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Review Article

Artificial reefs for coastal wetland and estuary protection and coral restoration: A review

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Abstract

Artificial reefs (ARs) have emerged as a potential solution to restore aquatic ecosystems and enhance coastal protection. ARs serve as an effective tool for promoting natural species recruitment and survival. Moreover, ARs provide essential microfiches for various marine organisms, facilitating breeding and nursery, vital for sustaining fish populations and enhancing fisheries. However, comprehensive analyses suggesting adequate management policies and strategies that promote sustainable use of ARs as coastal protection and coral rehabilitation are limited. This paper aims to systematically review the literature on artificial reefs to evaluate their effectiveness in these dual roles. A systematic literature review of 121 studies reveals that hydrodynamic optimization and material selection are the most studied factors influencing AR performance. The result shows that the integration of hydrodynamic principles, structural stability, and interlocking strength is essential for maximizing the effectiveness of ARs in coastal protection and marine ecosystem rehabilitation. However, developers must also navigate various risks, including environmental damage, structural failure, and the uncertainty of long-term effectiveness. By adopting proactive measures, such as thorough environmental assessments, adaptive management strategies, and the use of durable materials and more stable structures that reduce physical damage, AR developers can mitigate these risks and enhance the sustainability of projects.

1. Introduction

Artificial reefs (ARs) are human-made structures deployed in marine environments to mimic the characteristics of natural reefs. These structures can include various materials, such as sunken ships, concrete blocks, and specially designed reef modules, all aimed at enhancing marine habitat complexity and promoting biodiversity (Broadbent et al., 2019). The development of artificial reefs has evolved significantly over the years, driven by advances in marine ecology and engineering. Early artificial reefs were often simple structures, but modern designs incorporate complex features that enhance habitat suitability for many marine species (Mwaura et al., 2023). As the understanding of marine ecosystems continues to grow, the design and implementation of artificial reefs are increasingly informed by empirical research, ensuring that these structures effectively contribute to marine conservation and management goals (Xiang et al., 2024; Yang et al., 2023).

The pressing need for artificial coral reefs arises from the alarming degradation of natural coral ecosystems (Eddy et al., 2021), exacerbated by climate change (Hoegh-Guldberg et al., 2017), pollution (Zhang et al., 2019), and overfishing (Zaneveld et al., 2016). As these vital marine habitats decline, the associated biodiversity and ecosystem services are severely compromised. ARs have emerged as a potential solution to restore aquatic ecosystems and enhance coastal protection (Bracho-Villavicencio et al., 2023).

Dickson (2023) stated that ARs contribute to marine ecosystem stability by providing habitats for various marine species through the establishment of microniches that reduce competition among species. The structural complexity of ARs fosters biodiversity, creating niches that support fish populations and other marine organisms. This ecological enhancement is essential for recovering degraded marine environments and contributes to the overall health of coastal ecosystems. ARs can be constructed using environmentally friendly materials, promoting marine life while serving as an effective coastal protection (Jiang et al., 2020).

In addition to these ecological benefits, ARs also enhance sustainability in coastal management, especially erosion reduction and coastline protection. ARs effectively dissipate wave energy, which minimizes the impact of waves on shorelines, thereby reducing coastal erosion. ARs can decrease incident wave energy by up to 63 %, significantly enhancing shoreline stability and protecting against erosion. Ghiasian et al. (2021) and Xu (2019) found that ARs provide a sustainable method for protecting coastlines without the negative environmental impacts of traditional hard engineering solutions, such as seawalls and groins. ARs provide environmental, economic, and social benefits by enhancing biodiversity, reducing erosion, and promoting natural coastal defense. ARs can alter hydrodynamic conditions, creating calmer waters behind them, which promotes sediment deposition and shoreline stabilization (Ramm et al., 2021). Sediment trapping plays a crucial role in preserving beach morphology and preventing erosion, especially in regions exposed to strong wave action (Chowdhury et al., 2019). By functioning as breakwaters, ARs aid in stabilizing sediment and maintaining beach profiles, which are essential for coastal resilience. This suggests that strategically placing ARs can influence hydrodynamic patterns, enhancing sediment deposition and minimizing beach scouring (Kuang et al., 2020).

Furthermore, the strategic placement of ARs can enhance their effectiveness in coastal protection, making them a valuable tool in the management of coastal ecosystems facing the challenges of climate change and sea-level rise (Paxton et al., 2019). This wave dissipation is crucial for maintaining the integrity of coastal ecosystems and preventing land loss, especially in areas prone to severe weather events. Moreover, their ability to reduce the risk of infrastructure damage from storm surges and high waves contributes to the resilience of coastal communities. By mitigating the forces of nature, ARs help safeguard critical infrastructure, thereby reducing economic losses and enhancing community safety (Qu et al., 2023). Overall, integrating hydrodynamic principles in AR design bolsters coastal protection and supports marine ecosystems' sustainability, making them a vital tool in modern coastal management strategies.

Recent studies underscore the importance of artificial reefs in promoting natural species recruitment and survival, reinstating ecosystem structure and function, and enhancing the abiotic processes that influence community dynamics (Kallianiotis & Batjakas, 2023). For instance, artificial reef strategies can facilitate habitat restoration, which is crucial for maintaining marine biodiversity in the face of ongoing environmental challenges (Kallianiotis et al., 2023). Furthermore, the construction of artificial reefs has been shown to improve marine water quality, thereby contributing positively to the ecological health of surrounding areas (Wang et al., 2023).

Previous research has highlighted the ecological benefits of ARs, such as increased fish populations and habitat complexity (Folpp et al., 2020), but there has been insufficient emphasis on the engineering principles that govern their effectiveness in coastal protection. This study seeks to fill that gap by providing actionable insights into designing ARs that can withstand hydrodynamic forces while promoting coral recruitment and growth.

Moreover, the design of ARs must consider critical factors, such as marine hydrodynamics, structural stability, and interlocking strength, to ensure their long-term effectiveness. Integrating these engineering principles can enhance the ecological performance of ARs, making them more resilient to environmental stressors (Rouse et al., 2019). This paper seeks to offer practical recommendations for designing artificial coral reefs that enhance marine biodiversity and function as effective coastal protections, drawing on insights from various studies. It also aims to conduct a comprehensive review of the literature to assess the effectiveness of artificial reefs in fulfilling these two roles.

Furthermore, this research will suggest creating artificial coral reefs that consider essential factors such as construction materials, shape, and structural integrity. By synthesizing these design considerations, the study aims to propose a framework for developing multifunctional ARs that support marine life and serve as effective coastal protections.

This study applies the Benefit-Opportunity-Cost-Risk (BOCR) framework to evaluate various artificial reef alternatives for coastal protection and ecosystem restoration. The analysis identifies that ecological benefits and socioeconomic opportunities play dominant roles in decision-making, while cost and risk factors must be balanced for long-term sustainability. The results reveal that high-cost but low-risk reef configurations provide optimal outcomes in terms of both protection performance and ecological value. The study contributes a decision-support model that helps policymakers and coastal engineers prioritize artificial reef designs based on integrated environmental and economic considerations.

The findings of this study are expected to provide policymakers and practitioners with understanding of the multifaceted benefits of AR, advocating for their inclusion in integrated coastal zone management strategies. Ultimately, this research seeks to bridge the gap between ecological restoration and coastal protection, offering a pathway toward the sustainable management of coral reef ecosystems in the face of ongoing environmental challenges.

1.1 Nexus between artificial reefs and hydrodynamics

Hydrodynamics are a critical element in the design and functionality of artificial reefs, influencing their effectiveness in enhancing marine ecosystems and providing coastal protection. The interaction between water flow and artificial reef structures can significantly affect various ecological processes, including nutrient distribution, sediment transport, and the recruitment of marine organisms. For instance, Pan et al. (2023) highlight that the morphology of artificial reefs can create specific hydrodynamic conditions that promote circulation patterns beneficial for marine life. These patterns can enhance nutrient availability and facilitate larvae dispersal, which are essential for the sustainability of fish populations and overall reef health (Cortés-Useche et al., 2021).

Square ARs are a specific type of artificial reef structure, investigated for their hydrodynamic characteristics (Mao et al., 2023; Zhu et al., 2022). These square-shaped reefs are often deployed in coastal regions to enhance marine ecosystems and increase fishery production (Camp et al., 2022; Shu et al., 2022). This square artificial reef geometry has been shown to influence local hydrodynamics, which can affect the resistance and stability of these structures in the marine environment. A detailed understanding of these hydrodynamic effects is crucial for the effective design and deployment of artificial reefs to achieve the desired ecological and coastal protection benefits (Androulakis et al., 2020; Cardenas-Rojas et al., 2021).

Cylindrical ARs with fins are a specific type of reef structure with a cylindrical main body with additional fins or protrusions attached. The fins can alter the flow patterns, turbulence levels, and overall resistance of the reef to ocean currents and waves. Compared to simpler cylindrical reef designs, adding fins can increase the surface area and complexity of the structure (Cardenas-Rojas et al., 2021).

The development of artificial reefs has increasingly incorporated hydrodynamic modelling to predict and enhance their performance. Studies have shown that the shape, size, and configuration of artificial reefs can significantly alter local flow fields, affecting the aggregation and reproduction of marine organisms (Shu et al., 2021). For example, the hydrodynamic characteristics of artificial reefs can be fine-tuned to create optimal conditions for fish feeding and breeding, as well as to minimize sedimentation that could smother coral growth (Gong et al., 2023; Pan et al., 2023).

1.2 Significance of structure and materials in AR creation

The design and choice of construction materials are critical to the performance and functionality of artificial reefs, as they determine both ecological outcomes and structural durability (Dickson et al., 2023; Margheritini et al., 2021). Materials must withstand harsh marine conditions while providing suitable habitats for marine organisms (Soares et al., 2022). Recent shifts toward design-specific and environmentally friendly materials are partly driven by stricter regulations, ensuring both durability and ecological compatibility (Becker et al., 2020). Appropriate materials can promote the growth of marine life, reduce maintenance needs, and extend the operational lifespan of the reefs (Folpp et al., 2020; Higgins & Sobolev, 2021).

One of the artificial reef structures being developed in Indonesia is a hexagonal reef, known as SIMHAR (Structure of Interlocking Modular Hexagonal Artificial Reef) (Suwardi et al., 2025). This artificial reef will be implemented around Gili Ketapang, East Java, Indonesia. SIMHAR is expected to exhibit greater stability under strong currents and dynamic wave conditions because the units are interlocking, so they do not fall or shift easily compared to previous ARs that are arranged without interconnections between their units (see **Figure 1**). For field deployment, SIMHAR is designed with a height equal to two-thirds of the water depth, maintaining a minimum depth of two meters, and a minimum freeboard corresponding to half of the significant wave height, as illustrated in **Figure 2**.

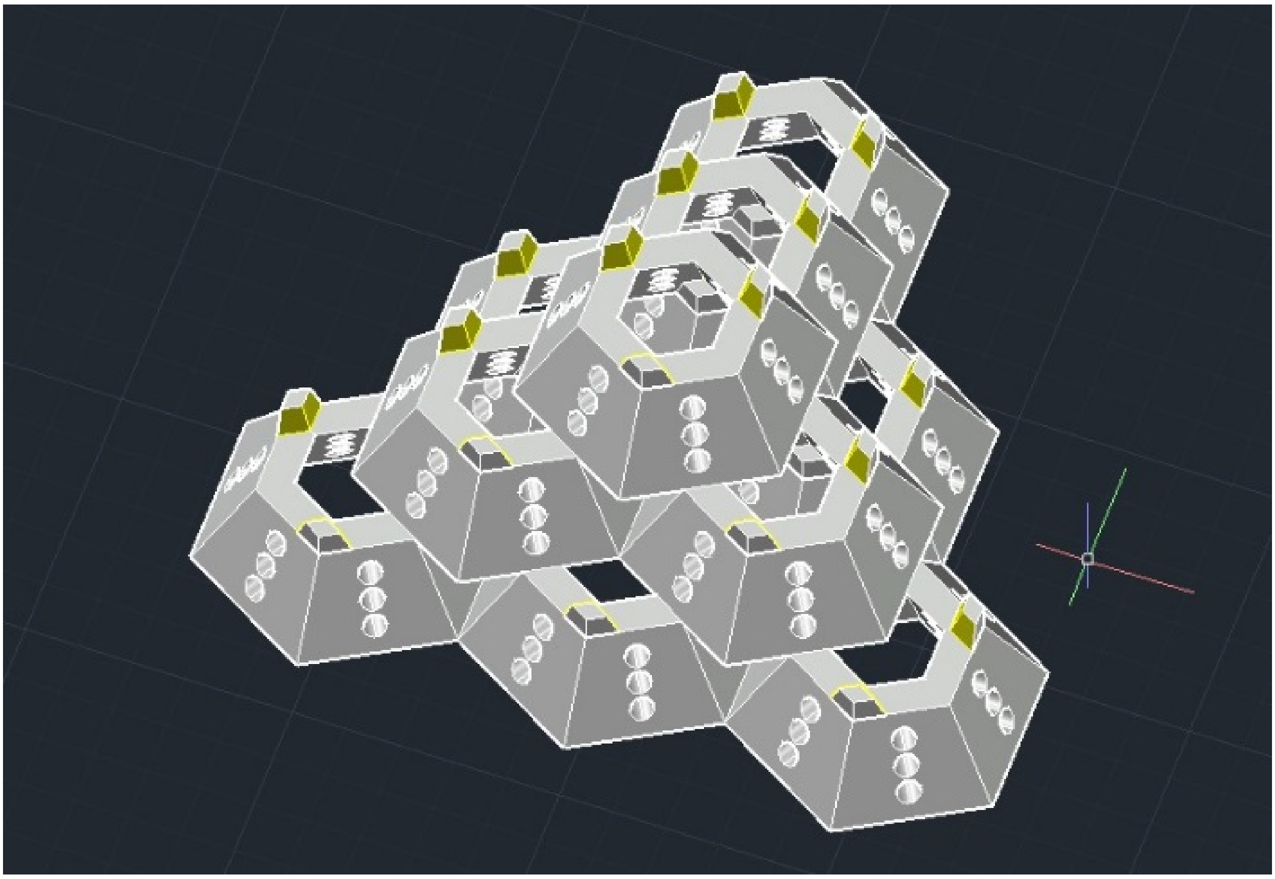


Figure 1 Interlocking design of SIMHAR.

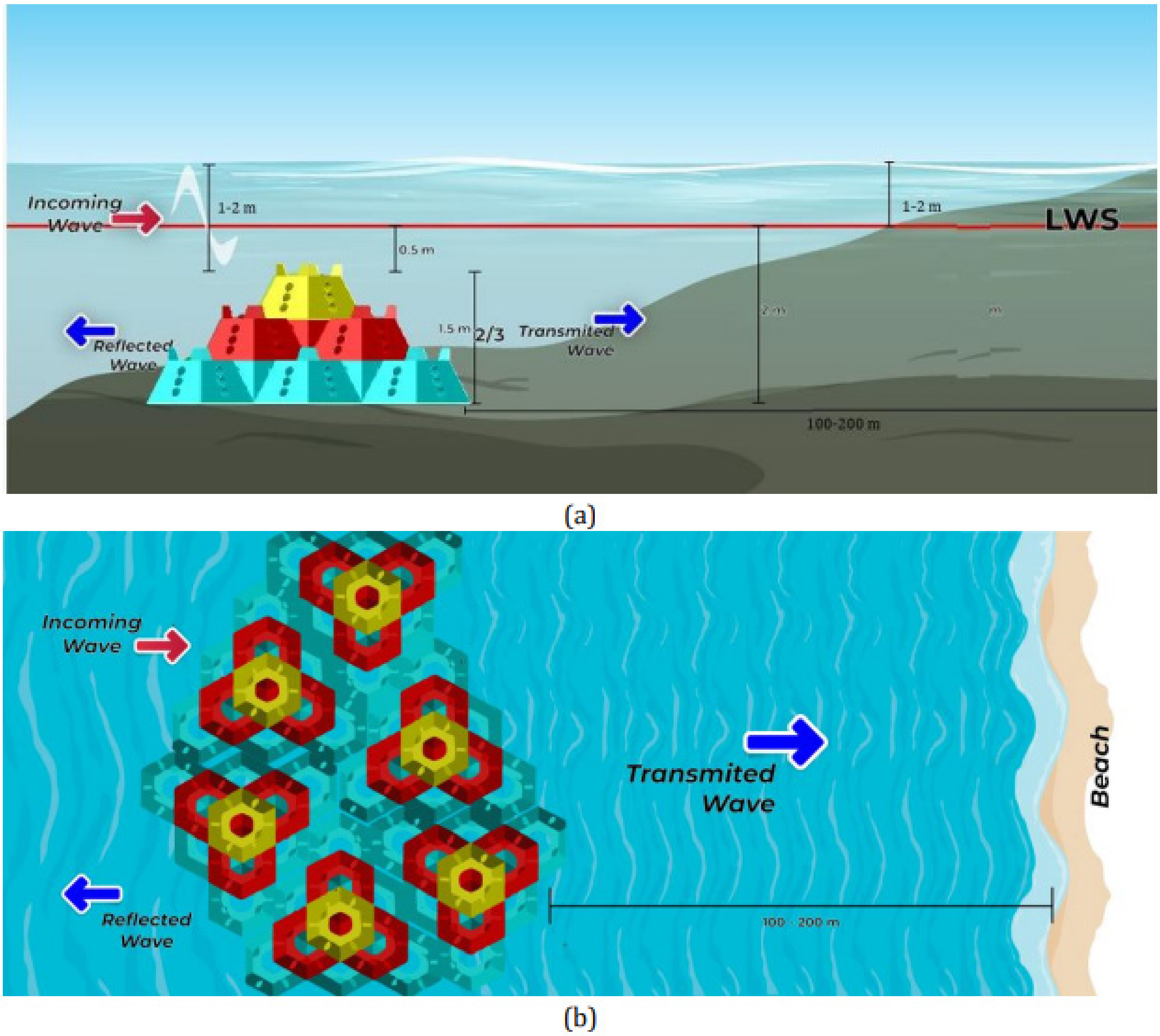


Figure 2 Design of location for placing SIMHAR in Gili Ketapang- (a) front view; (b) top view.

2. Materials and methods

PRISMA-based systematic literature reviews (SLR) were used in the current study. The SLR approach allows for a comprehensive synthesis of existing research, providing a robust framework to evaluate the diverse ecological, economic, and social dimensions associated with artificial reefs. By systematically collating and analyzing data from various studies, the SLR can reveal trends, gaps, and inconsistencies in the literature, thus facilitating a deeper understanding of the effectiveness of artificial reefs in different contexts (Xu et al., 2023).

2.1 Data collection

There are several stages applied to research using the SLR-PRISMA method, namely: 1) Defining Research Questions and Objectives; 2) Identification of Literature; 3) Data Extraction and Thematic Analysis; 4) Screening and Selection; and 5) Synthesis and Reporting (**Figure 3**).

The study followed four stages. First, the researcher reviewed artificial reef research to identify addressed aspects and emerging trends. Second, the keyword "artificial reef" was used for literature searches. Third, data were sourced from Scopus as a trusted database of high-quality articles. Fourth, selection criteria included: engineering topic, scientific article type, English language, publication period 2015 - 2024, and exclusion of predatory or discontinued journals. This process yielded 121 articles, categorized into hydrodynamics (12), structural stability (15), and interlocking strength (2). The synthesis of these findings provides an overview of the current state of artificial reef research, highlighting consistencies, contradictions, and future research opportunities.

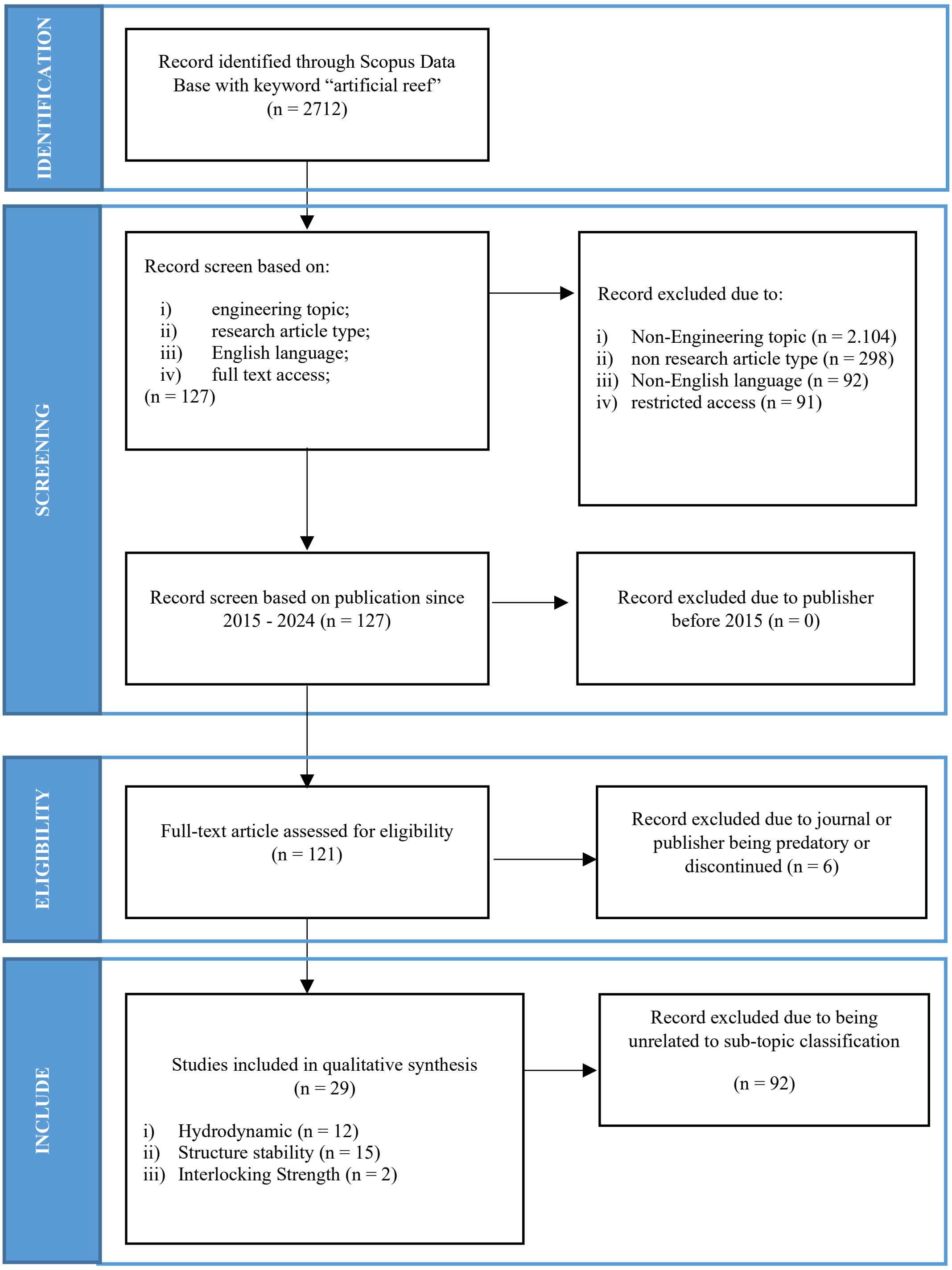


Figure 3 SLR filtering process with PRISMA approach.

3. Results and discussion

The three aspects (hydrodynamics, structure stability, and interlocking strength) show that ARs can serve as an effective solution for coastal protection and coral reef rehabilitation. ARs significantly contribute to reducing the risk of coastal erosion, increasing the stability of coastlines, and supporting marine habitats.

3.1 Hydrodynamic approach

A central theme across the reviewed literature is the ability of artificial reefs to dissipate wave energy, which is critical for coastal protection. The literature also discusses innovative designs that enhance the hydrodynamic performance of artificial reefs. For instance, the paper "Dissipation of Wave Energy by a Hybrid Artificial Reef in a Wave Simulator: Implications for Coastal Resilience and Shoreline Protection" by Ghiasian et al. (2021) quantifies how structural features of coral reefs contribute to wave energy dissipation, demonstrating that the presence of coral skeletons can significantly enhance the frictional dissipation of wave energy.

The suitability of the AR placement location determines effectiveness in coastal protection. Hydro-oceanographic parameters such as depth, slope, seabed substrate, wave height, current speed, and activity in the waters are taken into consideration in the hydrodynamic approach (Suwardi et al., 2025). Especially, extreme wave dynamics greatly affect the physical condition of ARs after sinking, for example, collapsing or shifting.

3.2 Structure stability

Based on the results of the paper filtration, 15 articles were selected, which were included in the structure stability topic. Those topics, discussing the relationship between interlocked strength and artificial reefs, reveal a multifaceted understanding of how structural integrity influences both the hydrodynamic performance and ecological outcomes of artificial reefs. Structural integrity, material selection, innovative design, and ecological considerations are all intertwined in determining the effectiveness of artificial reefs for coastal protection and coral reef rehabilitation.

A stable structure is essential for the longevity of artificial reefs, allowing them to endure harsh marine conditions, including storms and strong currents. The stability of artificial reefs also affects their hydrodynamic characteristics, which in turn influence sediment transport, nutrient cycling, and the reef's overall ecological function. This research is in line with that by Rahman et al. (2021), which indicates that a stable reef can maintain its shape and position. The structural integrity of artificial reefs influences the complexity and availability of habitats for marine organisms. A stable reef structure can provide more niches and shelter for fish and invertebrates, enhancing biodiversity (Rouse et al., 2019).

A submerged breakwater is subjected to various forces, primarily driven by hydro-oceanographic conditions, particularly wave dynamics, which in turn influence its physical stability. The stability of an artificial reef structure is determined by several forces, including wave, inertia, friction, lift, and gravity forces, as illustrated in **Figure 4**.

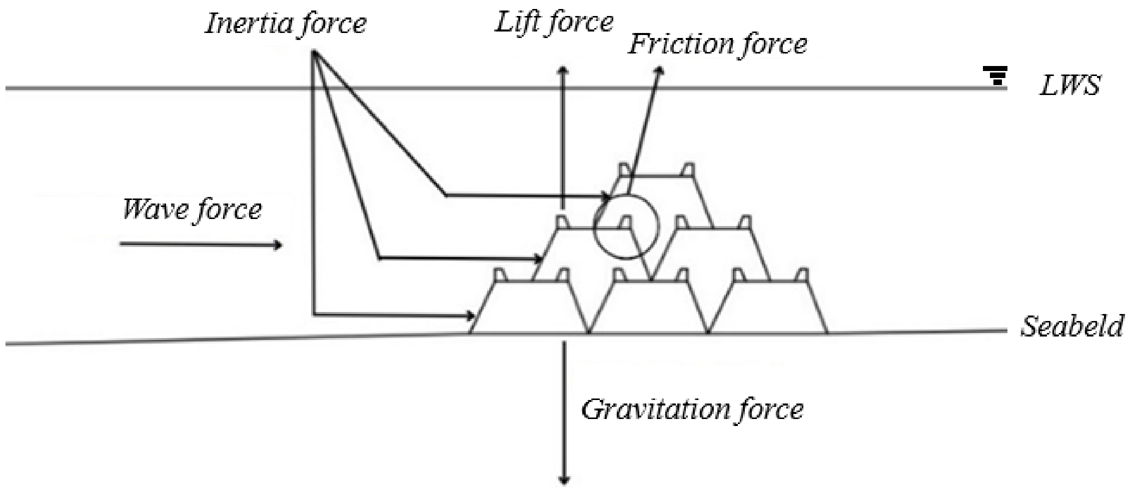
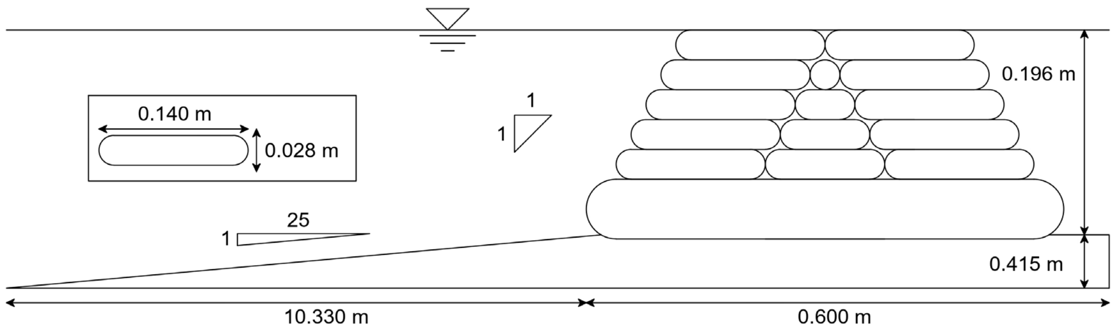


Figure 4 Forces acting on AR structure that affect stability of structure.

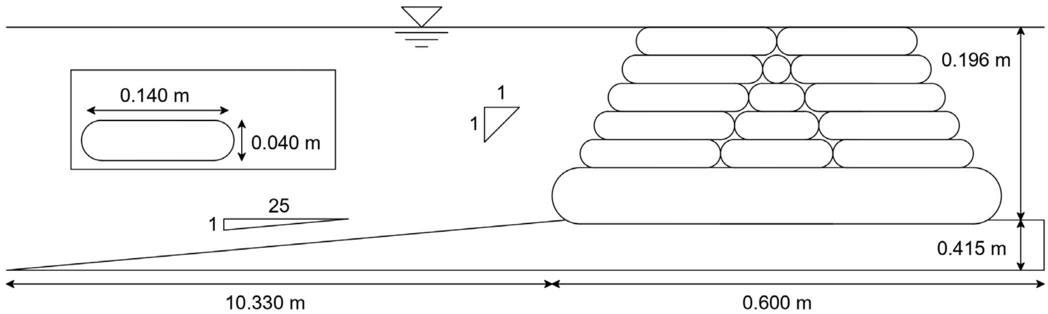
The stability of an underwater building structure can be visually assessed by observing the displacement of each unit. A structure is considered stable if the units do not shift beyond a certain threshold. A study on Geotextile Sand Container (GSC) (**Figure 5**) structures (Dassanayake & Oumeraci, 2012) employed a Damage Criteria (DC) classification (**Table 1**).

Table 1 New damage classification for individual GSCs and overall GSC structures.

Damage Classification - Individual GSC				
Stable	Horizontal displacement < 10 % of GSC length or upward rotation < 10°			
Displaced	Horizontal displacement 10 - 50 % or upward rotation 10° - 45°			
Detached	Horizontal displacement > 50 % or upward rotation > 45°			
Classification of damage GSC structural composition				
No Damage	Initial Displacement	Minor Damage	Major Damage	Failure
< 10 % GSCs displaced or no GSCs detached	10 - 50 % GSCs displaced or < 5 % GSCs detached	> 50 % GSCs displaced or 5 - 20 % GSCs detached	20 - 40 % GSCs detached	➢ 40 % GSCs detached

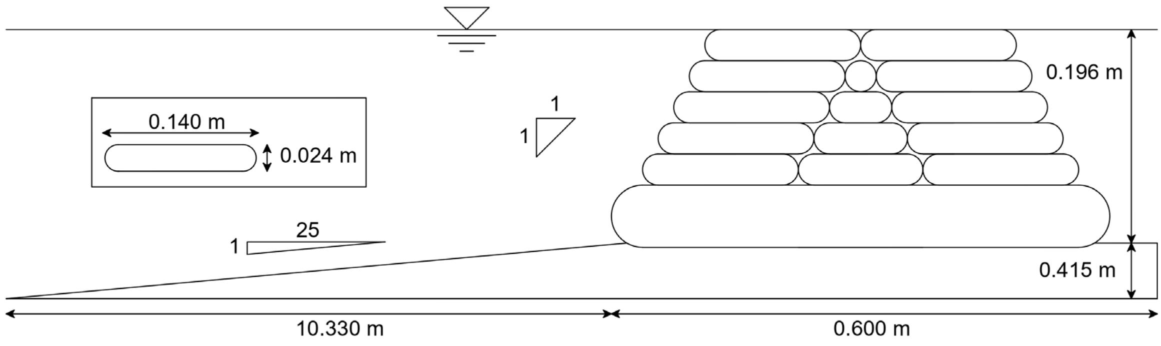


(a)

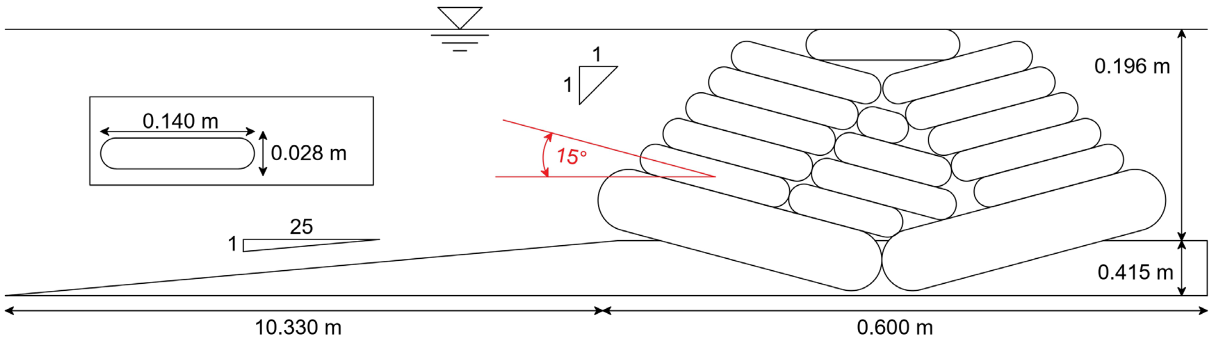


(b)

Figure 5 Model configuration and test sequence- (a) Nonwoven GSC filled to 80 %; (b) Nonwoven GSC filled to 100 %; (c) Woven and nonwoven GSC filled to 80 %; (d) Nonwoven GSC filled to 80 %, inclined 15° (Dassanayake & Oumeraci, 2012).



(c)



(d)

Figure 5 (continued) Model configuration and test sequence- (a) Nonwoven GSC filled to 80 %; (b) Nonwoven GSC filled to 100 %; (c) Woven and nonwoven GSC filled to 80 %; (d) Nonwoven GSC filled to 80 %, inclined 15° (Dassanayake & Oumeraci, 2012).

The damage level of non-interlocking hexagonal artificial reef structures can be quantified using the damage percentage (%), defined as the proportion of reef units that shift or move relative to the total number of structures. A reef structure is considered damaged if any structural unit moves at least 1 cm from its original position (Hanif & Dwito Armono, 2022). Experimental results from wave variation testing indicated that all configurations experienced some level of damage, with value of 5 % considered the upper threshold for structural stability (**Figure 6**).

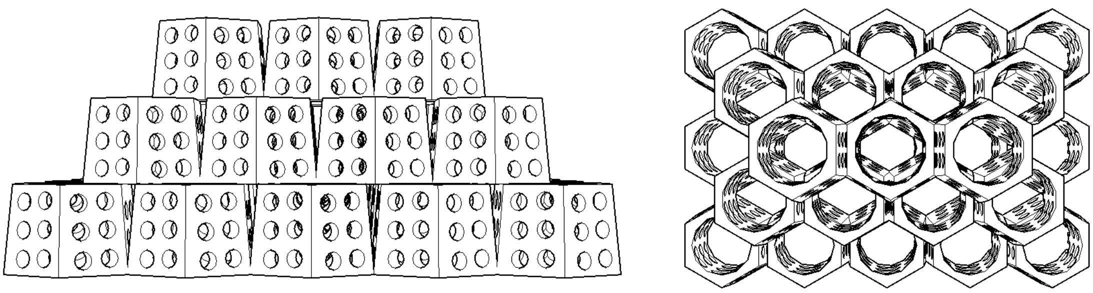


Figure 6 Experimental testing of cylindrical hexagonal artificial reefs- (a) Front view; (b) Top view (Hanif & Dwito Armono, 2022).

The Coral Reef Care (CRC) initiative utilized a cubic-frame artificial reef configuration, modifying it by incorporating smaller cube frames and perforated bricks into the larger cube structure to enhance its stability (**Figure 7**). The large cube structure experienced displacement and tilting beyond 360 degrees due to a storm following deployment (Veenland, 2023).

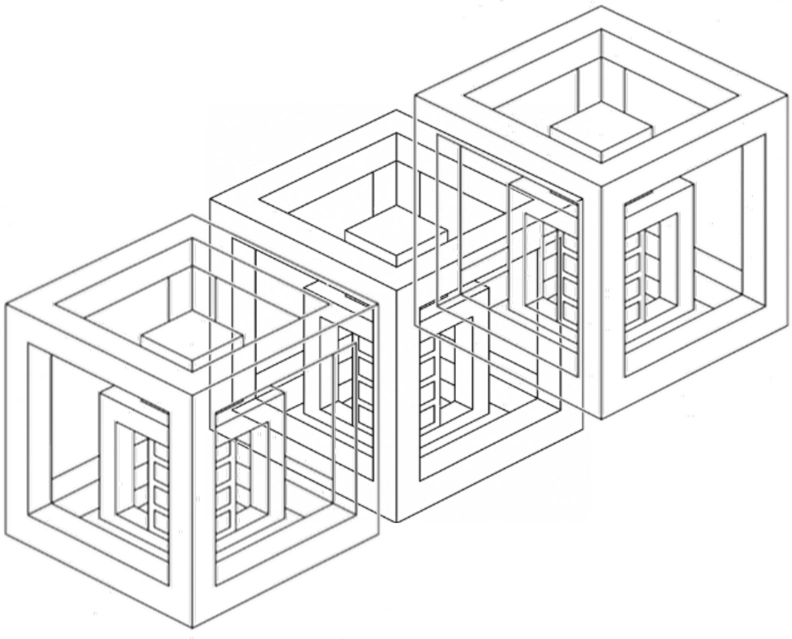


Figure 7 Modified CRC cube-frame artificial reef (Veenland, 2023).

The deployment of non-interlocking concave cylindrical artificial reefs (Arabesque type) for coral habitat restoration successfully facilitated coral colony growth after 3.5 years of monitoring (Al-Horani & Khalaf, 2013) (**Figure 8**). It is recommended that the structural stability of such artificial reefs be further analyzed to enhance their spatial arrangement for marine tourism purposes.

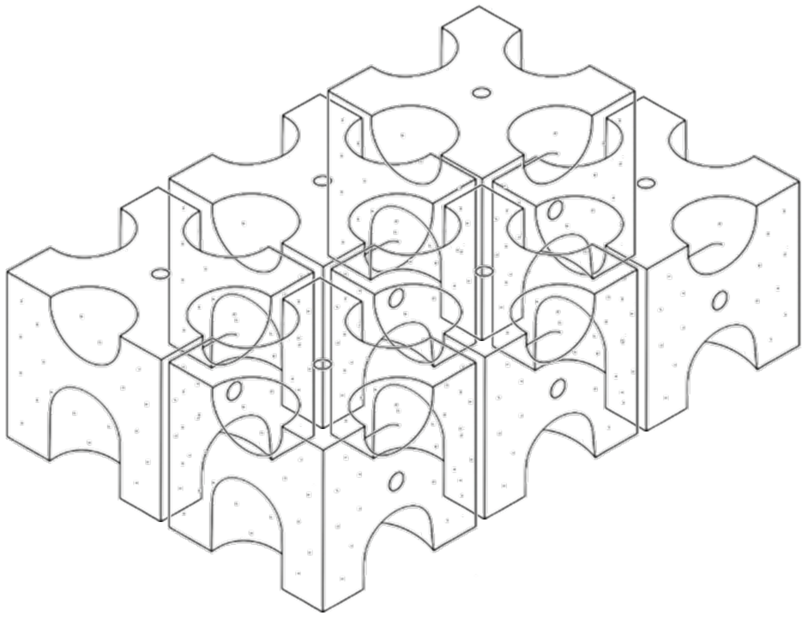


Figure 8 Arabesque model artificial reef (Al-Horani & Khalaf, 2013).

3.3 Interlocking strength

The relationship between interlocked strength and artificial reefs is crucial for understanding their structural integrity and ecological effectiveness. While not directly addressing interlocked strength, the two related studies on interlocking reef design provide insights into the hydrodynamic characteristics and ecological stability of artificial reefs, which are inherently linked to their structural design and performance.

The literature suggests that the interlocking strength of artificial reefs can influence their ecological performance. For example, research indicates that ARs with greater structural complexity, often achieved through effective interlocking designs, can enhance local fish populations by providing more niches and refuge from predators (Berman et al., 2023; Bracho-Villavicencio et al., 2023). This complexity not only supports biodiversity, but also contributes to the overall productivity of the reef ecosystem, as diverse habitats can sustain a wider range of trophic interactions (Barros et al., 2023).

While the two papers do not explicitly focus on interlocked strength, they underscore its significance in the performance of artificial reefs. The hydrodynamic stability provided by strong interlocking designs is essential for adequate coastal protection (Huang et al., 2024), while the ecological benefits derived from such designs contribute to the overall success of artificial reefs in supporting marine biodiversity (Bao et al., 2025). Future research should continue exploring the interplay between structural integrity and ecological outcomes to optimize artificial reef designs for coastal protection and habitat restoration.

3.4 Future prospects

3.4.1 Challenges in developing ARs

From the application of ARs in various locations, three key challenges have been identified: (1) maintenance costs, (2) design and construction planning, and (3) material selection and installation methods (**Figure 9**). This research is in line with the findings of several previous studies, such as Bahinting (2022), Banks et al. (2021), Chong et al. (2021), and Ramm et al. (2021).

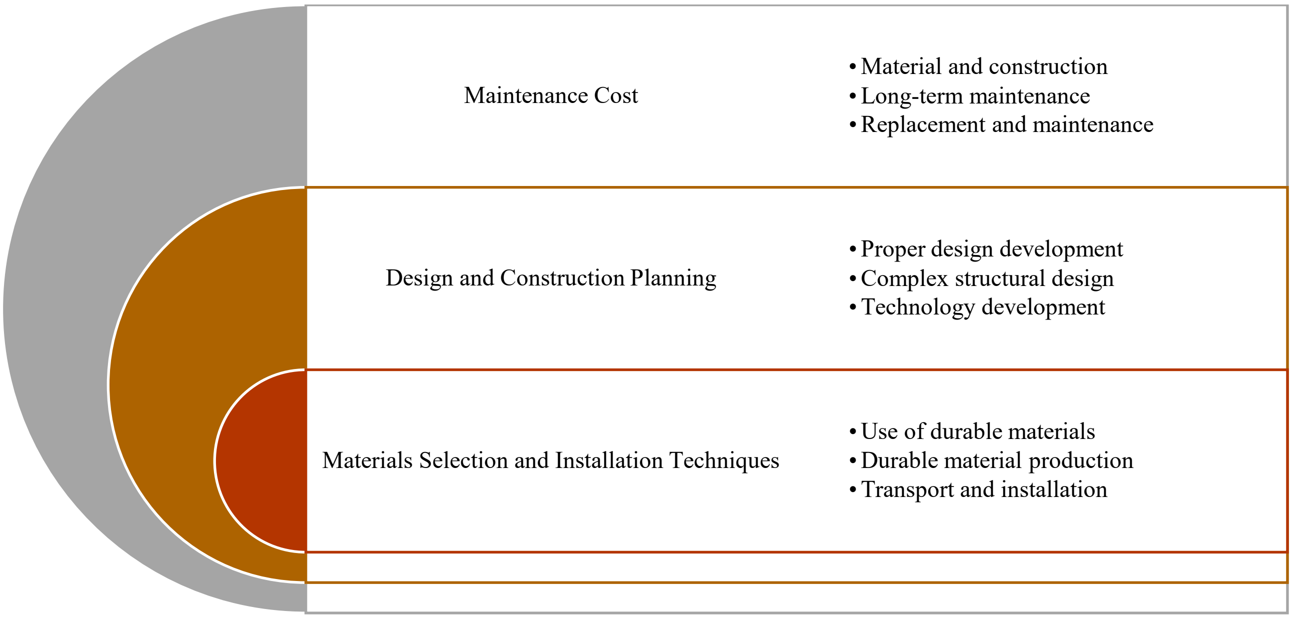


Figure 9 The challenges of AR development in the future.

The production and implementation of artificial reefs (ARs) face significant challenges, particularly in developing countries, due to various costs associated with their construction and maintenance. Material and construction costs are often the most substantial, as the choice of materials directly impacts both the initial investment and the long-term viability of the reefs. For instance, while concrete is commonly used for its durability and cost-effectiveness, alternative materials may be more environmentally friendly, but come at a higher price (Garg & Green, 2022). In developing countries, where budgets are often constrained, the high upfront costs can limit the feasibility of deploying ARs, leading to a reliance on less effective or lower-quality materials that may not withstand harsh marine conditions (Folpp et al., 2020).

Long-term maintenance is another critical cost factor that affects AR sustainability. Regular maintenance is essential to ensure that AR continues providing its intended ecological and protective benefits. In many developing countries, limited financial resources and technical expertise can hinder effective maintenance practices, leading to the deterioration of the structures over time (Yan et al., 2024). This situation is exacerbated by the complex structural design often required to optimize hydrodynamic performance and interlocking strength, which can increase initial construction costs and ongoing maintenance needs. Without proper design development and the use of durable materials, ARs may fail to perform effectively, resulting in wasted investments and missed opportunities for ecological restoration (Yoris-Nobile et al., 2023).

Moreover, transportation and installation costs can be prohibitive, particularly in remote or underserved regions where infrastructure may be lacking. The logistical challenges of transporting heavy materials and equipment can significantly inflate project budgets (Fahirah et al., 2024). In addition, the need for skilled labor to install complex AR designs can further strain financial resources, making it difficult for local communities to implement AR projects effectively. Addressing these cost-related challenges through innovative funding mechanisms, partnerships with the private sector, and developing cost-effective materials and designs will be crucial for enhancing the viability and effectiveness of AR initiatives in these regions.

However, there are still opportunities in the future, for the implementation of AR collaboration with the maritime industry presents another opportunity to leverage expertise in hydrodynamics and structural engineering, which can lead to more effective AR designs. By partnering with industry experts, researchers can develop ARs that are effective in coastal protection and economically viable. For example, studies indicate that the design and material selection for ARs can significantly influence their longevity and ecological productivity, suggesting that industry collaboration could lead to innovations that enhance both structural stability and ecological benefits (Lima et al., 2019). Additionally, the partnership can strategically plan the implementation of ARs in erosion-prone areas to mitigate coastal erosion effectively (Schuh et al., 2023). Research has shown that well-placed ARs can alter sediment transport dynamics, leading to increased sediment deposition and reduced shoreline retreat (Black & Steinhobel, 2021).

3.4.2 AR development risks and mitigation

Artificial reef (AR) developers face several risks that can impact the effectiveness and sustainability of their projects. At least three aspects of risks need to be considered in the development and installation of artificial reefs, namely: 1) environmental and ecosystem risk, 2) structural and design risk, and 3) external risk (**Table 2**). To mitigate these risks, developers should adopt a proactive approach, incorporating best practices and lessons from recent research.

To address the risk of environmental damage, AR developers should conduct thorough environmental impact assessments (EIA) before deployment. This process can help identify potential adverse effects on local ecosystems and inform the design of ARs to minimize such impacts. For instance, studies have shown that well-designed ARs can enhance biodiversity and ecosystem connectivity, mitigating adverse effects (O'Reilly & Willerth, 2023). Additionally, developers should consider using biodegradable materials that promote ecological benefits while reducing long-term environmental harm (Dickson et al., 2023). Ongoing monitoring of ecological impacts after deployment is essential to verify that artificial reefs function as intended, and to implement necessary adjustments based on observed results (Folpp et al., 2020).

Table 2 Risks of developing and installing artificial reefs.

No.	Environmental and ecosystem risk	Structural and design risk	External risk
1.	Environmental damage	Structural failure due to extreme currents	Uncertainty of long-term effectiveness
2.	Negative effect of ecosystem	Damage to inter-unit connection	Extreme weather
3.	Unwanted change in flow	Corrosion or degradation of joints	
4.		Complex structure expansion or adjustment	

The uncertainty surrounding the long-term effectiveness of AR can be addressed by implementing adaptive management strategies. This intention involves setting clear performance indicators and regularly assessing the ecological and structural integrity of reefs (Suwardi et al., 2025). For example, incorporating modular designs can facilitate easier adjustments and repairs, thereby enhancing the resilience of ARs to extreme weather and structural failures due to strong currents (Vieira et al., 2020). Developers should also invest in robust engineering practices that account for potential extreme weather impacts, ensuring that AR is designed to withstand such conditions without compromising their structural integrity (Escudero et al., 2021).

The design of artificial reefs (ARs) places particular emphasis on hydrodynamic aspects, structural stability, and interlocking strength. Advancing AR technology enables the creation of reefs that are more stable, effective, and efficient in handling wave and current forces. For instance, modular designs can be optimized to enhance wave energy dissipation while maintaining structural integrity, as demonstrated in studies that show how modular floating structures can effectively reduce wave loads and increase resilience against dynamic marine conditions (Li et al., 2022). This technological advancement not only maximizes the protective capabilities of ARs, but also supports the sustainability of marine ecosystems by creating habitats that promote biodiversity (Galdo et al., 2022).

To mitigate risks associated with corrosion or degradation of joints and damage to inter-unit connections, developers should prioritize using durable materials and advanced construction techniques. Research by Camba et al. (2021) indicates that selecting materials with high resistance to marine conditions can significantly extend the lifespan of ARs. Furthermore, AR developers should establish regular maintenance and inspections protocols to identify and address any structural issues before they lead to significant failures (Vieira et al., 2020). Developers can enhance the design and construction processes by fostering collaboration with structural technology experts, ensuring that ARs remain functional and practical over time (Yoris-Nobile et al., 2023).

Furthermore, the focus on innovation in eco-friendly materials and conservation-based projects can enhance the sustainability of ARs. Utilizing biodegradable materials or those that mimic natural reef structures can improve the ecological function of ARs while minimizing environmental impact (Chen et al., 2024). This approach aligns with the growing emphasis on sustainable coastal management practices, which balance human needs with ecological preservation. Private investment support can facilitate large-scale projects integrating these innovative designs, ensuring that ARs are deployed effectively to protect coastlines while enhancing marine biodiversity (Bracho-Villavicencio et al., 2024).

4. Conclusions

The research on artificial reefs (ARs) highlights the multifaceted benefits and challenges associated with their design, implementation, and maintenance. The integration of hydrodynamic principles, structural stability, and interlocking strength is essential for maximizing the effectiveness of ARs in coastal protection and marine ecosystem rehabilitation. However, developers must also navigate various risks, including environmental damage, structural failure, and the uncertainty of long-term effectiveness. By adopting proactive measures, such as thorough environmental assessments, adaptive management strategies, and the use of durable materials, AR developers can mitigate these risks and enhance the sustainability of their projects.

The future of AR development lies in a holistic approach that considers ecological, economic, and social factors. As the maritime industry evolves, embracing new technologies and innovative practices will be essential for creating effective and sustainable AR solutions. In addition, further research can analyze AR design to obtain the lowest wave transmission coefficient, while still considering hydrodynamics, structural stability, and interlocking strength, such as SIMHAR design.

The contribution of this research towards ARs is multifaceted, providing valuable insights for stakeholders involved in coastal management, environmental conservation, and marine resource development. Firstly, the study emphasizes the importance of integrating hydrodynamic principles and structural stability into AR design, which can significantly enhance the effectiveness of these structures in coastal protection. By recognizing the ecological aspect and hydrodynamical aspect, managers or researcher can explore innovative designs of hooks or lock mechanisms for ARs, the use of eco-friendly materials, or the use of non-hazardous and non-toxic waste, for example, fly ash bottom ash (FABA) or nickel slag.

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CRediT author statement

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