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Marine Bioinvasions Facilitated by Artificial Structures: Implications for Biodiversity and Sustainable Infrastructure Design

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Abstract

The development of artificial structures, offshore platforms, ports, and artificial reefs has significantly altered marine ecosystems, inadvertently facilitating marine bioinvasions. These structures provide settlement substrates and refugia for invasive species (NIS), accelerating their dissemination through ballast water, hull fouling, and biofouling communities. Bioinvasions disrupt indigenous biodiversity, alter trophic interactions, and threaten ecosystem stability. They also generate socio-economic expenses for fisheries, aquaculture, tourism, and infrastructure maintenance. Notable gaps in knowledge, particularly about long-term ecosystem alteration and local management practices, are highlighted by the findings. Mitigation needs multi-disciplinary answers in terms of ecological engineering, biosecurity policies, and policy measures. Antifouling surfaces and bioinvasion-proof adaptations represent design solutions that offer hope toward sustainable infrastructure. Marine infrastructure construction has to be harmonized with the conservation of biodiversity. Management must be based on international cooperation, new monitoring approaches, and adaptive policies to reduce NIS establishment. Integrated ecological modeling, stakeholder engagement, and technology-based monitoring need to be prioritized in future research to ensure maximum prevention and mitigation of bioinvasion.

1. Introduction

Marine invasive species succeed through adaptive traits, ecological flexibility, and human-mediated dispersal, posing major threats to global biodiversity conservation. The increasing development of human-made structures in marine environments has modified seascapes and reorganized ecological interactions (Todd et al., 2019). Although such structures, e.g., ports, offshore platforms, breakwaters, and artificial reefs, have been constructed to serve economic and coastal development, they have also inadvertently facilitated the spread of marine bioinvasions (Johnston et al., 2017). Through the provision of new habitats and settlement surfaces, artificial structures create hotspots for invasive species, allowing them to spread and become established in ecosystems where they were not originally present (Firth et al., 2021). These anthropogenic features alter natural habitats by providing hard substrates that facilitate colonization by marine organisms, including NIS (Bulleri & Airoldi, 2005; Castro et al., 2022; Schaefer et al., 2024). While artificial structures are often developed to support economic activities such as shipping, energy production, and tourism, they accidentally act as channels for biological invasions, enabling the spread of invasive species that can outcompete native biota, disrupt trophic interactions, and compromise ecosystem stability (FrédéricMineur et al., 2012; Glasby et al., 2007). Artificial structures function as ecological stepping stones that enable invasive species to expand into previously unoccupied coastal and marine habitats (Airoldi et al., 2015; Coolen et al., 2020). Several case studies have shown that artificial structures facilitate the rapid dispersal of invasive species, such as the tubeworm *Hydroides elegans*, *Hydroides sanctaecrucis*; oyster *Magallana angulata*, barnacle *Amphibalanus amphitrite, Austrominius modestus;* green alga, *Codium fragile spp. tomentosoides*) (Bulleri et al., 2006; Bulleri and Airoldi, 2005). These structures have the potential to act as the primary front for invasive species, which can lead to further proliferation into nearby natural ecosystems (Dumont et al., 2011).

The mechanisms in which these structures enhance bioinvasions are complex. First, these structures act as central hubs for maritime transport where these species are transferred via ballast water, hull fouling, or floating debris (Castro et al., 2022; FrédéricMineur et al., 2012; Giesler and Cottier-Cook, 2021). Second, these structures act as refugia, which protects invasive species from environmental stressors like, wave action and sedimentation, allowing the development of self-sustaining populations (Boon et al., 2023; Bulleri & Airoldi, 2005; FrédéricMineur et al., 2012). Finally, these structures can also cause "invasional meltdown", where one invasive species facilitates other invasive species through modification of the habitat or mutualistic interactions (Cavieres, 2021; Kuebbing, 2020). In particular, invasive oysters and mussels form biogenic reefs on artificial hard substrates and promote the settlement of additional invasive species (Reise et al., 2017). The physical characteristics of the artificial structures also plays an important role in bioinvasions. In contrast to natural habitats, artificial habitats usually contain complex three-dimensional (3D) topographies with varying degrees of predation (Monfort et al., 2021). These constructions often have vertically or overhanging surfaces (Schaefer et al., 2024), which is further unfavourable for native species that had adapted to horizontal or sloping environments, reinforcing the prevalence of invasive species. Artificial structures also foster biofouling communities, which can render optimal conditions for sessile invasive species and facilitate their colonization and expansion.

The introduction of filter feeders can greatly increase the rate of water filtration, resulting in the alteration of nutrient cycles (Jansen et al., 2019). This increase in filtration leads to changes in the whole ecosystem, including primary production and food web dynamics (Ozersky et al., 2012; Zhang et al., 2019). Invasive predatory species also can generate trophic cascades by lowering native prey populations, resulting in additional imbalances within marine ecosystems (Ebere et al., 2021). Moreover, bioinvasions generated by artificial structures may result in genetic uniformity, lowering the genetic variety of indigenous species and rendering ecosystems more sensitive to environmental changes (Leclerc et al., 2020). Beyond ecological consequences, invasive species within artificial substrate habitats severely disrupt economic and recreational activity (Lovell et al., 2006; Mayfield et al., 2021). Biofouling on vessels increases maintenance costs, hinders navigation, and obstructs maritime activity (Hadžić et al., 2022; Weber & Esmaeili, 2023). Similarly, invasive species can diminish fishing catches by competing with indigenous species for resources or by altering marine ecological equilibrium (Crăciun et al., 2025). The economic effects are seen in the decline of revenues from tourism caused by the overgrowth of invasive species, which lowers the aesthetic value of the seabed and prevents diving and coastal tourism (Hardiman and Burgin, 2010; Lovell et al., 2006). Moreover, artificial habitats can facilitate disease transmission by providing dense biofouling communities and shared surfaces where pathogens and parasites can easily spread among marine organisms. Such conditions pose significant challenges to biodiversity and the aquaculture sector. Such diseases can destroy a mass of valuable species and sabotage ecological systems, stressing the need for corrective measures in management (Behringer et al., 2020; Costello et al., 2021).

Although awareness of the issue is increasing, there remain important knowledge gaps in understanding how artificial structures promote the introduction and spread of invasive marine species. The lack of

standardized monitoring methods and effective mitigation measures further worsens the challenges of management efforts. Given these concerns, this review aims to address a central question: what are the existing knowledge gaps concerning (i) the ecological effects of artificial structures, (ii) their role in facilitating the invasion process, and (iii) the management strategies required to mitigate these impacts? To answer this, the review systematically examines how artificial structures act as channels for biological invasions, explores their ecological and conservation consequences, and highlights policy and management approaches to reduce bioinvasion risks.

2. Methodology

This review adopts a narrative and integrative approach to examine the role of artificial marine structures in facilitating marine bioinvasions and their subsequent ecological implications. The selection of studies was guided by relevance, thematic focus, and scientific rigor, emphasizing peer-reviewed literature published between 2015 to 2025.

2.1 Literature Sources and Search Strategy

Relevant literature was identified through a broad-based search of multiple scientific databases, including Web of Science, Scopus, and PubMed. The search was supplemented with grey literature and key institutional reports when necessary. Keyword combinations were employed using Boolean operators to maximize coverage. The main search terms included:

("artificial structures" OR "man-made structures" OR "marine infrastructure" OR "offshore platforms" OR "ports" OR "coastal defenses") AND ("marine bioinvasions" OR "invasive species" OR "invasive species" OR "biological invasions") AND ("biodiversity conservation" OR "ecosystem sustainability" OR "ecological impact")

The search was limited to studies published in English and focused on marine or estuarine environments. To ensure comprehensiveness, reference lists of key studies were also manually screened for additional relevant publications.

2.2 Selection Criteria

Studies were included based on the following considerations (Fig. 1):

- Focus on artificial marine structures such as ports, marinas, breakwaters, oil and gas platforms, artificial reefs, or floating installations.
- Discussion of the presence, colonization, or spread of invasive marine species associated with such structures.
- Description of ecological outcomes, such as changes in native biodiversity, trophic interactions, or ecosystem function.

- Consideration of management strategies, such as mitigation, restoration, or biosecurity interventions.

Studies were excluded if they: (1) focused solely on freshwater systems; (2) did not specifically address invasive or invasive species; (3) were commentaries, short communications, or lacked primary data or critical discussion.

2.3 Data Collection and Analysis Approach

Relevant information from selected studies was qualitatively synthesized. The following thematic areas were explored:

- Types of artificial structures and their spatial distribution.
- Taxonomic groups and functional traits of invasive species.
- Environmental conditions influencing invasions (e.g., temperature, salinity, and disturbance).
- Documented or predicted ecological impacts on marine biodiversity and habitats.
- Proposed or evaluated management responses, including policy implications and technological interventions.

Where applicable, comparative insights were drawn across structure types, species groups, and geographic regions to highlight emerging patterns and research gaps. This integrative review aims to provide a cohesive understanding of the pathways, risks, and responses related to marine bioinvasions mediated by human-made coastal and offshore structures.

3. Types of Artificial Structures

Globalization is a defining feature of the 21st century (Ehrenfeld, 2010), and with it has come a dramatic increase in marine trade. This surge in maritime activity has facilitated the global spread of marine species beyond their native habitats, and the trend shows no signs of slowing (De Beukelaer, 2014). A primary mechanism of this species redistribution is vessel-based transport, particularly through ballast water discharge and hull fouling (Hewitt & Campbell, 2007; Hewitt et al., 2009; Seebens et al., 2016; O'Brien et al., 2017).

Intra-coastal shipping, the movement of domestic cargo ships, recreational boats, and other small vessels, also plays a significant role in the regional spread of invasive species. These vessels often transport organisms from major ports to smaller marinas or harbours (Forrest et al., 2009; Hänfling et al., 2011). Major ports, which handle over one million tonnes of cargo annually, such as San Francisco and Los Angeles, have been shown to harbour significantly higher densities of invasive species (Foss et al., 2007). These ports serve as gateways not only for trade but also for biological invasions, driven by high propagule pressure from frequent international arrivals and short vessel turnaround times (Hopkins et al., 2021). Invasive marine species often possess life-history traits that enhance their invasive potential—such as rapid growth, early maturity, high reproductive output, and broad environmental tolerances (Piola

& Johnston, 2008; Crooks et al., 2011). Their adaptability allows them to thrive in degraded coastal environments, where they can outcompete native species, particularly when pollution levels are high. Studies indicate that invasive species are often more tolerant to pollutants, including heavy metals and turbidity (Johnston & Keough, 2002; Marraffini & Geller, 2015).

Artificial structures such as ports and offshore platforms often exhibit lower native biodiversity, creating ecological 'openings' that allow invasive species to establish with minimal resistance. This pattern is explained not only by the Enemy Release Hypothesis, which proposes that invaders face fewer natural predators and competitors in their introduced ranges, but also by the greater physiological tolerance of many invasive species to environmental stressors. Species such as ascidians have shown high resilience to pollution, temperature fluctuations, and salinity changes, enabling them to thrive in the disturbed and variable conditions typical of artificial marine environments (Zhan et al., 2015; Shea & Chesson, 2002; Bulleri & Airoldi, 2005; Ruiz et al., 2009; Dafforn et al., 2012).

3.1 Offshore Energy Platforms and Marine Structures

The offshore oil, gas, and renewable energy sectors have added a new layer to the issue of marine invasions. Offshore structures are prone to biofouling by sessile organisms, which can affect structural integrity, increase hydrodynamic drag, and impair cooling systems used in energy production (Glasby et al., 2007; Petes et al., 2008). These structures also act as vectors for transoceanic species transfer, particularly when constructed in one region and deployed in another. Moreover, frequent marine traffic among existing structures—such as supply vessels, maintenance ships, and service barges—facilitates the secondary spread of fouling organisms and invasive species across regional networks of installations. The proliferation of Offshore Wind Farms (OWFs) has added complexity to marine ecosystems. Submerged turbine bases function like artificial reefs, providing hard substrates for colonization by marine organisms and altering local habitats (Dannheim et al., 2020). These changes can enhance local biodiversity, including rare or threatened species, but also facilitate the spread of invasive species. Suspension feeders on these structures modify the flow of organic matter by removing living particles from the water column and depositing nutrient-rich (pseudo) faeces onto the seabed (Slavik et al., 2019; Coates et al., 2014; Lefaible et al., 2019).

Although beneficial to some species, these artificial reefs also alter ecosystem functioning. Increased organic matter deposition can affect sediment chemistry and infaunal communities. Meanwhile, warming and ocean acidification pose additional stressors, altering predator-prey dynamics and nutrient cycling in both benthic and pelagic systems (Queirós et al., 2015; Braeckman et al., 2014; Draper & Weissburg, 2019). Thus, understanding artificial reef impacts requires an integrative approach that includes food web modeling, stable isotope analysis, and nutrient cycling studies.

3.2 Aquaculture as a Vector for Invasive Species

Aquaculture has historically been a major vector for the introduction of invasive species (Carlton & Mann, 1996; Naylor et al., 2001; Ruesink et al., 2005). While aquaculture supports livelihoods and

economies in many coastal areas, the unintentional movement of associated species—including parasites, pathogens, algae, and biofouling organisms—has posed significant ecological risks (Carlton, 1996; Minchin, 2007). Unlike ballast water introductions, aquaculture-related invasions are often less studied but can be more successful, as species are deliberately introduced for cultivation in environments similar to their native range. These introduced species are typically selected for their resilience, rapid growth, and high yield, characteristics that also enhance their invasive potential.

Recent shifts toward the importation of larvae and juveniles have reduced the risk of unintentional introductions, but the ecological consequences remain significant. Impacts include reduced abundance and altered demographics of native species, and changes in community structure, often to the detriment of local biodiversity (Minchin et al., 2009; Miller et al., 2011; Ruiz et al., 2013). To mitigate these risks, global guidelines like the ICES Code of Practice have been developed to manage the movement of species for aquaculture purposes (ICES, 2005). However, enforcement and compliance remain challenges in many regions.

4. Ecological and Conservation Implications

The global increase in anthropogenic activities has profoundly transformed previously undisturbed marine and estuarine environments into human-modified habitats characterized by artificial structures such as pontoons, jetties, breakwaters, boating marinas, and commercial ports (Dugan et al., 2011). These man-made infrastructures often possess physical characteristics that diverge significantly from natural systems (Airoldi et al., 2005, 2009; Airoldi & Beck, 2007), resulting in environmental novelty and the creation of new artificial habitats (Glasby & Connell, 1999).

Coastal urban development and the construction of maritime infrastructure often alter local water dynamics, reducing circulation and increasing the accumulation of silt, nutrients, and pollutants (Johnston et al., 2011; Rivero et al., 2013). These changes can create favorable conditions for invasive species (NIS), which tend to colonize artificial structures more readily due to differences in substrate composition and habitat features. However, some studies contrast this trend, noting that natural reefs may sometimes harbor greater NIS abundance than artificial ones (Bumbeer & Rocha, 2016).

Artificial structures alter biodiversity and food web dynamics, often providing convenient footholds for invasive species that displace native species and disrupt trophic interactions. These disruptions can even lead to localized species extinctions. Several biotic and abiotic factors influence NIS establishment and success. Ecological interactions such as competition, facilitation, predation, and disease, as well as environmental conditions like temperature and salinity, can act synergistically to promote the ecological dominance of invasive species (Castilla et al., 2004). Hybridization between NIS and native species further threatens biodiversity by diminishing genetic diversity and ecosystem resilience. In some cases, invasive species can exacerbate other environmental problems. For example, certain bioinvaders contribute to harmful algal blooms or disrupt marine food chains by altering species interactions.

To mitigate these risks, ecologically informed strategies must be applied in the design, construction, and maintenance of artificial marine structures. Construction projects should account for the recruitment patterns of NIS and prioritize materials and designs that reduce their colonization potential. For instance, using natural substrates such as sandstone instead of concrete or wood can reduce NIS richness by approximately 30% (Glasby et al., 2007). Innovative materials like ECOncrete, fixed rather than floating structures, reduced shading, and limiting metal contaminants can also help minimize invasive colonization. Ongoing maintenance offers further opportunities for NIS control. Strategic timing of maintenance to avoid resource availability during peak reproductive periods of NIS can be effective (Airoldi & Bulleri, 2011). Additionally, enhancing biofilms that support native species or creating habitats with gentle gradients and connections to the benthos may promote native predator presence and resilience (Sella & Perkol-Finkel, 2015; Bishop et al., in press). Ultimately, a balanced approach that integrates conservation planning, biosecurity, and eco-engineering is essential to reduce the ecological impacts of artificial structures while supporting critical infrastructure needs.

4.1 Impacts on Biodiversity

Invasive species significantly disrupt native ecosystems by outcompeting, preying upon, hybridizing with, or introducing diseases to native species—often resulting in biodiversity loss and considerable economic costs (Bax et al., 2003; Pejchar & Mooney, 2009). Once established, NIS are difficult to remove and often become self-perpetuating.

One widely studied example is the invasion of Indo-Pacific lionfish (*Pterois volitans* and *Pterois miles*), which have wreaked ecological havoc in the Caribbean and Gulf of Mexico (Whitaker & Janosik, 2020; Green & Grosholz, 2021). Artificial structures provide rigid surfaces ideal for colonization, facilitating the spread of species like *Ascidia aspersa* and *Ciona robusta* in the Nuevo Gulf, where they compete with native organisms and alter resource dynamics (Tatian et al., 2010; Schwindt et al., 2014). Seasonal recruitment peaks of sessile organisms further increase invasion risks (Giachetti et al., 2019). Aquaculture systems are also affected by biofouling from invasive species that colonize machinery or outcompete bivalves for oxygen and food, resulting in reduced growth and tissue quality in cultured species (Bannister et al., 2024). On natural benthic communities, invasive organisms may outcompete native groups, reducing species richness (Aldred & Clare, 2014; Zhan et al., 2015). Biological traits such as high fecundity, adaptability, and rapid growth give NIS a competitive advantage, particularly in disturbed environments (Baker, 1986; Crawley, 1996). Disturbances that reduce native competition and increase resource availability may trigger "competitive release," accelerating NIS spread (Hobbs & Huenneke, 1992). Mechanisms such as apparent competition and reduced predation or parasitism (enemy release) further aid invasive species success (Keane & Crawley, 2002). Artificial structures also increase habitat complexity in ways that benefit invaders. Colonial ascidians such as *Botrylloides violaceus* and *Didemnum vexillum* dominate many coastal systems, displacing native species and altering community dynamics (Dijkstra et al., 2013). In the Adriatic Sea, the green alga *Codium fragile* ssp. *tomentosoides* has colonized coastal infrastructure extensively, transforming native assemblages and ecosystem functions (Bulleri & Airoldi, 2005).

Environmental factors such as eutrophication also influence invasion success. In nutrient-rich, low-oxygen systems, invasive species often dominate (Byers, 2009). While improved water quality may increase native biodiversity, it can also unintentionally favor NIS in ports and harbors (Carlton, 1996). Artificial structures also modify abiotic conditions such as hydrodynamics, water chemistry, and sediment characteristics, further influencing species assemblages. For example, mussel accumulation on offshore platforms creates shell debris that alters sediment composition and promotes further invasions (Bomkamp et al., 2004; Manoukian et al., 2023). Examples from the Gulf of Maine demonstrate how invasive species like *Membranipora membranacea* and *Codium fragile* prevent the re-establishment of kelp beds, important habitats for numerous marine organisms (Steneck et al., 2002; Johnson & Mann, 1988). Invasive predators such as the green crab (*Carcinus maenas*) and the Asian shore crab (*Hemigrapsus sanguineus*) have dramatically altered intertidal ecosystems by preying on native snails (*Littorina littorea*), reducing macroalgal cover and impacting trophic interactions (Trussell et al., 2006; Lohrer &Whitlatch, 2002; Freeman & Byers, 2006; Eastwood et al., 2007). These examples illustrate the cascading effects of invasive species on community structure and ecosystem processes. Adaptive management, early detection, rapid response, and international cooperation (e.g., ballast water management by the International Maritime Organization, IMO, 2004) are critical to preventing and mitigating marine bioinvasions.

Artificial structures, such as breakwaters, offshore platforms, piers, and aquaculture facilities, must be designed and managed with ecological foresight to preserve marine biodiversity and ecosystem function. Eradication efforts, such as the successful removal of *Caulerpa taxifolia* in California (Anderson, 2005), demonstrate the value of timely action, while delayed responses—as in the case of *Caulerpa webbiana* in the Azores—can lead to uncontrollable spread and costly intervention (Amat et al., 2008).

4.2 Challenges to Ecosystem Sustainability

The introduction of marine bio-invasive species represents one of the most significant threats to biodiversity loss on a global scale (Hopkins et al., 2021). Artificial structures are considered to be either man-made materials or natural materials shaped or displaced to serve a specific function for human activities. In the coastal waters of North America, approximately 90% of the invasive species inhabiting hard substrata were reported from docks and marinas (Mineur et al., 2012). These structures can apply hard substrates that may be scarce in the surrounding area, promoting the rapid growth of marine invasive species. Artificial structures like boating in energy installation create new habitats and “niche opportunities” for marine invasive species by offering environments that align with their environmental tolerances (Dafforn, 2017). In such ecosystems, human activities and invasive species can disrupt ecological balance and compromise long-term sustainability. The ecosystem services that are negatively affected by the highest number of invasive species are ocean nourishment, recreation and tourism, and lifecycle maintenance (Çinar et al., 2014). Programs for large-scale artificial structures should take into account the possible negative effects on fishery resources and ecosystems, including the promotion of undesirable species and a decline in water (Santos et al.,2008). Disease transmission from invasive

species might be the cause of increased mortality in native populations of commercially important species or in holding facilities (Çinar et al., 2014). Artificial reefs can encourage the growth of species that may pose public health hazards, including jellyfish and *Gambierdiscus* dinoflagellates. The increase of *Gambierdiscus* dinoflagellates on these reefs heightens the risk of ciguatera fish poisoning (CFP). Additionally, the presence of artificial structures in the Gulf of Mexico may aid in the range expansion of these species as sea surface temperatures rise, thereby increasing the long-term risk of ciguatera (Schulze et al., 2020).

This diminished flow can also lead to the accumulation of contaminants such as heavy metals, hydrocarbons, and organic matter, which may favour the dominance of pollution-tolerant invasive species (Dafforn, 2017). These species can attack native species of the marine area, affect the food chain, and destroy the normal ecosystem. Artificial structures can accelerate the spread of marine invasive species along coastlines. The dramatic impacts of Spartina alterniflora and its hybrids on benthic food webs and ecosystem structure and function have been well documented in San Francisco Bay (SFB), California, where their dense root systems trap sediments, alter tidal flow, and displace native marsh vegetation, ultimately reducing habitat availability for native invertebrates and shorebirds (Williams & Grosholz, 2008).For instance, the invasive coral *Oculina patagonica* and the alga *Undaria pinnatifida* have proliferated more rapidly along coastlines as a result of these man-made structures (Dafforn, 2017). For instance, the Pacific oyster (*Crassostrea gigas*) can overtake native mussel beds. In the Mediterranean, *Bracludontes pharaonis* has replaced the native *Mytilaster minimus (citation?)*. The scleractinian coral *Oculina patagonica* can outcompete local corals, overgrow sessile invertebrates, and eradicate algae at its growth margins (citation?). The introduction of invasive species can lead to a shift in dominance from native species to these invaders, resulting in changes to habitat structures and affecting the organisms that depend on them (Çinar, 2014). The colonization of artificial structures by invasive species can facilitate the establishment of other invasive species, leading to a process called “invasional meltdown”. Immobile artificial structures can modify natural dispersal patterns, especially along sedimentary coastlines. This can promote the introduction and proliferation of invasive species into nearby natural environments (Mineur et al., 2012). Invasive species can significantly alter the cycling and storage rates of carbon and nitrogen in coastal ecosystems by changing sediment composition, primary productivity, and decomposition processes (Williams & Grosholz, 2008). Copper toxicity in marines could enhance the dominance of exotic species over native populations (Susick et al., 2020). Eradicating marine bioinvasive species can be difficult in marine environments once self-sustaining populations have formed, and the consequences may be permanent (Castro et al., 2022). Mitigation efforts, like those aimed at eliminating *C. webbiana* in the Azores, can fail despite the use of targeted structure. Marine urban sprawl can facilitate the spread of invasive species, while native species do not benefit in the same way (Ferrario et al., 2016).

Various activities, including human actions and climate change, can lead to long-term degradation of ecosystems. The environmental impact of Submerged Static Artificial Structures (SSAS) and the ecological significance of their biofouling communities are gaining attention as artificial structures like seawalls and revetments become more common globally (Hopkins et al., 2021). Invasive filter-feeding

species can disrupt nutrient cycling by increasing sedimentation, which diminishes pelagic production and reduces energy in the water column. Furthermore, bioturbation from these invasive species can alter oxygen distribution in sediments, enhance solute exchange with the water column, and influence nutrient cycling (Çinar et al., 2014). Invasive species can alter the composition and dynamics of ecosystems by outcompeting or preying on native species (Vilà et al., 2010), modify genetic traits via hybridization (citation?), and introduce new diseases (Castro et al., 2022). For instance, introduced predators can create significant ripple effects across different trophic levels in freshwater ecosystems (Vilà et al., 2010). Certain invasive species, like *Tubastrea coccinea*, are highly effective at competing for space, often displacing local coral species and causing tissue necrosis in colonies that come into contact with them (Schulze et al., 2020). Additionally, artificial structures and habitats along with heavy maritime traffic, can lead to the emergence of hotspots for marine invasive species (Castro et al., 2022). Mobile artificial structures such as ships, barges, and pontoons can transport species across large geographical barriers, leading to the introduction of invasive species into new biogeographical areas. Specifically, barges and pontoons can gather significant amounts of fouling organisms during extended periods of inactivity, meaning they carry established fouling communities when moved (Mineur et al., 2012). Man-made structures like breakwaters and dredged channels can restrict tidal currents, which may result in stagnant conditions and unusual levels of dissolved copper, oxygen, temperature, and turbidity (Susick et al., 2020).

Many invasive species threaten critical habitats such as sublittoral algae, seagrass meadows, and coralligenous communities, all of which provide essential ecosystem services. This degradation can lead to a decline in biodiversity and a reduction in vital services, including food supply, water purification, coastal protection, and the support of life cycles (Cinar et al., 2014). Invasive species can adversely affect food supply by damaging key habitats for fish populations and triggering toxic algal blooms, resulting in economic losses for fisheries and aquaculture. The introduction of artificial structures often alters community composition, typically favoring invasive species. This shift can displace native species and change natural habitats (Mineur et al., 2012). For example, the spread of the periwinkle *Littorina saxatilis* has been associated with breakwaters along the coastline of Belgium, which lacks natural rocky shores. The Australasian barnacle Austrominius modestus (*Elminius smodestus*) has also been found to colonize concrete breakwaters rapidly in the Netherlands. Invasive species can compete with native species for essential resources like food and habitat, resulting in a decrease in native populations. Additionally, they may hunt native species, further disturbing the food web and the overall (Mineur et al., 2012). Invasive sessile organisms can take up more space than native species in artificial structures (Susick et al., 2020). Various species exhibit distinct preferences regarding the type and placement of artificial structures. Recognizing these preferences is essential to prevent unintended outcomes (Santos et al., 2008).

4.3 Mitigation Strategies

Artificial structures negatively impact native species, disrupt ecosystems, and serve as hotspots for invasive species, leading to long-term ecological imbalance and economic damage. Invasive species

threaten fisheries, aquaculture, and coastal industries and are difficult and costly to remove once established. Therefore, effective mitigation strategies are essential for marine conservation, economic sustainability, and biodiversity protection.

One effective approach is designing eco-friendly artificial structures by incorporating sustainable materials and innovative designs. The use of non-toxic antifouling coatings, such as silicone- or fluorine-based coatings, can discourage invasive species without harming native organisms (Sella & Perkol-Finkel, 2015). Sustainable and biodegradable materials, such as eco-concrete, help preserve native marine life while reducing the risk of NIS colonization. For example, using specially formulated concrete (e.g., ECOncrete®) instead of standard concrete can reduce NIS richness by up to 50% and increase native species richness by approximately 43% (Sella & Perkol-Finkel, 2015). Additionally, pH-neutral surfaces discourage invasive species growth while promoting native biodiversity.

Structural design modifications can also enhance native biodiversity. Rough and crevice-rich surfaces mimic natural habitats and promote native species dominance, whereas smooth surfaces favor invasive species. Modular designs with complex nooks and crannies provide hiding spaces for native filter feeders and grazers that help control invasive populations. Floating reefs and dynamic substrates can further adjust to discourage NIS growth, while fixed structures, as opposed to shallow floating platforms, can reduce NIS richness by 28% (Dafforn et al., 2009b). Additionally, self-cleaning surfaces prevent the attachment of invasive species. The control of shading and artificial light exposure is another crucial factor, as reducing artificial lighting can limit the attraction of invasive species larvae. Studies have shown that reducing shading through specific structural modifications can decrease NIS dominance by 50–90% (Kim & Micheli, 2013).

Habitat integration and biosecurity measures further mitigate the spread of invasive species. Hybrid natural-artificial structures, such as combining artificial reefs with natural rock formations, support native species colonization and reduce biofouling. Living seawalls, which incorporate native marine flora and fauna, help minimize invasive species proliferation. Designing habitats that support native predator species can further regulate NIS populations, as increasing native predator abundance on artificial structures can reduce NIS dominance by approximately 50% (Simkanin et al., 2013). Additionally, "pre-seeding substrates" with native fouling species, such as habitat-forming algae, has been shown to reduce NIS occupation by up to 33% (Dafforn et al., 2012).

Hydrodynamic and environmental considerations also play a vital role in mitigating NIS proliferation. Structures should be designed to optimize water flow and minimize stagnant zones, which serve as breeding grounds for invasive species. Encouraging natural water circulation enhances the dispersal of native larvae by preventing stagnation zones and improving oxygenation, while the increased flow also reduces biofouling buildup by limiting the settlement of invasive species larvae on submerged surfaces. Temperature regulation through reflective coatings or submerged cooling zones can prevent the establishment of temperature-sensitive invasive species. Continuous monitoring and adaptive management are crucial for long-term success. Smart monitoring systems, including AI-driven sensors

and real-time surveillance, can detect invasive species early and allow for prompt intervention. Routine biofouling surveys, underwater drones, remotely operated vehicles (ROVs), and environmental DNA (eDNA) testing can detect NIS before visible signs appear. Citizen science initiatives that engage local divers, fishers, and marina staff can further enhance detection efforts. Advanced AI-driven machine learning algorithms can assess invasion risks based on environmental conditions and vessel traffic patterns (citations?).

Early detection and rapid response (EDRR) are essential for managing new invasive species introductions. A coordinated framework involving detection, identification, verification, and rapid assessment allow for efficient intervention (Westbrook, 2004). Immediate containment measures, such as physical removal of NIS via divers, suction devices, or underwater scraping techniques, can prevent further spread. Implementing biofouling management plans, including cleaning ship hulls, pilings, and offshore platforms, further reduces the risk of secondary invasions. Biological and chemical controls, such as introducing native predators and targeted biocontrols (e.g., specific bacteria or parasites), can help regulate invasive species. The application of environmentally safe biocides in targeted areas eliminates NIS without harming native species (Reaser & Waugh, 2007).

Quarantine measures and traffic control strategies should also be enforced to prevent NIS introduction. Temporary access restrictions in affected areas and strict ballast water and biofouling regulations can limit species transfer. Long-term prevention strategies require data sharing, regional cooperation, and policy development. Establishing international collaborations enables real-time data exchange and coordinated response strategies. Implementing strict biosecurity laws and enforcing penalties for noncompliance can enhance mitigation efforts. Post-eradication monitoring is also critical to ensuring that invasive species do not re-establish themselves. Moreover, integrated management frameworks are necessary for sustainable mitigation efforts. Policies and regulations, such as adherence to the Ballast Water Management Convention (BWMC) and Environmental Impact Assessments (EIAs), should be enforced for all artificial marine structures. Compliance with EDRR protocols should be mandated, and penalties for noncompliance must be imposed. Establishing marine protected areas (MPAs) around artificial structures enhances native species resilience by reducing human disturbances such as fishing and anchoring, allowing populations to recover and maintain genetic diversity. The protection also creates refuges where native species can recolonize surrounding impacted areas. Collaborative management among government agencies, port authorities, marine industries, and conservation groups is essential to reducing bioinvasions. Education programs for recreational boaters, fishermen, and divers on invasive species identification and reporting can enhance stakeholder engagement (citations?).

Finally, continued research and adaptive management are necessary to refine mitigation strategies. Scientific studies on bioinvasive control methods, eco-friendly infrastructure designs, and innovative adaptation techniques should be supported. Practical implementation of research findings and technological advancements will enhance the effectiveness of mitigation efforts. Funding through grants, environmental fees, and corporate investments in sustainable maritime development can ensure long-term success (Piola & Johnston, 2008). By integrating ecological, technological, and policy-driven

approaches, effective mitigation strategies can safeguard marine biodiversity and ensure the sustainability of coastal and offshore ecosystems.

5. Policy and Management Perspectives

The spread of invasive marine species continues to rise due to artificial structures, demanding strong international frameworks to address the threat. The *Ballast Water Management Convention* (BWMC), established by the International Maritime Organization (IMO), exemplifies a key regulation to mitigate invasive species release through ballast water discharge (Dafforn et al., 2012; Brodie et al., 2014). However, the Convention also reveals the inherent difficulty in securing multilateral cooperation to tackle transboundary environmental threats. Despite being a cornerstone initiative, its implementation faces challenges related to inconsistent enforcement, limited technical resources, and varying national commitments. Moreover, BWMC addresses only one introduction pathway, leaving others such as ship hull fouling and aquaculture vectors relatively unregulated (Soares et al., 2022). Continued research efforts assess its efficacy and propose adaptive improvements to cope with emerging threats (Khaskheli et al., 2023). For regions sharing marine ecosystems, cross-national coordination is essential. Harmonized monitoring, unified enforcement, and regional data-sharing mechanisms are vital for strategic implementation (Cormier et al., 2022). Without globally standardized protocols, fragmented responses persist, undermining holistic invasive species management (Loh et al., 2019). Therefore, while the Ballast Water Management Convention lays the groundwork, a multi-vector regulatory framework remains essential for effective control of marine biological introductions (Fig. 2).

The sustainable design and retrofitting of artificial marine structures are critical to mitigating the spread of invasive marine species. Construction guidelines must prioritize materials and configurations that deter unwanted colonization (Dafforn et al., 2012). Structural variables such as surface roughness, material composition, and overall complexity significantly influence species settlement patterns. Empirical evidence suggests that smooth, minimally complex surfaces lower colonization likelihood (Airoldi & Bulleri, 2011). Horizontal installations have been associated with enhanced algal growth, while vertical surfaces more commonly attract sessile invertebrates (Brodie et al., 2014).

To reduce future retrofit costs, the inclusion of ecological criteria during the design phase is critical. In support of this, eco-engineering interventions, including the addition of surface textures and microhabitats to artificial marine structures, have been shown to enhance native biodiversity and potentially reduce invasive species colonization across various global settings (Strain et al., 2018). These projects demonstrate how fine-scale structural interventions can shift settlement patterns and support native species dominance.

However, these retrofitting measures can be costly, sometimes involving significant financial investments, highlighting the need for scalable and cost-effective solutions (Morris et al., 2018). Retrofitting methods generally focus on anti-fouling coatings, textural modifications, and the promotion of native species through habitat-enhancing features (Dafforn et al., 2012; Soares et al., 2022). Selecting

effective interventions requires assessments of species assemblages and structural conditions. Ongoing innovation must yield retrofit strategies that are not only ecologically sound but also economically viable across various structural types (Brodie et al., 2014). Moreover, monitoring programs remain indispensable, as they evaluate the long-term success of interventions by tracking biodiversity dynamics over time (Loh et al., 2019).

Successful management of invasive species associated with artificial structures demands coordinated stakeholder collaboration. Policymakers are responsible for establishing regulatory frameworks, allocating resources, and embedding scientific evidence into enforceable policies (Airoldi & Bulleri, 2011; Khaskheli et al., 2023). Simultaneously, construction companies, engineers, and port authorities must adhere to ecologically informed design and retrofitting standards that minimize the risks posed by introduced species (Dafforn et al., 2012; Brodie, 2014). Transparent communication and knowledge exchange between scientists and infrastructure developers ensure that new structures align with best ecological practices.

To support these top-down approaches, citizen science initiatives have successfully engaged local communities in invasive species detection and reporting, demonstrating the value of public participation in marine conservation efforts (Delaney et al., 2008; Edgar et al., 2016). These initiatives exemplify the potential of early detection and empowerment of local communities.

Public awareness and community engagement are equally vital. Residents in coastal zones often possess local ecological knowledge and play a frontline role in identifying and reporting new marine species introductions (Soares et al., 2022). Education and outreach campaigns can enhance this capacity by increasing understanding of ecological threats and appropriate mitigation actions. Campaigns must target diverse audiences using inclusive, multilingual, and multi-platform strategies (Jacquet et al., 2010; Qian et al., 2021).

Research-driven communication materials rooted in both global and local contexts encourage broader participation (Tanalgo & Hughes, 2021). The use of citizen science tools and participatory mapping can further democratize conservation, fostering stewardship among coastal populations. Accordingly, engagement strategies must undergo periodic evaluations to ensure they remain effective amid shifting environmental and societal dynamics (Ison et al., 2021).

Ultimately, integrating science-based policies, ecologically informed infrastructure, and public engagement forms a triad of defense against marine invasive species. Such a holistic approach strengthens biodiversity conservation in the face of increasing human impact on marine environments. Aligning international conventions, local governance, engineering innovation, and community participation offers a comprehensive framework to sustainably manage the risks associated with species introductions via artificial marine structures.

6. Future Research Directions

Understanding the role of artificial structures in facilitating marine bioinvasions is essential for designing robust biodiversity conservation and ecosystem sustainability strategies. This review addresses key questions concerning the ecological effects of artificial structures, their role in the invasion process, and the management strategies required to mitigate these impacts. Highlighting these existing knowledge gaps, it provides a foundation for future research to integrate technological innovation and interdisciplinary collaboration in combating marine bioinvasions. One of the most pressing challenges in studying marine bioinvasions is the lack of long-term monitoring data. Current research often emphasizes short-term ecological assessments, which fail to capture the dynamic and evolving nature of invasion processes (Strayer et al., 2006). Establishing standardized and long-term monitoring programs is critical for assessing invasion trends, ecological consequences, and the effectiveness of management interventions (Hulme et al., 2006). Furthermore, the absence of historical baselines complicates the differentiation between natural species dispersal and anthropogenically driven invasions. Addressing this gap requires access to high-resolution temporal and spatial data and the integration of historical records, ecological surveys, and environmental datasets.

While the roles of shipping, aquaculture, and offshore energy installations in spreading invasive species are well-documented, the underlying mechanisms driving these invasions remain inadequately understood (Costello et al., 2021). Key vectors such as hull fouling and ballast water discharge continue to be major contributors to species introductions, yet their interactions with artificial substrates require further investigation (Seebens et al., 2017). Additionally, floating infrastructures like offshore wind farms, oil rigs, and floating solar platforms may act as "stepping stones", enabling species to extend their geographic ranges (Adams et al., 2014). Future research should analyze how these structures facilitate connectivity and colonization across regions.

Artificial structures alter local environmental conditions, including hydrodynamics, light penetration, and nutrient availability, often creating favorable ecological niches for invasive species (Gibson et al., 2012). Research is needed to evaluate how these modifications impact species composition, community structure, and trophic dynamics. Longitudinal and comparative studies incorporating genetic, ecological, and environmental data could offer insights into the evolutionary adaptations of invasive species colonizing artificial environments (Carroll et al., 2007).

Advancements in biomimetic and antifouling technologies hold promise for mitigating marine bioinvasions. The development of non-toxic, environmentally friendly coatings that deter invasive species while preserving native biodiversity is a growing research frontier (Adeboye et al., 2023). Materials such as nanostructured surfaces inspired by shark skin and biopolymer-based antifouling agents are being explored as sustainable alternatives to traditional chemical treatments (Kapoor et al., 2022). Future efforts should focus on integrating these materials into marine infrastructure designs, especially in high-risk areas such as ports, marinas, and aquaculture facilities.

Emerging technologies like remote sensing and artificial intelligence (AI) are revolutionizing bioinvasion monitoring. Satellite-based remote sensing enables real-time, large-scale detection of invasion hotspots,

while UAVs and AUVs equipped with imaging systems enhance surveillance of submerged structures (Yang et al., 2022). AI-driven predictive models using machine learning can process vast ecological, climatic, and anthropogenic datasets to forecast invasion risks with high accuracy (Hamdan et al., 2024). Additionally, environmental DNA (eDNA) techniques allow for early detection by identifying genetic traces of invasive species in water samples (Zaiko et al., 2016). Integrating eDNA analysis with AI tools can significantly strengthen rapid response mechanisms.

Marine bioinvasion research must be grounded in interdisciplinary collaboration, combining expertise from ecology, engineering, and social sciences. Ecologists should investigate the interactions between invasive and native species, as well as the long-term consequences of artificial habitats (Strayer et al., 2010). Engineers can design eco-engineered surfaces and biosecure infrastructure that reduce colonization risks while supporting local biodiversity (Schaefer et al., 2020). Social scientists play a critical role in policy design, public education, and promoting community-based biosecurity efforts (Campbell et al., 2020).

Incorporating traditional ecological knowledge (TEK) from coastal communities can also enrich scientific understanding and guide context-specific management strategies (Silva-Ávila et al., 2025). Effective stakeholder engagement from port authorities and energy companies to local fishers—will be key in developing inclusive and implementable solutions.

Effective regulation of bioinvasion pathways requires robust policy frameworks. While international agreements such as the Ballast Water Management Convention provide foundational controls, there is a need for region-specific policies that reflect local ecological conditions and vector intensities (Gollasch & David, 2021). Cross-border cooperation, data-sharing, and joint enforcement initiatives can significantly enhance regional biosecurity. Policymakers should also consider economic instruments, such as tax incentives or subsidies, to promote the adoption of eco-friendly antifouling technologies (Rath et al., 2021). Strengthening port inspection systems, establishing risk-based monitoring protocols, and encouraging industry accountability will be essential for reducing invasion risk from maritime infrastructure.

7. Conclusion

In short, the artificial creation of structures in marine ecosystems has, without a doubt, facilitated the invasion of invasive species into ecosystems, with profound ecological disruptions and compromising marine biodiversity. These structures serve as habitats as well as stepping stones for invasive species, which compete with native organisms, disrupt trophic interactions, and alter ecosystem processes. The implications are not just of loss of biodiversity but also include economic impacts on aquaculture, fisheries, tourism, and ecological restoration. Thus, it becomes imperative to implement urgent and coordinated action to address the dangers of marine bioinvasions through artificial structures. The findings of this review highlight certain policy and management measures that would be capable of mitigating the negative impacts of artificial structures on marine ecosystems. International cooperation

is essential in the development of standardized biosecurity protocols for ballast water management, hull cleaning, and biofouling control. Regional cooperation and agreements are capable of harmonizing efforts in the monitoring and regulation of the movement of invasive species along global shipping lanes.

Declarations

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CRediT for Authors Contribution

Md. A. A. M. H.: Conceptualization, methodology, visualization, writing the original draft, reviewing, and editing the manuscript. **G. S. D.:** Writing an original draft, reviewing, and editing the manuscript. **I.J.E., M.I.H., M.S., R.D., N.H.:** Contributed to literature research, drafting, reviewing, and editing the manuscript. **M. M. P., Md. H. I., F. Y., M. M., and Mst. T. T.:** Writing original draft. All authors read the full manuscripts.

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This research did not involve human participants, animals, or any direct ethical issues. Therefore, ethical approval was not required for this study.

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No data were used in this research. The study is based on a systematic review and analysis of existing literature and published data.

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Figures

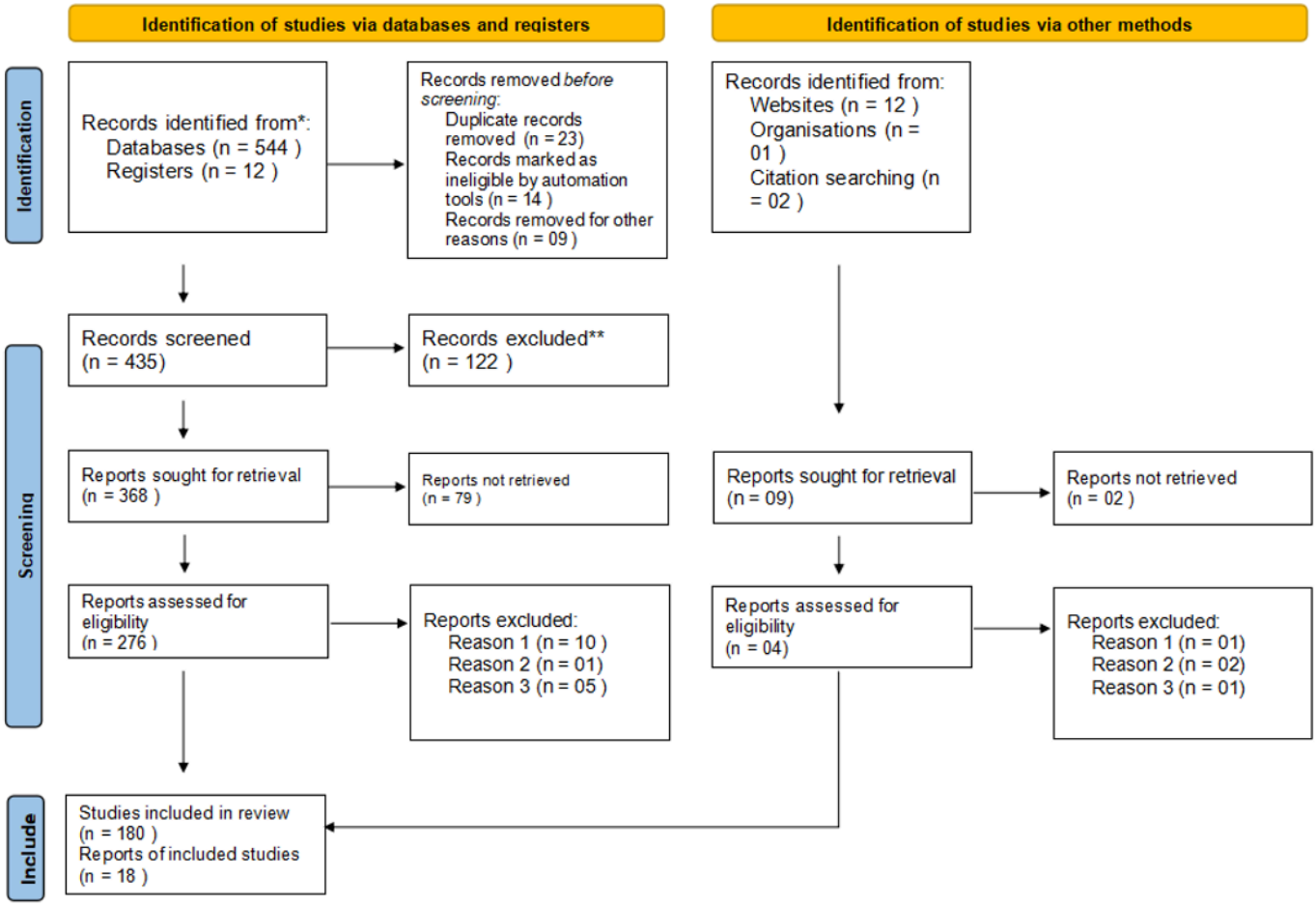


Figure 1

PRISMA flow diagram illustrating the study selection process, including identification, screening, eligibility assessment, and inclusion of studies. Reasons for exclusion are explained in section 2.2.

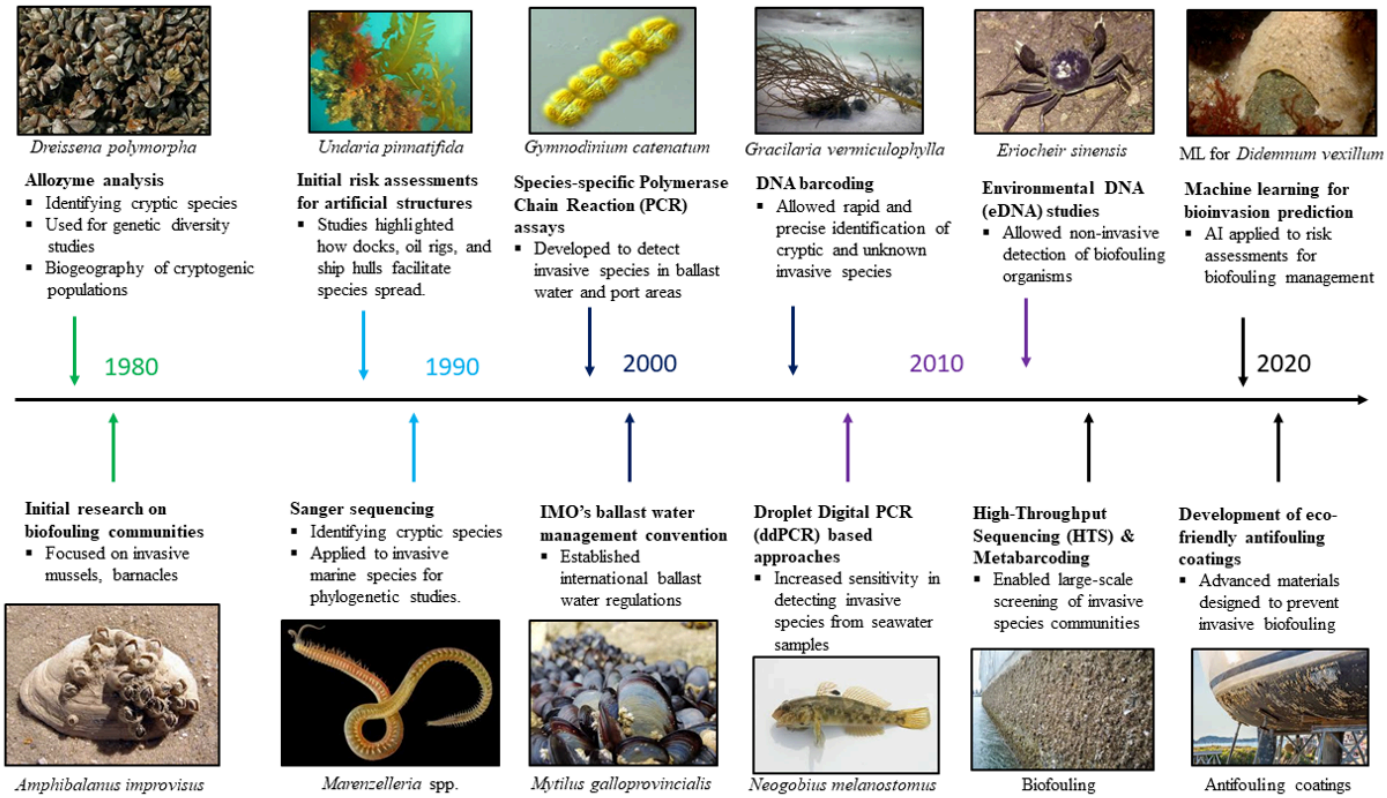


Figure 2

Policy and Management Framework for Artificial Structures in Marine Bioinvasions.