on the feasibility of deploying an NbS within a specific context, but it is also tied to the identification of suitable interventions in sites and locations as well (Gonzalez-Ollauri *et al.*, 2023).

Another implementation framework that included several processes in the planning stage is the one proposed by Suedel *et al.* (2022). The main process consisted of investigating the site environment by identifying and analysing any site-specific hydrodynamic conditions that might affect the design and functionality of a project. However, the acceptable levels of risk and health of the ecosystem based on past and present conditions may not be the best guide for adaptation to different contexts in the future (Brown *et al.*, 2015).

Therefore, a framework developed by Albert *et al.* (2021) involved creating visions and scenarios. The study suggested that such a framework may be useful in stimulating creative and imaginative thinking, allowing for the consideration of different perspectives to better site NbS within a given landscape. It is related to model simulations, which can evaluate different restoration scenarios at multiple spatial and temporal scales and is considered a crucial method for evaluating restoration designs (Viehman *et al.*, 2023). Hence, scenario analysis will be carried out together with other tools such as multi-criteria assessment, risk assessment, and cost-benefit analysis to provide an appraisal for alternatives (Brown *et al.*, 2015).

Other important processes identified in the review included developing initial cost estimation and identifying and procuring funding in the planning stage. Lastly, an action plan for connecting project objectives to specific actions (e.g., resourcing, who does what, when, and how) should be developed in the planning stage, with indicators to measure the effectiveness of each action (Kumar *et al.*, 2021; Dunlop *et al.*, 2023).

Design Stage

In the design stage, two articles generally discussed the process of designing preferred measures without referring to specific design techniques (Mayer-Pinto *et al.*, 2017; Kumar *et al.*, 2020), while two other studies emphasised the application of technical specifications and engineering science to the design of selected measures without providing further detailed explanations (Kumar *et al.*, 2020; Dunlop *et al.*, 2023).

Another five frameworks focused on the process of selecting preferred measures at this stage (Brown *et al.*, 2015; Vojinovic *et al.*, 2017; Suedel *et al.*, 2022; Dunlop *et al.*, 2023; Viehman *et al.*, 2023). The preferred alternative was to select from a shortlist of options generated during the planning stage, with the study by Suedel *et al.* (2022) highlighting the need to consider factors such as cost, the range and magnitude of biodiversity, and the social and economic benefits of the measures when selecting a preferred alternative.

Most of the implementation frameworks involved the design stage, including the selection and design of preferred measures; however, the study by Albert *et al*. (2021) also included the step of designing the implementation process. This is because the solution strategies require a focus on place-specific contexts and the need to overcome multiple barriers to implementation (Albert *et al*., 2021). Furthermore, the research by Vojinovic *et al*. (2017) further developed the conceptual landscape layout plan after the measure was selected.

Additionally, there is one other study that established a five-step process for designing natural topography-based eco-engineering habitat units for artificial structures (Evans *et al*., 2021). The five-step process consists of conducting a baseline survey, identifying biological selection, identifying topographic selection, identifying engineering selection, and manufacturing the enhancement design. This study developed a detailed process to enable the creation of ecologically informed designs that will enhance the benefits of biodiversity within a burgeoning ocean sprawl.

Implementation Stage

This review highlighted the lack of frameworks focused on the implementation stage. Even when such frameworks existed, those studies only mentioned the implementation stage perfunctorily or did not provide any detailed explanation. Several studies reported on the implementation and construction processes at this stage, but ten studies did not offer detailed procedures (Wise *et al*., 2014; Brown *et al*., 2015; Whelchel *et al*., 2018; Calliari *et al*., 2019; Albert *et al*., 2021; Chávez *et al*., 2021; Kumar *et al*., 2021; Suedel *et al*., 2022; Dunlop *et al*., 2023; Viehman *et al*., 2023), while two studies only recommended the process of developing and approving the adaptive management plan in the implementation stage without further explanation (Nazarnia *et al*., 2020; Suedel *et al*., 2022).

Additionally, two journals recommended the processes for obtaining approval for biodiversity-enhanced design, specifications, materials, construction schedules, and licensing (Suedel *et al*., 2022; Dunlop *et al*., 2023). According to Suedel *et al*. (2022), construction is only initiated after obtaining approval for its biodiversity-enhanced design, specifications, choice of materials, and construction schedule. The study also indicated that stakeholders with biodiversity experience should provide oversight to ensure that features are constructed as designed, and any required engineering modifications should not interfere with these features to maximise biodiversity. The research by Mamo *et al*. (2022) further emphasised that construction practices should include environmentally friendly methods to minimise any environmental and social disturbance. It also stated that priority should be given to durability to reduce the need for maintenance.

It is worth noting that only one study mentioned the processes of site assessment and material collection (Dunlop *et al*., 2023), applying courses and training for workers, preparing implementation manuals, guidelines, protocols, quality criteria, and operating procedures (Kumar *et al*., 2020), and developing environmentally friendly construction practices (Mamo *et al*., 2022), respectively.

Monitoring and Evaluation Stage

This review identified only three processes relevant to this stage. A total of 14 studies emphasised the need for the process of monitoring, assessing, and evaluating the implemented measures (Wise *et al*., 2014; Brown *et al*., 2015; Mayer-Pinto *et al*., 2017; Whelchel *et al*., 2018; Calliari *et al*., 2019; Nazarnia *et al*., 2020; Kumar *et al*., 2020, 2021; Albert *et al*., 2021; Chávez *et al*., 2021; Mamo *et al*., 2022; Suedel *et al*., 2022; Dunlop *et al*., 2023; Viehman *et al*., 2023).

A total of 10 studies highlighted the processes of applying adaptation management (Mayer-Pinto *et al*., 2017; Whelchel *et al*., 2018; Calliari *et al*., 2019; Nazarnia *et al*., 2020; Albert *et al*., 2021; Mamo *et al*., 2022; Ostrow *et al*., 2022; Suedel *et al*., 2022; Viehman *et al*., 2023; Dunlop *et al*., 2023). According to the review, all implementation frameworks focusing on the entire stages of implementation were involved in this stage. The monitoring and evaluation stage has been recognised as being as important as the design stage for the successful delivery of NbS (Dunlop *et al*., 2023).

The study by Suedel *et al*., (2022) referred to this stage as the operations stage, which begins after the project is fully constructed, enabling the project to be implemented with optimal performance. This stage involves monitoring the performance of a system to evaluate its response to challenges and to determine whether the objectives of the system have been achieved (Mayer-Pinto *et al*., 2017; Suedel *et al*., 2022; Dunlop *et al*., 2023; Viehman *et al*., 2023). The differences between expected and actual outcomes reveal whether and how the interventions should be modified to address these differences and mitigate any potential new challenges (Mayer-Pinto *et al*., 2017; Suedel *et al*., 2022). Thus, the information obtained from the monitoring process can be used to evaluate recovery and inform adaptive management (Viehman *et al*., 2023).

The study by Mayer-Pinto *et al*. (2017) further reported that this evaluation should continue throughout the entire lifespan of the coastal development to identify and incorporate any new opportunities for interventions. Therefore, both monitoring and evaluation plans are critical for making decisions based on the available information when assessing alternative options and management strategies (Poff *et al*., 2015). Lastly, it was found that reporting on findings and lessons learned is vital in the monitoring and evaluation stage, as it can serve as an evidence base and address any gaps to improve future project implementation (Mayer-Pinto *et al*., 2017; Kumar *et al*., 2021; Suedel *et al*., 2022; Mamo *et al*., 2022; Dunlop *et al*., 2023).

Discussions

This section examines how eco-engineering, Nature-based Solutions (NbS), and adaptive approaches address the phases for sustainable coastal development, focusing on identifying missing or underutilised processes critical to integrating eco-engineering. The inception phase forms the foundation for sustainable coastal development, where project challenges, goals, and contexts are initially defined. Across the reviewed frameworks, this phase is extensively discussed, particularly in NbS and adaptive approaches. Key processes include problem identification, risk/hazard assessment, establishing an action group, defining the baseline and setting objectives, establishing funding strategies, and recognising enabling and constraining external factors.

While the identified processes are well-represented in sustainable coastal development frameworks, eco-engineering considerations are often absent at this stage. This gap is critical, as the early integration of ecological enhancement objectives can significantly influence the subsequent stages of design and implementation. For example, identifying opportunities for habitat restoration or enhancement during the inception stage can help define the project baseline and guide objective setting, shaping the entire project planning towards a design that enhances biodiversity. Furthermore, only one framework explicitly addresses enabling and constraining external factors such as economic, political, demographic, and environmental trends, which are essential for anticipating broader system dynamics and aligning project goals with future conditions (Calliari *et* al., 2019).

Another underrepresented but essential process is the development of funding strategies. Although highlighted by only one framework, inadequate and intermittent funding remains a major barrier to maintaining NbS efforts (Chee *et* al., 2021), especially in developing regions

(Rahman, 2022; Giang & Khanal, 2024; Suhardi *et* al., 2024). Including this process early in the inception phase could help secure long-term commitment and resource allocation for eco-engineering integration.

Additionally, while stakeholder engagement is widely acknowledged, most frameworks fail to specify how and when stakeholders should be involved. This timing is crucial, as early formation of action groups and stakeholder mapping can influence both feasibility assessments and project acceptance. Moreover, the timely involvement of stakeholders can significantly enhance the multi-functionality of the proposed alternatives (Fitzsimons *et* al., 2019). The inception phase, therefore, needs to move beyond broad principles to more actionable guidance, particularly in supporting cross-sector collaboration that integrates ecological, social, and engineering expertise.

The planning phase is where alternatives are identified, assessed, and prioritised. Most existing frameworks emphasise NbS multi-functionality, promoting nature-based designs that offer co-benefits such as biodiversity enhancement, flood risk reduction, and recreation. However, few provide mechanisms to systematically integrate eco-engineering principles into the solution space. Key processes such as understanding biological context, conducting morphological analysis, abstraction, emulation, envisioning scenarios, performing assessments, prototyping, and investigating suitability and climate resilience are essential for developing effective eco-engineering interventions. However, these steps, commonly used in biomimicry and bio-design (Hinkelman *et al*., 2023; Perricone *et al*., 2023; Temmink *et al*., 2023), are largely missing from mainstream planning frameworks. These methods help translate biological functions into engineering strategies, enabling innovation that extends beyond nature-based solutions. Their absence from previous NbS and adaptive approach frameworks limits the potential for more creative and ecologically informed infrastructure.

The review also reveals that most frameworks support iterative and participatory processes, allowing planning to adapt to new information or stakeholder feedback for more climate-resilient alternatives (Calliari *et al*., 2019). This is a strength of previous frameworks and highlights the critical need for eco-engineering design loops to be integrated into these iterative structures, ensuring that solutions evolve alongside ecological data and design feedback. These processes were also supported by Bridges *et al*. (2021), whose study suggested that when new information is discovered or revealed during later stages, previously completed stages can be revisited and further refined.

Economic considerations are also underrepresented. Although cost-benefit analyses are occasionally mentioned, only a few frameworks emphasise initial cost estimation and funding alignment during the planning stage, even though these are critical as they will affect not only the selection of alternatives but also the method of implementation (Gonzalez-Ollauri *et al*., 2023). Similarly, the development of an action plan is rarely detailed, yet it is a vital process because it serves as the bridge between planning and implementation, outlining tangible steps to achieve a project's stated goals and objectives (Schaefer, 2018).Overall, planning efforts often focus heavily on identifying the most appropriate solutions for NbS, while critical biomimicry processes are frequently overlooked. These efforts would benefit from a more deliberate inclusion of eco-engineering processes, particularly those that help design interventions inspired by, but not limited to, natural systems.

A study by Dunlop *et al*. (2023) highlighted that the design stage is crucial for determining whether selected measures align with the environmental constraints of the target site, making it critical for the successful delivery of NbS. However, the design phase is arguably the most underdeveloped in existing frameworks. While many provide robust guidance on identifying problems and shortlisting preferred alternatives, few go further to translate these into detailed technical specifications, a gap that is particularly critical for eco-engineering.

Eco-engineering's potential lies in its ability to integrate ecological and structural design. Yet, the design phase often lacks explicit processes to facilitate this integration. For example, processes such as biological selection, topographic modelling, and engineering selection are rarely included. Only one study proposed designs that replicate natural topography on marine artificial structures (Evans *et al*., 2021), despite the clear need to move beyond using nature solely as a source of services and towards using nature as a model for form and function. To date, the exploration of biological and ecological domains has mainly focused on how nature provides ecosystem services, rather than on how to design and implement infrastructure as nature would, which aligns more closely with the biomimicry domain (Bianciardi *et al*., 2023).

Developing a conceptual layout plan is another important but often overlooked process. Such plans can visualise biodiversity enhancements and identify synergies or conflicts early in the design phase. Additionally, the design of the implementation process and the confirmation of project costs are often excluded. Given the high costs and significant manpower typically required during the implementation stage (Ritz, 1994), these aspects should be considered essential in the design phase. Designing the implementation process must ensure that resources are managed and utilised effectively and efficiently during implementation.

The design phase, therefore, needs to be more fully developed across all framework types. Integrating eco-engineering requires explicit processes to guide the translation of ecological principles into structural designs, ensuring that the resulting solutions are both ecologically meaningful and technically feasible. Implementation is the most technically demanding phase, yet it is also where the fewest frameworks provide detailed guidance. This is particularly problematic for eco-engineering integration, which often involves novel materials, complex site conditions, and cross-sector coordination.

Across the reviewed frameworks, general steps such as implementation and construction are mentioned. However, the integration of implementation manuals, guidelines, protocols, quality criteria, operating procedures, approval and licensing, and adaptive management plans is inconsistent. These processes are critical, particularly in coastal and maritime construction, where volatile conditions from waves, storms, currents, and tides have led to major accidents and fatalities (Cruickshank & Cork, 2005). Furthermore, during this stage, some design features may require adaptation, even after the construction of the selected alternative has commenced, to prepare for and respond to such volatility and unpredictability (Suedel *et al*., 2022). Adaptive plans allow for adjustments during the construction, monitoring, and evaluation phases in response to unforeseen ecological or engineering challenges.

Site assessment and material selection are critical in eco-engineering projects, as the complexity of the habitat and type of material may need to be modified to maximise ecological outcomes (Mamo *et al*., 2022), yet these topics are only briefly discussed. The need to alter traditional concrete compositions or incorporate recycled materials to reduce ecological impacts is rarely mentioned, despite strong evidence supporting their effectiveness (Huang *et al*., 2016; Natanzi *et al*., 2021). These processes directly affect biodiversity outcomes, especially when constructing in sensitive coastal habitats. Similarly, the inclusion of capacity-building elements such as short courses and training, was limited to a single framework, even though scientific and knowledge gaps are often barriers to successful NbS and eco-engineering implementation (Chee *et al*., 2021).

Another notable absence is the lack of environmentally friendly construction practices. As coastal development seriously threatens our natural ecosystems, it is significant to adopt environmentally friendly construction methods to enhance environmental and social outcomes (Mamo *et al*., 2022). Including a "mitigation hierarchy" during the planning and operational stages of the project can help reduce the negative impacts on ecosystems (Tallis *et al*., 2015). Therefore, this phase requires a more flexible and knowledge-informed implementation protocol, especially for projects that push the boundaries of traditional engineering through eco-design.

Monitoring and evaluation are consistently cited as essential across all frameworks throughout project lifecycles. Most frameworks acknowledge the need to monitor outcomes and assess performance for the project's long-term success. This stage has been identified as one of the most important for the successful delivery of NbS (Dunlop *et al*., 2023), as corrective actions can be taken with adaptive management to achieve the stated interim and end goals (Webb *et al*., 2019).

Adaptive management is frequently highlighted as a core principle across most frameworks, particularly for its role in establishing feedback loops that support iterative learning and continuous improvement. Eco-engineering frameworks often incorporate structured processes to "close the loop", thereby operationalising adaptive management in practice. Defined as a systematic and iterative approach to decision-making under uncertainty, adaptive management relies heavily on monitoring and evaluation to inform adjustments over time (World Bank, 2017). Its integration is therefore essential, not optional. Projects should embed adaptive management and maintain monitoring efforts until a relative equilibrium is reached, enabling timely corrective action when necessary (Pioch *et al*., 2018).

One key gap is the absence of a process for reporting lessons learned or building an evidence base for future design. While some frameworks call for post-implementation assessments, systematic documentation of outcomes remains rare. Without this, scaling and replicating successful eco-engineering interventions becomes difficult. Thus, increasing the evidence base requires consistent and transparent reporting of both outcomes and lessons learned. This process is essential not only for improving future projects but also for ensuring accountability in terms of both financial investment and environmental impact (Seddon *et al*., 2021).

Ultimately, the successful delivery of nature-based projects depends on embedding the monitoring and evaluation phase with adaptive management throughout the project lifecycle. Projects that prioritise these processes are more likely to deliver meaningful and long-lasting benefits. A failure to integrate adaptive management with monitoring can lead to missed opportunities for improvement and undermine the long-term success of eco-engineering.

Building on this analysis and discussion, the following framework synthesises critical processes into a cohesive structure that directly addresses the research gap identified in this study: The lack of structured, phase- and process-specific guidance for integrating eco-engineering across the coastal infrastructure lifecycle. While previous eco-engineering frameworks are often fragmented or overly generic, the framework developed in this study, as illustrated in Figure 3, offers a novel contribution by aligning key processes across five main construction phases: Inception, planning, design, implementation, and monitoring & evaluation**.** It also embeds cross-cutting considerations such as spatial dynamics, stakeholder engagement, and adaptive management loops. This integration not only promotes a more consistent and context-sensitive application of eco-engineering but also supports retrofitting and forward-planning efforts in line with sustainability objectives such as SDG 14: Life Below Water.

Figure 3 presents this integrated framework, illustrating how lessons drawn from existing frameworks inform a forward-looking model for eco-engineering integration. By synthesising insights from diverse literature and practice, the framework establishes a foundation for more operational, adaptive, and context-sensitive

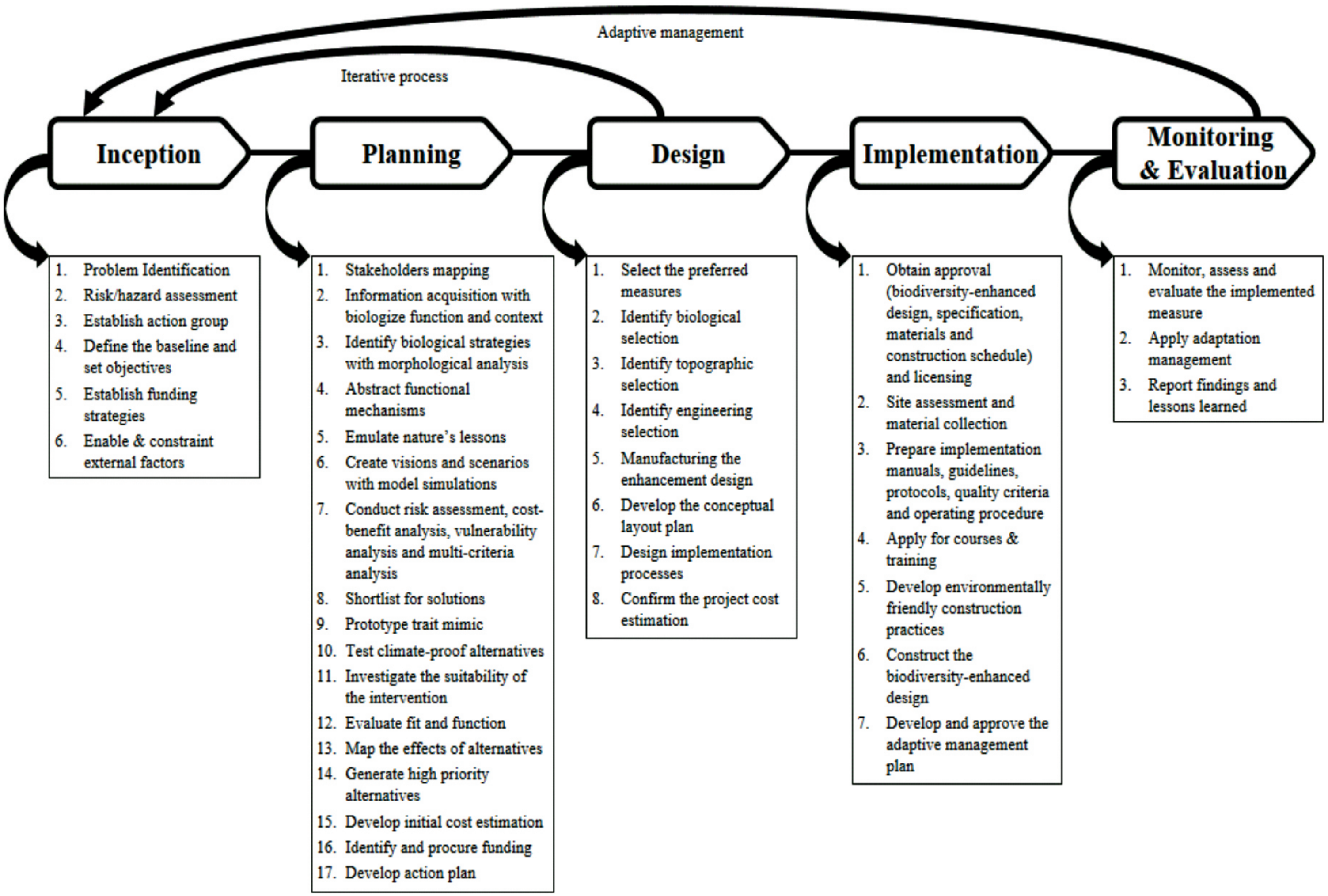

Figure 3: The crucial processes in each of the stages for eco-engineering integration

implementation of eco-engineering in coastal development.

Conclusion and Recommendation

Coastal areas will continue to face the impacts of climate change and coastal squeeze, necessitating urgent adaptation strategies to enhance resilience. While several frameworks for sustainable coastal development have been proposed, they vary significantly in structure. This review distilled five core stages common across these frameworks: Inception, planning, design, implementation, and monitoring and evaluation, and identified the critical processes within each stage. These stages are often iterative, allowing for the integration of new information and the addressing of emerging challenges. Notably, most frameworks incorporate adaptive management and involve interdisciplinary collaboration throughout the project lifecycle.

Key processes for each stage include:

- Inception: Problem identification, risk/hazard assessment, establishment of an action group, defining the baseline and setting objectives, establishment of funding strategies, and enabling and constraining external factors.
- Planning: Stakeholder mapping, information acquisition with biological function and context, identifying biological strategies through morphological analysis, abstracting functional mechanisms, emulating nature's lessons, creating visions and scenarios with model simulations, conducting risk assessments, cost-benefit analyses, vulnerability analyses, and multi-criteria analyses, shortlisting solutions, prototyping trait mimicry, testing climate-proof alternatives, investigating the suitability of interventions, evaluating fit and function, mapping the effects of alternatives, generating high-priority alternatives, developing initial cost estimates, identifying and procuring funding, and developing an action plan.
- Design: Selecting the preferred measures, identifying biological selection, identifying topographic selection, identifying engineering selection, manufacturing the enhancement design, developing the conceptual layout plan, designing the implementation processes, and confirming the project cost estimate.
- Implementation: Obtaining approval and licensing, site assessment, and material collection, preparation of implementation manuals, guidelines, protocols, quality criteria, and operating procedures, applying for courses and training, developing environmentally friendly construction practices, constructing the biodiversity-enhanced design, and developing and approving the adaptive management plan.
- Monitoring and Evaluation: Monitoring, assessing, and evaluating the implemented measures, applying adaptation management, and reporting findings and lessons learned. These findings support the future development of a comprehensive eco-engineering framework for both new and existing coastal infrastructure. Importantly, while existing eco-engineering frameworks outline general implementation steps, they often lack guidance specific to retrofitting versus new developments. Additionally, eco-engineering is frequently considered too late in the design process, limiting its effectiveness. To address this, eco-engineering principles must be integrated from the earliest stages of project planning, especially in the preliminary design phase, to ensure that ecological priorities are embedded from the outset. This study categorised key processes across the five main stages, offering a foundation for future research. Further work is recommended to explore how eco-engineering can be systematically integrated into coastal construction practices to enhance biodiversity outcomes from burgeoning ocean sprawl.

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Conflict of Interest Statement

The authors declare that they have no conflict of interest.

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