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Review

# Global review of eco-engineering research with recommendations for nature positive outcomes in coastal ecosystems

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ABSTRACT

Coastal urbanisation and climate change pressures have intensified interest in eco-engineering solutions to enhance biodiversity and support sustainable coastal development. This study presents a systematic review of applied eco-engineering research conducted exclusively in urbanised seascapes, following PRISMA guidelines. Literature searches in Scopus, Web of Science, and ProQuest (January 1980 – June 2024) identified 6698 records, of which 128 studies met inclusion criteria. These represented 160 interventions across 26 countries spanning tropical, subtropical, and temperate zones. Interventions were categorised by design type, infrastructure, application phase (retrofit or construction), and target assemblage to evaluate ecological performance relative to unmodified controls. Results show that 143 interventions (89 %) increased species abundance or richness, whereas 17 (11 %) produced neutral or negative effects. Textured panels were most frequently applied (37 %), followed by transplantation (20 %), artificial rockpools (9 %), and pits and grooves (9 %). Simple, low-cost microhabitat additions consistently delivered positive outcomes across climate zones. Yet few studies co-reported asset-relevant engineering metrics along with the ecological part. Persistent research gaps include the absence of baseline data, long-term monitoring, cost-effectiveness assessment, and invasive-species evaluation, together with limited evidence from tropical regions. Findings demonstrate that eco-engineering provides an effective and scalable pathway to improve ecological performance of coastal infrastructure when designs are context-specific, structurally sound, and integrated into planning and retrofitting. Linking biodiversity responses with basic performance and cost information will help translate these ecological successes into widely adoptable, nature-positive coastal development.

## 1. Introduction

The coastal zone continues to experience more pressure as a result of population increase and the desire that people have to live in coastal areas. Global coastal populations are projected to exceed one billion by mid-century, intensifying land-use change and habitat loss in already vulnerable environments (Li et al., 2023; Neumann et al., 2015). Recent analyses confirm that anthropogenic activities, including coastal reclamation, urban sprawl, and altered land cover, have accelerated the degradation of coastal wetlands and intertidal habitats, particularly in climate-sensitive regions (Mahdian et al., 2023; Mahdian et al., 2024). These transformations have profound implications for biodiversity, ecosystem services, and the resilience of coastal communities. Additional developments-including waterfront housings, bridges, moorings, ports, marinas, boat ramps, fish farms, and oil platforms further intensify these pressures (Bishop et al., 2017). Alongside these pressures, coastal regions are increasingly threatened by climate change impacts, including stronger storms, more frequent cyclones, and sea-level rise, all of which place substantial stress on both human and ecological systems (Bernier et al., 2024; Celliers and Ntombela, 2015).

The growing need to protect coastal communities and critical infrastructure from climate-induced wave hazards and sea-level rise has intensified reliance on marine grey infrastructure such as seawalls and breakwaters, where the spatial distribution of wave overtopping remains a key factor in ensuring the resilience of coastal cities and infrastructure (Apine and Stojanovic, 2024; Dong et al., 2021; Dugan et al., 2011; Kent et al., 2024). While this review prioritises ecological outcomes from applied, in-situ interventions, we position it as

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complementary to the engineering literature and note that wider adoption will ultimately require coupling biodiversity monitoring with hydraulic performance assessment and predictive modelling. Breakwaters and seawalls have now replaced large areas of the coastline, for example, over 50 % of the natural shoreline in the United States has hard engineering protection (Bugnot et al., 2020). This pattern is evident across the North Sea region, where substantial portions of national coastlines are already fortified—for instance, nearly 46 % of England's and about 32 % of Northern Ireland's shorelines are protected by engineered defences (Masselink et al., 2020). Approximately 57 % of China's coastline has been modified or armoured (Li et al., 2023). Additionally, even along the Great Barrier Reef World Heritage Area (GBRWHA), the combined linear length of the urbanised shoreline constitutes nearly 10 % of its coastline, which presents a challenge for managers to continue approving development over conservation outcomes (Waltham and Sheaves, 2015). These alterations are compounded by the expanding construction of ports and marinas, which also contribute to similar transformations along coastlines.

The implementation of coastal armouring, predominantly crafted from concrete and rocks, has been observed to significantly alter habitat structure, complexity, and texture, influencing species composition within coastal ecosystems (Bugnot et al., 2020). These alterations manifest both adverse (Bulleri and Chapman, 2004, 2010; Saengsupavanich et al., 2022) and positive impacts (Bradley et al., 2023; Burt and Bartholomew, 2019; Grizzle et al., 2016) on the biodiversity of coastal seascapes. What this means is that our understanding of the ecological value of urbanised seascapes is incomplete (Bradley et al., 2023; Bulleri and Chapman, 2010; Dafforn et al., 2015). Usually, these marine urban seascapes have been viewed as contributing to adverse ecological impacts (Heery et al., 2017; Todd et al., 2019). This is likely a consequence of the reported conclusion that artificial marine structures in urban seascapes support lower biodiversity when compared to natural rocky environments (Chapman, 2003; Dennis et al., 2018). Seawalls or breakwaters are usually built in a vertical orientation and generally lack complexity or features that would otherwise support marine life (Browne and Chapman, 2011; Browne and Chapman, 2014; Perkol-Finkel et al., 2018). Habitat fragmentation in the urban seascape is a consequence of the ad hoc way in which we develop coastlines, often resulting from the replacement of natural habitats, such as sandy beaches, with artificial concrete structures like seawalls. This alteration changes habitat characteristics and consequently affects the species it can support (Bishop et al., 2017; Dennis et al., 2018). In comparison, more recent evidence is emerging that potential ecological gains can be made in urbanised seascapes (Airoldi et al., 2021; Bradley et al., 2023). As more studies report various contradicting effects of the urbanised seascape, it is undeniable that urbanisation will only continue along coastal areas, giving rise to the urgent need for more information to better plan for and conserve coastal ecosystems more broadly.

Eco-engineering initiatives aimed at restoring and enhancing the ecological value of breakwaters, seawalls, ports, and other marine infrastructure have been steadily increasing (Aguilera et al., 2023; Bishop et al., 2022; Dafforn et al., 2015; Schaefer et al., 2023a). Concurrently, there has been a notable development of literature reviews and frameworks designed to catalogue and assess the varied impacts of these eco-engineering designs (Bugnot et al., 2018; Dafforn et al., 2015; Firth et al., 2024; O'Shaughnessy et al., 2020; Strain et al., 2018). Recent advances have also applied artificial intelligence and machine-learning models to predict and optimise eco-engineering outcomes, such as wave overtopping at modified seawalls (Habib et al., 2025) and wave–vegetation interactions in hybrid defences (Torabbeigi et al., 2024). However, the current systematic review focuses exclusively on applied eco-engineering interventions implemented in uncontrolled, real-world environments, rather than laboratory or modelling studies, to ensure that outcomes reflect genuine ecological performance under complex site-specific conditions.

Further progress in eco-retrofitting and hybrid sea-defence approaches has extended eco-engineering beyond biodiversity enhancement to include wave attenuation, sediment stabilisation, and coastal resilience under climate stress. Studies such as Kent et al. (2024), Apine and Stojanovic (2024), and Dong et al. (2021) demonstrate that incorporating ecological enhancement features into conventional defences can deliver multifunctional benefits while maintaining structural integrity. These developments highlight a growing shift toward hybrid infrastructure designs that integrate ecological and engineering performance criteria to promote sustainable coastal protection.

Recent work has begun to systematise the engineering dimension of hybrid and eco-engineered defences. Notably, Xu et al. (2025) synthesised 95 studies on the hydraulic performance of hybrid sea defences, highlighting their promise for coastal resilience but also exposing key gaps in terminology consistency, quantitative field evidence (e.g., overtopping and runup), and validated design guidance under extreme conditions. Complementing that engineering-centred perspective, this review compiles real-world eco-engineering interventions applied in urbanised seascapes and evaluates ecological outcomes—including species richness, abundance, and functional response—across climate zones, structure types, and implementation phases (retrofit versus construction). We further examine geographic representation, baseline and monitoring deficiencies, invasive-species considerations, and instances where simple, scalable microhabitat designs can achieve ecological gains.

Despite these efforts, the outcomes of existing initiatives continue to show considerable variability from study to study. For instance, similar designs have yielded differing results in terms of species richness and abundance when implemented in diverse locations (Strain et al., 2021). This observed variability, alongside the rapid expansion of eco-engineering in recent years, underscores a pronounced inconsistency highlighting the complex ecological responses to engineered structures. Such variability underscores the urgent need for a systematic review that not only presents straightforward results but also reports additional factors such as pre-construction baseline studies, geographical focus, cost-effectiveness, and the potential for mass production of current eco-engineering designs for stakeholders. This systematic review is dedicated exclusively to applied eco-engineering studies conducted exclusively in urbanised seascapes worldwide. It thoroughly examines ports, marinas, wharves, seawalls, breakwaters, and other initiatives within these settings. Accordingly, this systematic review focuses on applied eco-engineering studies in urbanised seascapes worldwide, examining ports, marinas, wharves, seawalls, breakwaters, and related infrastructure to provide a nuanced understanding of stressors unique to developed coastal environments—conditions often absent in natural or remote settings.

### 1.1. Study objectives

Coastal eco-engineering has advanced rapidly, yet much of the literature remains fragmented across experimental, conceptual, and modelling studies. Few analyses have consolidated field-based evidence to determine how applied interventions perform ecologically under the complex, site-specific conditions of urbanised seascapes. This review addresses that critical gap by quantitatively synthesising global outcomes of eco-engineering applied to real marine infrastructure—from seawalls and breakwaters to ports and marinas—spanning tropical, subtropical, and temperate regions.

The study aims to:

- Determine global patterns and variability in ecological performance by comparing biodiversity responses (species richness and abundance) across structure types, climates, and application phases (retrofits versus new construction).
- Identify the design attributes most strongly associated with positive ecological outcomes, such as surface texture, habitat complexity, and

structural form, to infer design principles transferable across contexts.
- Assess implementation practicality, including scalability and economic feasibility where data are available, to gauge the potential for mainstreaming eco-engineering in coastal planning and retrofitting.
- Expose systemic knowledge gaps—notably the lack of baseline data, long-term monitoring, invasive-species assessment, and integration with engineering performance metrics—to guide future research and policy priorities.

By consolidating evidence from 160 real-world interventions, this review provides one of the first comprehensive, quantitative syntheses of applied eco-engineering in urbanised marine settings. It advances public and scientific understanding by identifying which design strategies consistently enhance biodiversity without compromising structural integrity, offering a pathway toward nature-positive, resilient coastal infrastructure.

## 2. Methodology

### 2.1. Literature search

The systematic review performed here followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al., 2021). The PRISMA approach provided a template for a comprehensive search, screening, and analysis of the literature relating to eco-engineering applications such as increasing surface complexity, transplantation, reducing slopes, and modifying the designs of artificial structures in urbanised coastal ecosystems. We searched three databases: Scopus, Web of Science (WoS), and ProQuest for studies published between January 1980 and June 2024. Detailed search strings used for the review are provided in Appendix A - Table 1. All records were downloaded and managed using Endnote (version 20.4.1). The PRISMA approach guided study exclusions based on predefined inclusion and exclusion criteria. Additionally, grey literature was examined through a post-systematic search to identify any additional supplementary sources, primarily accessed via Google, universities, eco-engineering production companies and government websites, as presented in Fig. 1. The screening process was conducted by the primary author. By design, we excluded laboratory and purely modelling studies to focus on applied, in-situ interventions on existing or newly built assets in urbanised seascapes, ensuring performance is assessed under real operational stressors.

### 2.2. Data extraction

The systematic search process identified a total of 6698 studies/papers, which were subsequently narrowed down to 128 studies (Fig. 1) after applying the inclusion and exclusion criteria. The inclusion and exclusion criteria for the selected studies are detailed in the Supplementary Materials. The studies were categorised by the type of eco-engineering intervention (e.g., the addition of textured panels, transplantation, etc.), the type of marine infrastructure (e.g., seawall, breakwater, pontoon), and latitudinal zones to assess the focus of the studies. The success of the eco-engineering materials was evaluated via comparisons with existing non-engineered structures and their effectiveness in attracting targeted fauna. All identified studies are summarised in Appendix B – Studies Database.

Studies that tested eco-engineering on multiple structures (e.g., textured panels on seawalls and ropes on pontoons) were entered as separate records per structure (Appendix B – Studies Database). A similar approach was applied to locations; studies with sites more than five kilometres apart were logged as a distinctive entries to evaluate location-specific outcomes. This process expanded the original 128

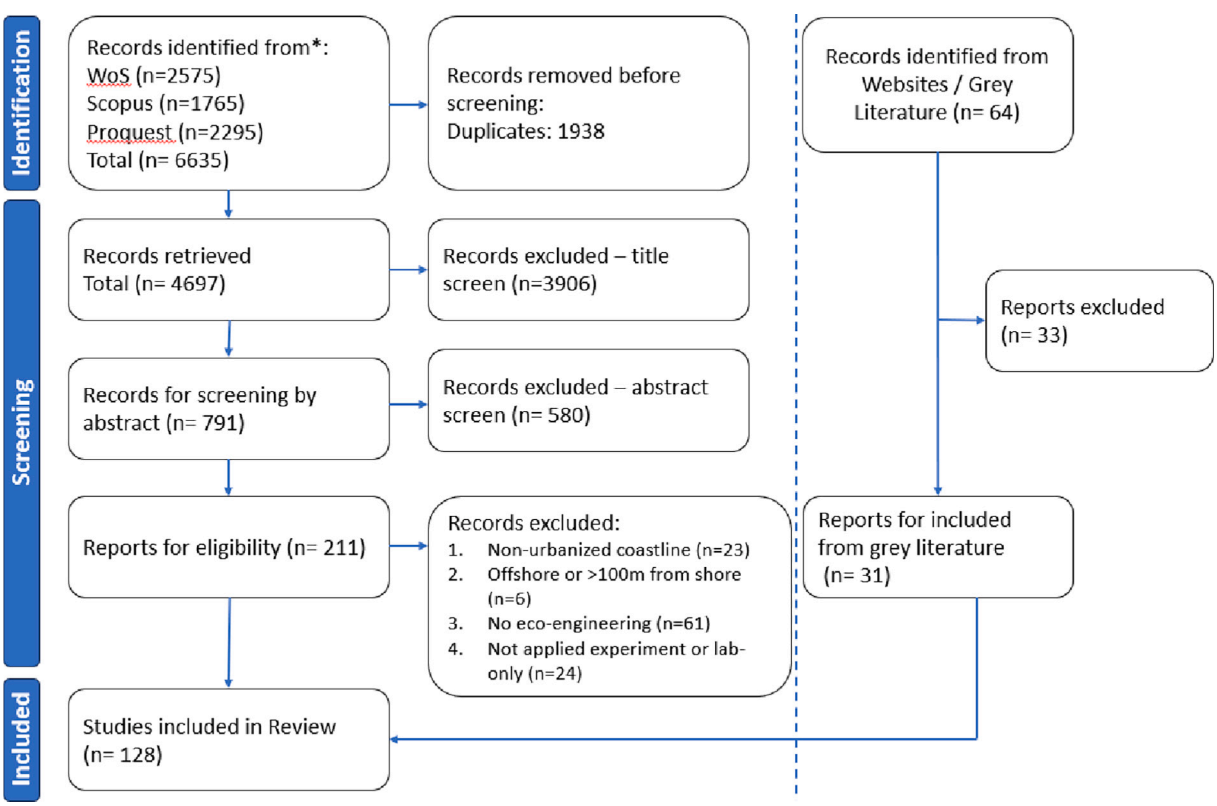


**Fig. 1.** Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flowchart illustrating the stages of search, screening, and analysis in a systematic review on eco-engineering in marine urbanised coastlines. Literature sources include Scopus, Web of Science, ProQuest, and Grey Literature. Modified from Page et al. (2021).

papers to 160 eco-engineering studies across different locations, with results reported by the number of studies rather than individual papers.

Data analysis, including the generation of descriptive statistics and the creation of illustrative figures, was performed using R Software (Team, 2023). In addition to qualitative synthesis, descriptive statistics were compiled to characterise publication patterns, geographic coverage, and intervention categories. Each record was assigned attributes including publication year, climate zone, structure type, and intervention design. Frequency distributions were then calculated to identify temporal trends (1980–2024), regional biases, and outcome proportions (positive, neutral, negative). We also summarised temporal trends, the proportional use of intervention types, venue concentration, and the prevalence of baselines, invasive-species assessment, monitoring duration, and cost metrics to assess the depth and comparability of the evidence base.

## 3. Results

The final dataset comprised 128 applied eco-engineering studies published between 1980 and 2024, representing 160 individual interventions. Research output accelerated markedly after 2010, increasing from fewer than five studies per year before 2000 to more than 20 annually in the 2020s, with 88 % of all publications produced after 2010 (median year 2018). Approximately 85 % of the studies were peer-reviewed journal articles, reflecting growing academic engagement in this field. Across all interventions, 143 (89 %) reported positive ecological outcomes—typically increased species abundance or richness relative to unmodified structures—while 17 (11 %) documented neutral or negative effects. These patterns confirm a strong overall tendency for eco-engineering to enhance biodiversity in urbanised marine environments.

Of the 128 included papers, publication outlets were highly concentrated. *Ecological Engineering* alone published 43/128 (~34 %). A second tier contributed modest shares—*Marine Environmental Research* (~6 %), *Marine Ecology Progress Series* (~4 %), *Journal of Experimental Marine Biology and Ecology* (~4 %), and the engineering venues *Coastal Engineering* and ICE *Maritime Engineering* together (~4–5 %)—with additional contributions from *Marine Pollution Bulletin* and *Journal of Applied Ecology* (~2–3 % each). The remaining ~45–50 % were distributed across more than 25 journals (e.g., *Environmental Management, Frontiers in Marine Science, PLoS One, Ecology, Ecology & Evolution, Biological Conservation, Science of the Total Environment, Estuarine, Coastal & Shelf Science, Marine & Freshwater Research, Hydrobiologia, Journal of Coastal Research, Journal of Sea Research, Urban Ecosystems, JMSE*). Grey literature (theses, technical reports, conference papers) comprised ~10–15 % of records. However, this venue concentration reflects our keyword strategy: search terms were tuned to applied eco-engineering and biodiversity/ecological outcomes, which likely preferentially retrieved ecology-focused studies and under-sampled engineering-centric work (e.g., papers centred on overtopping/runup, structural reliability, or materials testing), thereby biasing the corpus toward ecological reporting.

### 3.1. Eco-engineering categories

The majority of the eco-engineering studies, 130 out of 160 (81 %), relied on a single design approach, such as artificial textured panels, rockpools, or drilling pits and grooves, while 30 studies (19 %) employed multiple approaches, often combining transplantation with other complex structures like textured panels. Some multiple-intervention efforts used enhanced concrete materials in conjunction with artificial textured panels. Of the eco-engineering interventions, 108 out of 160 (68 %) were retrofitted or attached to existing marine infrastructure, while 52 out of 160 (32 %) were implemented during the

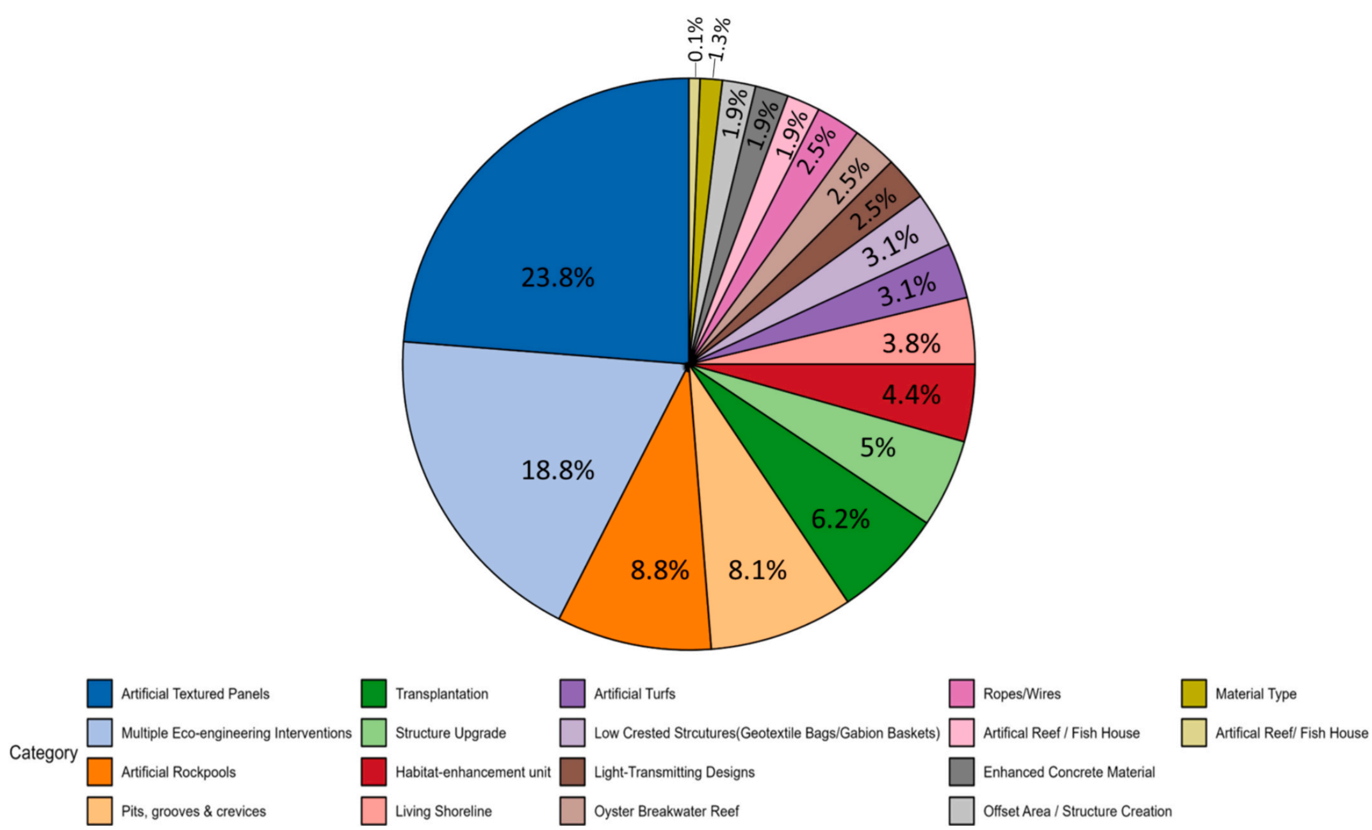


**Fig. 2.** Pie chart illustrating the proportions of eco-engineering interventions applied across studies, highlighting the relative use of approaches such as textured panels, transplantation, artificial rockpools, and others. Definitions for each eco-engineering category are provided in Appendix A.

construction phase, through structure modification, or as standalone structures (e.g., fish houses).

Artificial textured panels were the most applied eco-engineering intervention, appearing in 59 out of 160 studies (37 %). Of these 59 studies, 64 % focused exclusively on manipulating panel complexity. Additionally, 24 % combined textured panels with species transplantation efforts, and 12 % integrated enhanced concrete materials with the panels. This preference likely stems from the existing presence of marine infrastructure, such as seawalls and breakwaters, where retrofitting textured panels offers a practical and effective solution.

Species transplantation was the second most common intervention, reported in 32 out of 160 studies (20 %), often as part of a multi-faceted eco-engineering approach combined with other interventions, such as textured panels. This was followed by artificial rockpools (9 %), pits, grooves, and crevices (9 %), and structure upgrade interventions (5 %), where seawalls or breakwaters were rebuilt with eco-engineering features.

Fewer studies were conducted in other categories, including habitat enhancement units (4 %), living shorelines (4 %), artificial turfs (3 %), low-crested structures (3 %), artificial reefs/fish houses (3 %), oyster breakwater reefs (3 %), ropes/wires (3 %), enhanced concrete materials (2 %), offset areas/structure creation (2 %), and material type modifications (1 %), as presented in Fig. 2. These figures represent single-intervention studies; however, many studies employed multiple interventions, often integrating transplantation with other approaches to enhance ecological outcomes.

### 3.2. Research location

Regionally, the 160 eco-engineering studies originated from 26 countries spanning tropical (26 %), subtropical (32 %), and temperate (42 %) climate zones. Australia and the United States hosted the highest number of applied initiatives, each with 37 (23 %), followed by the United Kingdom with 22 (14 %) and Singapore with 11 (7 %), illustrated in Fig. 3. Other notable contributors included the Netherlands ($n = 8$; 5 %), France, Ireland, and Italy (each $n = 5$; 3 %), and Israel and Brazil (each $n = 4$; 3 %). The remaining studies were dispersed among China, India, Malaysia, Spain, Portugal, and several single-country cases such as Bangladesh, Chile, Mexico, Morocco, New Zealand, South Africa, Taiwan, and the UAE. When categorised by climate zones, the subtropical zone accounted for the majority of studies (71 out of 160, 44 %), with 8 % showing no significant effect on species richness or diversity compared to the non-eco-engineered sections of the same structure. The temperate zone included 66 studies (41 %), 15 % of which reported no significant impact. The tropical zone had the fewest studies (23 out of 160, 14 %), with 9 % showing no significant effects. These studies were conducted across 26 countries. However, when viewed by continent, Europe emerged with the greatest number of reported eco-engineering initiatives (50 out of 160 studies, 31 %). At the same time, North America and Australia were also significant contributors. In contrast, only two studies in Africa reported eco-engineering initiatives.

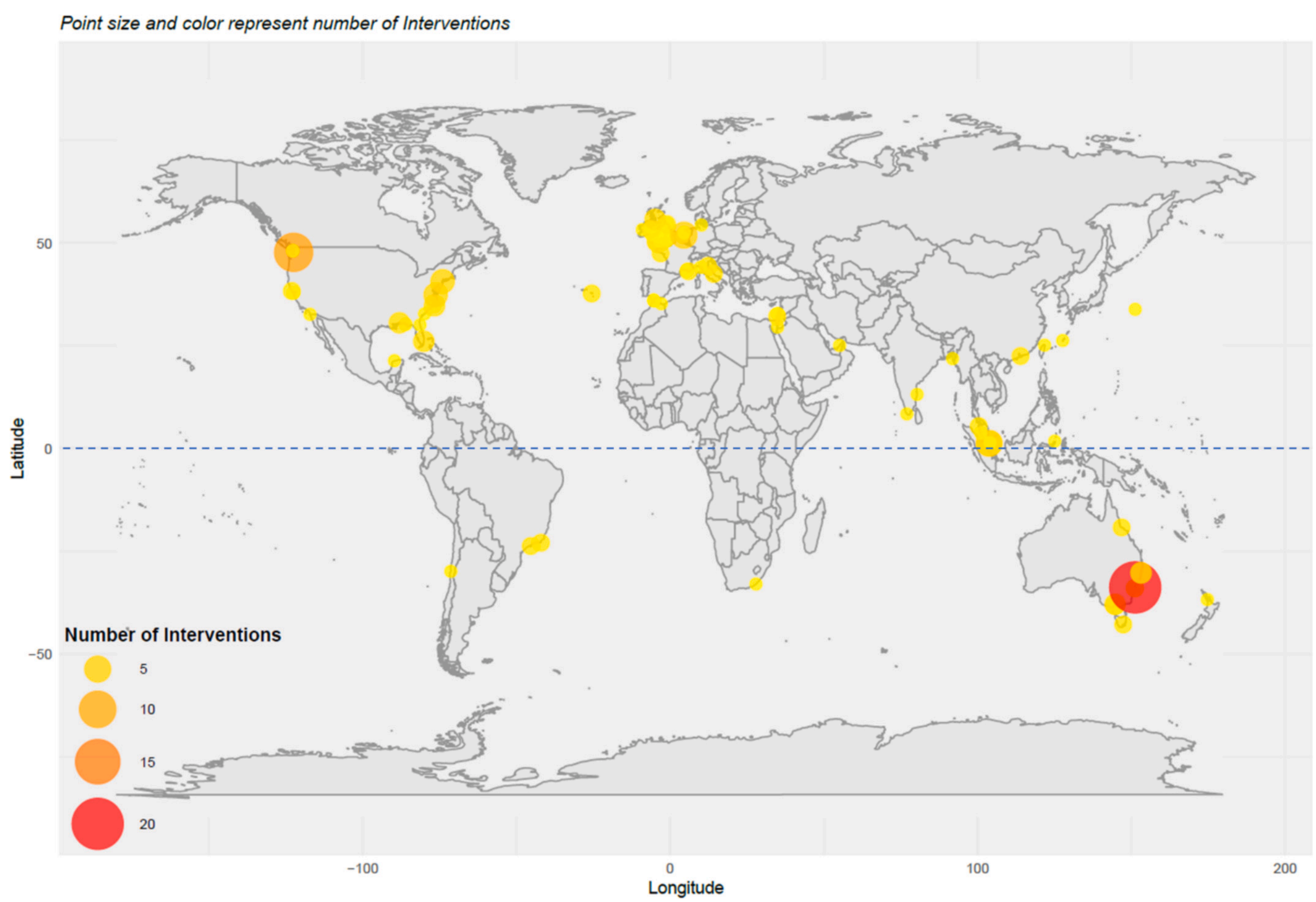


**Fig. 3.** World map showing the distribution of eco-engineering studies, with locations clustered into circles. Each circle represents a group of studies, with larger circles indicating regions with a higher concentration of studies.

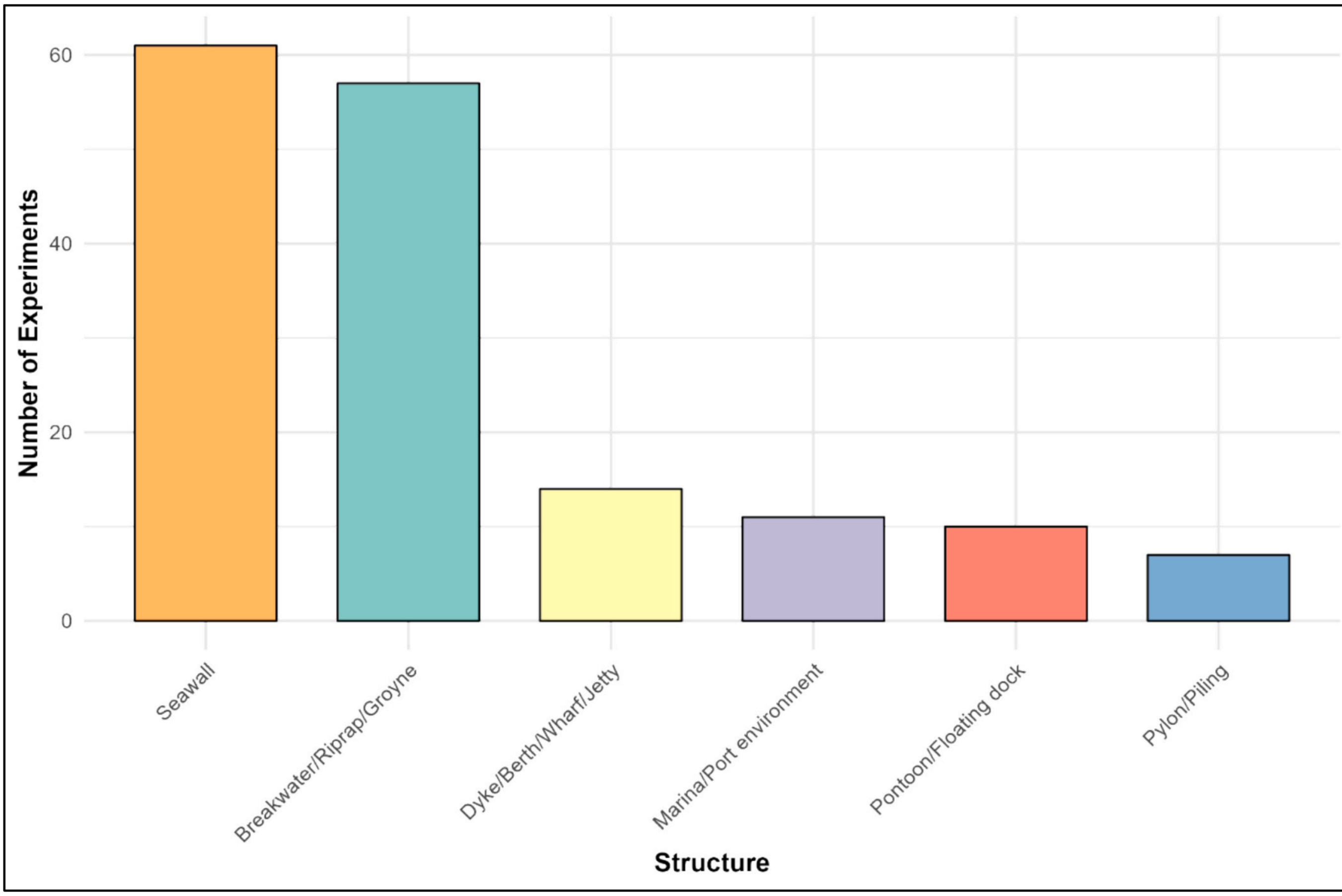


**Fig. 4.** Distribution of eco-engineering studies across various types of marine infrastructure within urbanised coastal seascapes.

### 3.3. *Artificial structures*

Among the 160 eco-engineering studies, the majority were conducted on sloping/vertical seawalls (61 out of 160, 38 %) and breakwater/riprap/groyne structures (56 out of 160, 35 %). Dyke/berth/wharf/jetty structures accounted for 9 % of the studies, followed by those in marina/port environments (8 %). Pontoons/floating docks were the focus of 6 % of the studies, while pylons/pilings had the fewest interventions (4 %) (Fig. 4). Additionally, only four studies examined the application of eco-engineering initiatives across multiple structural types within a single study to test their effectiveness.

### 3.4. *Targeted species*

The benthic assemblage emerged as the most frequently targeted group in eco-engineering interventions, featuring in 90 out of 160 studies (56 %) primarily aimed at enhancing benthic community structure and habitat complexity. Among these 90 studies, 81 (90 %)

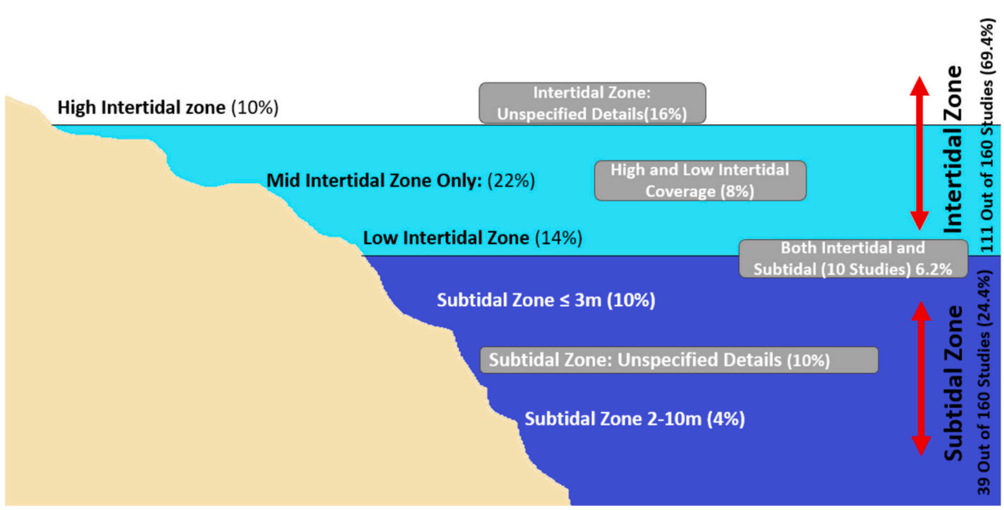


**Fig. 5.** Distribution of eco-engineering studies across intertidal and subtidal zones, represented as percentages indicating the proportion of studies conducted in each zone.

also included mobile epifauna, and 5 (6 %) reported outcomes involving benthic assemblages, mobile epifauna, and fish assemblages. Additionally, several interventions aimed to enhance the abundance of specific functional groups, including fish assemblages, oyster assemblages, barnacles, mussels, corals, mangroves, seaweed, and seagrass, reflecting a diverse approach to improving ecological outcomes in marine environments.

In addition to these community-level interventions, 40 out of 160 studies (25 %) specifically targeted individual species or families. These interventions often involved seeding species such as bivalves, corals, and seaweed to assess survival rates and potential to enhance the surrounding community. The remaining interventions focused on outcomes for specific species or families, including juvenile salmonids, groupers, limpets, oysters, and corals.

### 3.5. Invasive species

Out of 160 studies, 135 (84 %) did not investigate the presence or absence of invasive species. Six studies (4 %) reported the presence of invasive species but did not assess the impact of eco-engineering interventions. In contrast, 19 studies (12 %) examined how eco-engineering interventions influenced invasive species. Among these, 74 % showed positive outcomes, indicating that eco-engineered structures limited invasive species more effectively than traditional marine infrastructure, whilst 16 % found no significant effect. Only 11 % indicated a higher prevalence of invasive species on eco-engineered structures. Notably, both studies reporting negative results originated from the Artificial Turfs category, showing a higher abundance of invasive species on pontoons and pylons compared to non-engineered counterparts.

### 3.6. Experimental approach

A total of 111 studies out of 160 (69.4 %) were conducted in the intertidal zone, 39 studies (24.4 %) in the subtidal zone, and 10 studies (6.2 %) spanned both zones (Fig. 5). Within the intertidal zone, studies were distributed as follows: 22 % focused exclusively on the mean tidal level, 16 % did not specify a particular subzone, 14 % targeted the low intertidal zone (including 6 % extending from low to mean tidal levels), 10 % occurred in the high intertidal zone (including 3 % spanning from low to mean tidal levels), and 8 % examined both high and low intertidal zones or the full tidal range. For the subtidal zone, 10 % of studies were conducted at depths $\leq$3 m, another 10 % did not specify depth, and 4 % explored deeper ranges from 3 to 10 m.

The most common survey duration was 12 months, observed in 43 out of 160 studies (27 %). The average survey duration across all studies was approximately 15.2 months, with a standard deviation of 18.5 months. A total of 64 out of 160 (40 %) had survey durations of 3 months or less, while 42 out of 160 (26 %) lasted 2 years or more. Additionally, 6 out of 160 (4 %) did not report specific survey durations, with some labelled as preliminary results.

Reporting the application scales of the studies proved challenging because methodologies varied. Some studies presented total intervention areas, while others only indicated the number of replicates (e.g., five panels per design) without specifying distances between them. This inconsistency complicated attempts to summarise overall study scales.

## 4. Discussion

Overall, eco-engineering demonstrated significant potential to enhance marine biodiversity, with the majority of studies reporting positive outcomes such as increased species abundance and richness compared to traditional, unmodified structures. However, results varied notably by climate zone, infrastructure type, and intervention approach, indicating the importance of context-specific design considerations. Taken together, the evidence supports eco-engineering as an effective biodiversity tool, while underscoring that effectiveness is contingent on local setting, structure, and design. The following discussion explores key insights derived from these findings, highlighting factors influencing the effectiveness of eco-engineering strategies, research gaps identified across regions and habitats, and recommendations for future eco-engineering initiatives aimed at optimizing ecological outcomes in urbanised coastal environments.

### 4.1. Eco-engineered retrofit categories

The dominance of retrofitting eco-engineering designs, as a more nature positive solution to existing and new marine infrastructures like seawalls and breakwaters highlights a shifting desire toward living shorelines globally (Dugan et al., 2011). Focusing on retrofits is also pragmatic: it enables low-cost, low-disruption trials on assets already due for maintenance and provides near-term biodiversity gains without wholesale rebuilds. This emphasis on retrofitting is reflected in the intervention mix: microhabitat additions—textured panels, transplants, rockpools, and pits/crevices—collectively comprised ~75 % of all applications and delivered consistently positive biodiversity responses across climate zones, whereas more structurally intensive or hybrid designs remain under-tested (<5 % each).

The category of artificial rockpools was implemented across all three climate zones—Tropical, Subtropical, and Temperate, and consistently increased species abundance and richness, resulting in success in all studies, regardless of design or location. Notably, Bishop et al. (2022) highlighted among various artificial textured panel category designs, rockpool panels demonstrated some of the best outcomes in terms of species richness. However, long-term monitoring remains essential, as rockpools in low-energy and sheltered areas may be prone to sand accumulation and sedimentation, potentially limiting their effectiveness over time (Firth et al., 2016). Also, the significant variation in the performance of artificial textured panels across different latitudes underscores the necessity of adapting eco-engineering practices to local anthropogenic factors. This diversity in effectiveness is highlighted by Strain et al. (2021) as part of the World Harbour Project, which underscores that “one size does not fit all” in eco-engineering practices. Furthermore, 3D printing technology was mainly used in fabricating these panels, and while innovative, it introduces additional complexities. Scaling these technologies to meet large-scale production demands faces significant hurdles, particularly in maintaining competitive costs. This highlights a critical gap between technological advancements and practical application in eco-engineering, stressing the need for continued innovation and economic feasibility assessments to enhance the scalability and effectiveness of such interventions (Iftekar et al., 2023).

Combined interventions also showed promise. The creation of artificial textured panels formed from enhanced concrete that integrates biomaterials with conventional concrete, thereby fostering conditions that are more favourable for benthic communities. Products such as ECOncrete have been shown to significantly enhance ecological functionality by supporting the formation of benthic habitats while having a lower carbon climate cost (Perkol-Finkel et al., 2019). Additionally, the transplantation of artificial textured panels was tested across various latitudes, with most studies reporting successful outcomes in enhancing transplanted species and their associated communities. However, varied outcomes were observed, such as those reported in a study from Penang Harbour, Malaysia, where the results were less favourable (Chee et al., 2021). These discrepancies underline the importance of context-specific research to fully understand and optimise the benefits of eco-engineering solutions.

The systematic search also identified two systematic reviews that examined the influence of material type on benthic assemblages. Both reviews concluded that rocky substrates, followed by concrete, support the highest abundance within the overall benthic community (Dodds et al., 2022; Grasselli et al., 2024). However, other studies presented nuanced findings. For example, gabbro (coarse-grained, intrusive igneous rock) was found to promote higher coral recruitment on breakwaters compared to concrete (Burt et al., 2009). In contrast, a study reported no significant differences in recruitment among concrete, granite, limestone, and sandstone (Hartanto et al., 2022).

Finally, a widely successful and cost-effective intervention involved creating pits, grooves, and crevices on existing structures. All studies reported increased species abundance or richness in modified structures compared to unmodified ones. Despite being one of the most straightforward and most affordable eco-engineering approaches, this method requires careful evaluation from an engineering perspective. Increasing the number of holes and crevices on existing structures may compromise their structural integrity and pose risks to their durability and functionality.

### 4.2. Eco-engineered constructed categories

The constructed category of eco-engineering interventions differs notably from retrofitting as it involves integration during the initial construction phase of coastal infrastructure, is implemented as standalone units such as fish houses, or involves complete structural modifications, upgrades, or even removals of existing structures like living shorelines. Similar to retrofit categories, interventions such as pits, grooves, and crevices and artificial rockpools can be incorporated into the design of coastal structures, including breakwaters and seawalls, during the construction phase. These interventions have consistently demonstrated success in enhancing species abundance and richness. When implemented at the design stage or during structural upgrades, this cost-effective solution eliminates the risk of compromising structural integrity, a concern that often arises when such modifications are applied to existing infrastructure.

Another approach involves upgrading structures while incorporating eco-engineering principles. A prime example is the Seattle seawall upgrade, where a combination of increased light, reduced infrastructure (e.g., pier pilings), enhanced texture, and a shallower seafloor significantly improved habitat functionality for juvenile salmonids, adding only about 2 % to the overall project budget (Accola et al., 2022). Additional structure upgrades could include light-transmitting designs integrated into existing structures to enhance light availability for benthic communities and seagrasses. Similarly, habitat enhancement units, either incorporated within existing structures as modifications or implemented as standalone larger units, have shown promising results. For example, companies like ECOncrete have successfully achieved ecological improvements through such approaches, demonstrating their potential in enhancing marine biodiversity and the functionality of artificial structures.

Several eco-engineering approaches beyond commonly used interventions also hold promise for enhancing ecological outcomes within urbanised marine environments. Artificial reefs and fish houses, typically utilised to restore coral reefs and support fish communities in natural settings, have shown significant success even within urbanised seascapes, particularly marinas, by effectively enhancing local fish assemblages and potentially benefiting fisheries (Komyakova et al., 2019; Patranella et al., 2017; Scyphers et al., 2015). Similarly, the living shoreline approach, predominantly applied in sheltered areas like Puget Sound and Chesapeake Bay in the United States, aligns closely with natural habitat restoration strategies. While effective, its use remains restricted to low-energy environments, limiting applicability in more exposed, high-energy areas. Nevertheless, integrating natural materials within coastal defence structures is recommended wherever feasible to simultaneously protect shorelines and enhance local habitats. Additionally, offset areas—habitats restored adjacent to impacted locations—have demonstrated effectiveness in compensating for environmental losses, as successfully implemented in Puget Sound, USA (Cheney et al., 1994; Toft et al., 2013), underscoring their potential as valuable strategies in urban ecological restoration efforts. Given these varied but context-dependent outcomes, future eco-engineering research should prioritise evaluating and adapting these promising methods across diverse geographical and environmental contexts to optimise their ecological benefits.

### 4.3. Research location

Tropical zones are particularly vulnerable to severe weather events, such as tropical cyclones (Seneviratne et al., 2021). This vulnerability has prompted the construction of defence structures like seawalls and breakwaters in an attempt to assist with coastal protection. Despite this, tropical zones reported the fewest eco-engineering interventions, with only 23 studies. Notably, 11 of these were conducted in Singapore, leaving significant regions such as tropical Africa, the Arabian Peninsula, and much of South America largely unexplored. For example, only two studies were conducted in Brazil, two in Tropical Australia (Townsville), and one in India. This scarcity of studies highlights the urgent need for more research to evaluate the applicability of eco-engineering interventions in tropical zones, as most trials have been concentrated in subtropical and temperate regions.

This global imbalance indicates that eco-engineering research remains heavily skewed toward high-income, temperate countries, where technical capacity, funding, and established infrastructure facilitate experimental trials. By contrast, data from tropical developing nations—where coastal vulnerability is often greatest—remain sparse, limiting understanding of ecological performance under different climatic, hydrodynamic, and socio-economic conditions. Designs optimised in temperate zones may not translate effectively to tropical environments, where bioerosion, recruitment dynamics, and algal overgrowth differ significantly. Expanding field-based research in tropical regions is therefore critical to establish transferable eco-engineering frameworks suited to diverse coastal settings.

As climate change intensifies and sea levels continue to rise, coastal cities increasingly face flood risks. In response, the construction of coastal defence structures has become more prevalent (Bisaro et al., 2024). For example, European coastal cities on the Mediterranean have proactively incorporated eco-engineering, with Europe reporting the most eco-engineering studies as a continent. These initiatives are integrated alongside defences to mitigate environmental impacts and enhance ecological resilience. However, across the entire continent of Africa, only two eco-engineering studies have been reported—one in South Africa and one in Morocco. This stark contrast underlines a critical need for African nations to integrate eco-engineering efforts with their expanding coastal defences to better cope with the challenges posed by climate change.

Such regional disparities also raise concerns about equity in global coastal adaptation strategies. Tropical and subtropical regions face accelerating coastal development and population growth, yet tropical regions remain underrepresented in eco-engineering literature. Bridging this knowledge divide requires coordinated international research programs, cross-disciplinary collaboration, and inclusion of local ecological and engineering expertise to ensure context-appropriate designs that enhance both biodiversity and resilience.

The distribution of eco-engineering studies in the countries with the most reported eco-engineering studies, like Australia and the United States, reveals significant regional disparities in research focus. In Australia, for instance, 21 studies were concentrated in Sydney, leaving other major regions underrepresented. Similarly, in the United States, the bulk of research was in the Northwestern and Northeastern regions, such as Puget Sound and Chesapeake Bay, with other areas receiving scant attention. In contrast, countries like the UK and Singapore exhibited more uniform coverage of eco-engineering studies across their coasts.

When analysing types of eco-engineering interventions by region, Australia primarily focused on artificial textured panels and artificial rockpools, while the United States also prioritised artificial textured panels but emphasised additional categories like living shorelines, oyster breakwater reefs, and offset areas. These trends suggest that eco-engineering studies are concentrated in specific regions, with unique intervention preferences in each location. This regional specialisation not only constrains generalisation of findings but also highlights the need for comparative, cross-regional analyses to evaluate which interventions perform consistently across environmental contexts. Developing such synthesis is essential to support global guidance on scalable, climate-resilient eco-engineering applications.

### 4.4. Artificial structures

Most studies evaluate the effectiveness of eco-engineering interventions in enhancing biodiversity through the implementation of new designs. However, only a few studies have examined the application of these initiatives across multiple structural types within a single study to assess their effectiveness comprehensively. For instance, Paalvast et al. (2012) tested a similar eco-engineering design on both pilings and pontoons, with both structures demonstrating positive outcomes in increased biodiversity. Similarly, Adams et al. (2021) applied eco-engineering interventions to three structures: pilings, pontoons, and breakwaters. However, it was found that the highest richness of taxa was supported by the eco-engineered pontoons compared to pilings and breakwaters. There is a need for further research that compares similar designs across different structures to determine the most favourable designs for stakeholders. For example, a port manager often has various options like dykes, berths, pontoons, breakwaters, and pilings. Therefore, understanding the effectiveness of different designs across these structures could be invaluable for making informed decisions about which eco-engineering solutions to implement.

### 4.5. Targeted species

General benthic assemblages often serve as the primary focus in eco-engineering interventions, without a specific emphasis on species. To ensure the success of these initiatives, it is crucial to conduct baseline studies that identify the species present in the surrounding environment. Understanding the habitat preferences and ecological requirements of these species allows for the design of eco-engineering structures that support the colonization of the targeted communities. Key factors such as habitat complexity, surface roughness, exposure time for sensitive species, shelter, and light conditions can be carefully manipulated to enhance ecological outcomes. Given the complex nature of these interventions, further research is essential to refine our approaches and maximize the ecological benefits of eco-engineering efforts. This will enable more informed decisions that align with the specific ecological dynamics of each site, ensuring that the interventions promote biodiversity and ecological health effectively.

### 4.6. Invasive species

The effectiveness of eco-engineering initiatives in controlling invasive species can be questionable. Although 143 out of 160 studies reported successful outcomes in terms of species richness and abundance, 135 studies overlooked the investigation of invasive species presence. This gap may be attributed to the high costs associated with advanced techniques such as environmental DNA (eDNA) analysis, which is essential for identifying invasive species. Moreover, ships arriving from diverse environments often act as vectors for non-indigenous species, introducing them via ballast water and hull fouling, thereby increasing the likelihood of urban seascapes such as ports to host invasive organisms (Mineur et al., 2012).

This lack of investigation raises concerns about the results, as certain eco-engineering interventions might inadvertently facilitate the proliferation of invasive species. For instance, Schaefer et al. (2023b) demonstrated that specific material types and habitat complexities could encourage dominant invasive species to colonise artificial structures. Notably, two studies from this systematic review, conducted in France, found that Artificial Turfs on pontoons and pylons facilitated the establishment of invasive species. On a positive note, increasing reviews and studies are focusing on the role of eco-engineering in either mitigating or inadvertently supporting invasive species, offering valuable insights for future research and practice (Dafforn, 2017; Schaefer et al., 2024).

### 4.7. Establishing baselines and ensuring long-term monitoring

The majority of studies in this systematic review did not incorporate baseline research, which is a critical step in designing effective eco-engineering interventions. Evans et al. (2021) recently proposed a five-step framework emphasising the importance of baseline studies. This process begins with site-specific baseline surveys, including the collection of biological and topographical data, to understand the environmental conditions and target species. The subsequent steps—design, application, and monitoring—are then informed by this foundational knowledge. This method ensures that interventions are tailored to specific site conditions rather than being implemented with limited planning and relying on a chance for positive outcomes.

Furthermore, over 68 % of the eco-engineering intervention surveys lasted less than a year. This limited duration is concerning, as seasonal changes and community succession could significantly alter outcomes over time. For instance, while some interventions initially promoted benthic assemblages, the benefits were negated when a sheltered site was eventually filled with sand after two years (Firth et al., 2016). These findings highlight the importance of both baseline studies and long-term monitoring to comprehensively assess the sustainability and effectiveness of eco-engineering interventions.

### 4.8. Key insights, gaps, and implications

Most applied interventions—especially simple microhabitat additions (textured panels, rockpools, pits/crevices, targeted transplants)—consistently improved richness/abundance across structure types and climate zones, with strongest evidence on seawalls and breakwaters. Evidence remains geographically and thematically uneven: studies cluster in a few high-income regions, intertidal settings dominate, and invasive-species responses are rarely assessed, limiting transferability to tropical, high-energy, and data-poor coastlines. Core practical gaps are the absence of site baselines, short survey horizons, and sparse reporting of cost/maintenance, which together constrain synthesis and scalability. Where relevant to adoption, we note that ecological outcomes are seldom paired with basic asset-relevant observations; future trials should add light-touch performance co-metrics without shifting the emphasis away from biodiversity.

Linking ecological gains to engineering performance. A consistent limitation across the corpus is that few applied studies co-report hydraulic metrics relevant to design (e.g., overtopping, runup, reflection, roughness changes) alongside biodiversity outcomes, and almost none benchmark against probabilistic performance targets or extreme-event behaviour. Without shifting emphasis away from ecological responses, we note that this disconnect hinders uptake in engineering practice, where adoption decisions depend on both ecological benefit and asset-level performance, reliability, and maintenance. Accordingly, we recommend co-designing monitoring to add a small set of standardised observations (and, where feasible, datasets suitable to calibrate predictive models) so that eco-enhancements can be represented in design tools and guidance without burdening ecological studies.

Geographic skew further limits generalisation: about two-thirds of interventions come from four countries, while many tropical nations have zero or a single trial. This matters because ecological processes, bioerosion rates, recruitment dynamics, and algal overgrowth differ markedly across climate zones. Tropical Africa, much of South America, the Arabian Peninsula, and many SIDS remain under-tested; even in well-studied nations, activity clusters around a few hubs (e.g., Sydney; Puget/Chesapeake). Closing these gaps requires targeted expansion into the tropics and data-poor coastlines, with replication across hydrodynamic regimes, materials, and structure types to derive ecology-led transfer functions usable by practitioners.

Practical lessons indicate near-term adoption pathways. Simple retrofits—textured panels, rockpools, pits/crevices, targeted transplants—consistently boost richness/abundance on seawalls and breakwaters and are cost-efficient, provided they are paired with site baselines and invasive-species screening. Living shorelines and oyster reefs perform well in low-energy settings; in higher-energy sites, hybrid designs (e.g., armour units with eco-texture, light-penetrating elements) can secure ecological gains without compromising structural integrity. Light-transmitting upgrades and pier de-densification improve juvenile fish passage in working waterfronts, while 3D-printed units offer design flexibility but face cost and production bottlenecks that warrant durability and lifecycle testing.

To move from promising pilots to decision-grade practice, priorities are: multi-site, replicated trials of under-represented Nature-based-Solutions NbS categories in priority regions; a minimum reporting set (asset context, baseline methods, monitoring duration/frequency, materials/specs, inspection/maintenance plans, unit costs where feasible) to enable meta-analysis; and co-measurement of ecological, engineering, and socio-economic metrics to inform asset-level design. Region-specific steps include establishing tropical demonstration corridors (e.g., port/marina networks) with shared protocols; embedding NbS options in national design manuals and permit pathways; blended finance (public works + climate funds + private concessionaires) to de-risk first-of-kind deployments; and capacity building with local agencies and Small and Medium Enterprises SMEs for fabrication, installation, and monitoring.

Finally, risk management should be mainstreamed: routine biosecurity checks (including eDNA where feasible), shading/sediment-infill assessments, and post-storm inspections tied to adaptive maintenance. Addressing these gaps—through longer BACI (Before–After–Control–Impact) based monitoring, co-reporting of performance and cost, and targeted regional expansion—will convert a fragmented portfolio into an actionable, scalable evidence base for nature-positive, engineering-credible coastal resilience.

## 5. Conclusions, limitations, and future directions

### 5.1. Key findings

Across 160 applied interventions from 128 studies, eco-engineering consistently enhanced biodiversity in urbanised seascapes (143/160; 89 % positive outcomes). Simple, low-cost microhabitat retrofits—textured panels, rockpools, pits/crevices, targeted transplants—comprised ~75 % of applications and delivered the most reliable gains across climate zones, particularly on seawalls and breakwaters. However, some penetrative treatments (e.g., drilled voids or deep grooves) can compromise structural health (e.g., saltwater ingress, reinforcement corrosion, stress concentrations). Therefore, integrating the engineering dimension is essential. Meanwhile, intervention classes with direct relevance to protection design (living shorelines/oyster reefs, light-penetrating surfaces, geosynthetic/gabion systems, modular habitat units) are under-tested (<5 % each), limiting conclusions on scalability, maintenance, and longevity. Evidence is also geographically skewed (two-thirds from four countries), intertidally biased (~69 % of studies), and rarely assesses invasive species (84 % no assessment). Crucially for engineering uptake, few field trials co-report hydraulic or asset-level performance (overtopping, runup, reflection, roughness, durability/failure modes), constraining integration into design guidance and lifecycle planning. Microhabitat additions on working defences can be effective but must be treated as engineered alterations to avoid compromising structural health (e.g., permeability, corrosion, stress concentrations).

### 5.2. Study limitations

This review intentionally focuses on field implementations and excludes laboratory/model-only studies, so some hydraulic/structural insights from controlled settings are not captured. Heterogeneous reporting (metrics, baselines, variance, durations) precluded a full meta-analysis and required descriptive statistics; publication bias toward positive findings may persist. Cost, O&M and embodied-carbon data were sparse; mixed-intervention designs and inconsistent area/replicate reporting limit dose–response and spatial scaling inferences. Regional representation may also reflect language and availability biases.

### 5.3. Directions for future research and adoption

1. **Co-measurement for engineering uptake:** Pair biodiversity metrics with standardised hydraulic/structural indicators (overtopping/runup, reflection/roughness proxies, durability/failure modes, inspection cycles) and report unit costs; where feasible, release datasets suitable for calibrating predictive/ML models.
2. **Stronger designs, longer horizons:** Implement BACI/gradient designs with replication and variance reporting; include pre-intervention baselines and monitor >12 months to capture seasonality, extreme events, and maintenance cycles.
3. **Site-specific, safe deployment:** Match interventions to tidal regime, latitude, species pools, and stressors; in high-energy sites favour hybrid or bolted/modular units and light-transmitting elements over penetrative drilling; treat retrofits as structural modifications with pre-check analyses and inspection plans.
4. **Nature-based siting rules:** Use living shorelines/oyster reefs primarily in low-energy settings; deploy hybrid eco-textured armour where soft options are infeasible.
5. **Materials and practical innovation:** Advance eco-enhancing/low-permeability concretes, recycled aggregates, and 3D-printed modules; report durability, inspections, and whole-life performance.
6. **Biosecurity and unintended effects:** Embed routine invasive-species surveillance (eDNA where feasible) and track shading, sediment infill, debris entrapment, and predator aggregation with predefined mitigation.
7. **Scalability, cost, and comparability:** Document footprint/volume, installation logistics, O&M/inspection plans, and embodied carbon; adopt a minimum reporting set (asset context, baselines, monitoring frequency/duration, materials/specs, ecological + hydraulic indicators, costs).
8. **Geographic expansion:** Prioritise underrepresented regions (e.g., tropical Africa, the Arabian Peninsula, much of South America, and SIDS); establish multi-site “demonstration corridors” (port/marina networks) with shared protocols across hydrodynamic regimes and structure types.

**Bottom line:** Eco-engineering is a viable and potentially scalable pathway to nature-positive coastal infrastructure—particularly via targeted retrofits—but wider adoption within resilience schemes hinges on joint reporting of ecological and engineering performance (including hydraulic and structural indicators), extension of monitoring beyond one year, and deliberate expansion across under-represented regions and intervention types to generate decision-grade guidance.

## Declaration of generative AI and AI-assisted technologies

During the preparation of this work the authors used ChatGPT in order to improve the readability and language of the manuscript. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

## CRediT authorship contribution statement

**Ahmed K. Gad:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Michael A. Rasheed:** Validation, Supervision, Project administration, Funding acquisition. **Paula J. Cartwright:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration. **Nathan J. Waltham:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: (Nathan J. Waltham reports a relationship with North Queensland Bulk Ports that includes: funding grants. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.)

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## Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoleng.2025.107855.

## Data availability

Data will be made available on request.

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