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REVIEW

Recent Advances in Sustainable Concrete and Steel Alternatives for Marine Infrastructure

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ABSTRACT

Marine infrastructure is increasingly vulnerable to harsh environmental conditions that accelerate the degradation of traditional materials such as Portland cement concrete and carbon steel. This review systematically investigates recent advancements in sustainable alternatives, including geopolymer concrete, engineered cementitious composites (ECC), bio-concrete, fiber-reinforced polymers (FRPs), and bamboo, stainless steel, and steel-CFRP hybrid bars. Each material is evaluated based on marine durability, mechanical performance, environmental impact, and cost feasibility using life cycle assessment, durability modelling, and a multi-criteria decision-support framework. The results reveal that geopolymer concrete and FRP reinforcement's exhibit superior corrosion resistance and environmental benefits, while ECC and steel-CFRP composites offer structural resilience with moderate environmental trade-offs. However, challenges remain in long-term performance validation, standardization, and market integration. The review concludes that a combined approach involving innovative materials, computational tools, and sustainability assessment is essential for advancing marine infrastructure. Outlook recommendations include focused field studies, development of regulatory guidelines, and interdisciplinary collaboration to drive the practical adoption of eco-efficient materials in coastal and offshore construction.

Keywords: Bio-Concrete Self-Healing Materials; Corrosion-Resistant Reinforcement; Fiber-Reinforced Polymer (FRP) Composites; Geopolymer Concrete; Life Cycle Assessment in Construction; Sustainable Marine Infrastructure

1. Introduction

This review is organized in the following manner to help readers navigate its content and structure effectively. Section 1 introduces the challenges in marine infrastructure and the environmental motivation for sustainable alternatives. Section 2 outlines theoretical frameworks and includes a discussion on the role of FEA in evaluating material behaviour under marine loads. Section 3 reviews recent research on sustainable concrete alternatives, such as ECC, geopolymers, and bio-concrete. Section 4 focuses on steel alternatives including FRP composites, bamboo, and stainless-steel reinforcements. Section 5 identifies current gaps in the literature related to long-term durability, cost analysis, and standardization. Section 6 synthesizes the findings using a comparative framework and a multi-criteria decision-support model. Section 7 concludes with key insights and recommendations for future research and adoption in practice. All the sections are presented in **Figure 1**.

Marine infrastructure, encompassing ports, harbours, coastal defences, and offshore platforms, faces relentless degradation from harsh environmental conditions. The synergistic action of chloride-induced corrosion, relentless wave action, dynamic tidal fluctuations, and aggressive biological attacks presents a formidable challenge, severely compromising the structural integrity and significantly curtailing the service life of conventional construction materials, particularly ordinary Portland cement concrete and carbon steel [1].

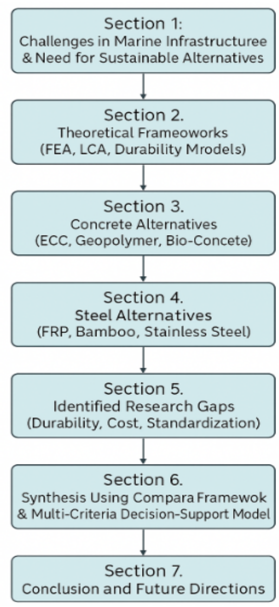

Figure 1. Flowchart illustrating the structured review.

Infrastructure owners are increasingly seeking extended service life, reduced maintenance demands, enhanced resilience, and improved sustainability for coastal structures, revealing that traditional construction materials often fall short of meeting these multifaceted requirements without costly and frequent interventions that may compromise safety [2]. This has led to the investigation and implementation of innovative and sustainable alternatives that not only exhibit superior durability and resistance to marine-specific deterioration mechanisms but also minimize the environmental footprint associated with material production and construction processes [3]. The deterioration of concrete structures in the marine environment is quite complex and involves chemical reaction between seawater and cementitious material, physical attack of waves and phase transition on tidal zone concrete surface, which could result in the weakening, spalling and the delamination of marine concretes [4]. To mitigate these degradation mechanisms, methods such as the use of supplementary cementitious materials to retard chloride penetration rates and, more potentially, the examination of alternative binder systems are employed. Introducing the requirements of sustainable construction into marine construction plans makes it imperative to explore the utilization of environmentally friendly materials and methods for the construction process, which can support the sustainable development of the marine economy and guarantee the long-term structural safety.

Traditional concrete in seawater is vulnerable to various degradation forms, such as chloride-induced steel corrosion, sulphate attack, alkali-silica reaction and physical erosion [5]. The penetration of Cl− ions from seawater causes the de passivation of the rebar, generating an electrochemical corrosion attack known as rebar corrosion, which causes rebar section loss, concrete cracking, and eventually structural failure [5]. The deterioration of concrete exposed to marine environments is a major issue, particularly because a large number of the world's mega-cities are situated in coastal zones [6]. This enhances the exposure of RC to corrosive marine environment [7]. As a result, the penetration of chloride and the subsequent chloride induced corrosion of reinforcement is one of the main factors that can significantly shorten the service life of these structures [8]. The use of suitable concrete materials will be important for durability in these aggressive marine environments [9]. Seawater Seawater, with a salinity of about 3.5 wt. % of Na^+, Cl^-, Mg^{2+}, Ca^{2+}, K^+, and SO_4^{2-} is of prime importance on the deterioration process. These ions are able to enter the pores of concrete and react with its constituents, resulting in structural deterioration [10]. In some areas, the nature of construction aggravates the problem, e.g., using sea sand and aggregates contaminated with chloride.

The environmental costs associated with conventional concrete and steel production, in particular high emissions of carbon dioxide during cement production and energy-extensive processes for making steel, have been brought to the global attention, deemed to make a turn towards greener construction. Such an approach to sustainable options for marine infrastructure construction is driven by a combination of achieving better structural performance together with a reduction of environmental footprint. Alternate materials would need to have similar or greater mechanical properties, improved resistance to marine environment-related degradation, and lower carbon footprint than existing materials. This extensive review focuses on the latest developments in sustainable concrete and steel alternatives for use in marine infrastructure, with an overview of their constituents, performances and environmental advantages. This review also emphasizes the lack of knowledge on the long-term behaviour of new materials, in particular environmental concrete, when applied to marine structures [1,4].

This chapter highlights the imperative for sustainable materials in marine infrastructure as a result of the rapid degradation of conventional materials such as Portland cement and carbon steel in harsh marine environments. The impact of environmental influences on traditional construction methods, plus the need for higher level of maintenance and shorter life span, has led to the search for materials and products with superior durability and environmental friendliness.

2. Theoretical Frameworks for Sustainable Marine Infrastructure

FEA-Based Evaluation of Material Behaviour under Loads

Finite Element Analysis (FEA) has become an important tool to model the structural behaviour of innovative materials used in marine structures under a wide range of loading conditions. Active marine environments are notorious for the heavy presence of chloride, wave load, corrosion and temperature variation that goes to require pre-design research.

FEA enables the simulation of stress-strain behaviour, crack propagation, and failure modes in concrete composites, reinforcement systems, and hybrid materials. It also supports the integration of material degradation models to predict long-term durability under cyclical and sustained loads.

Applications of FEA in marine infrastructure include:

1. Evaluation of geopolymer and ECC behaviour under axial, flexural, and shear loads.

2. Analysis of bond strength in FRP and steel-CFRP composites with varying surface treatments.

3. Simulation of chloride diffusion effects on reinforced members.

4. Coupled FEA-CFD modelling for wave impact on pile and deck structures.

Recent studies have demonstrated the value of FEA in validating experimental results and optimizing reinforcement layouts. For instance, researchers used FEA to validate the bond performance of Steel-CFRP bars in coral concrete, while simulated the enhanced flexural strength of GFRP-reinforced concrete beams in saline environments.

By integrating FEA into the material development and structural design process, engineers can reduce material usage, enhance safety margins, and extend service life—key pillars of sustainable marine construction.

The theoretical underpinnings for developing sustainable marine infrastructure revolve around minimizing environmental impact while maximizing structural performance and longevity [11]. Life Cycle Assessment has been increasingly used as a framework to quantitatively evaluate the environmental burdens associated with different construction materials and methods, encompassing resource extraction, manufacturing, transportation, construction, use, and end-of-life stages. This exhaustive analytics enables to take informed decisions in the selection of materials, driving the selection of the alternatives with less environmental impact. The attention on a long-term commercial feasibility along with the sustainability aspects is crucial requiring a frame work of assessment, which takes together technical, economic and environmental aspects. It is hoped that this framework will promote the identification and prioritization of research studies aimed at developing or enhancing materials for eco-friendly construction [12].

Durability prediction is a key step for forecast the long service life and lower maintenance needs of materials in aggressive marine environment for the structural engineers. Chloride ingress, corrosion, and biofouling are among the deterioration mechanisms included into these models to predict structural components remaining service lives. Reliable prediction of degradation can enable engineers to select materials more wisely, design proper protection and apply efficient maintenance, extending the life cycle of marine structures. In addition, the principles of circular economy are being applied in the field of sustainable marine infra-structure (i.e., reuse and recycle of materials, waste reduction, resources efficiencies, and so on).

Durability modelling is very important to predict the performance of materials in marine environments with a time perspective and in relation to the chloride ingress, the corrosion rates, the effects of temperature and humidity. More advanced models take the combined action of several mechanisms of degradation, which allows a more accurate service life prediction along with an optimized choice of materials. A performance-based design is also a key part of sustainable marine infrastructure, as it moves away from specifying pre-packaged materials towards performance requirements that directly support the intended service life and performance of the structure. This provides an incentive to focus on based materials and art styles which perform in a specific manner without having to fit into preconceptions about how this should be done. The design of sustainable materials also requires a thorough knowledge of the degradation processes under marine conditions, such as the role of micro-organisms, radiation from ultraviolet sources, and abrading. The theoretical framework has represented in **Table 1**.

To do so, one must have a good understanding of the type of environment the materials are subject to, as materials that may be satisfactory in one type of environment stand a much greater chance of deteriorating in another. Computational modelling methodologies, such as finite element analysis (FEA) and computational fluid dynamics (CFD), are being used more and more to simulate the response of marine structures subjected to different types of service loading, for example wave, earthquake, and ship impact loadings.

Table 1. Theoretical frameworks for sustainable marine infrastructure.

Framework Component	Purpose	Significance
Life Cycle Assessment (LCA)	Quantitatively evaluates environmental burdens throughout the material life cycle.	Supports sustainable material selection and minimizes environmental impact.
Durability Modeling	Predicts long-term material performance under marine deterioration mechanisms.	Improves structural longevity and informs protective maintenance strategies.
Circular Economy Principles	Encourages reuse and recycling of materials.	Minimizes resource depletion and supports waste reduction in marine projects.
Performance-Based Design	Focuses on achieving functional and service-life criteria rather than strict material specifications.	Promotes use of innovative materials tailored for marine durability and performance.
Environmental Degradation Understanding	Analyzes deterioration factors such as microbial action, UV exposure, and abrasion.	Aids in selecting and developing materials resistant to marine-specific challenges.
Computational Modeling Techniques	Simulates marine structural behavior under varied loads using FEA and CFD.	Enhances predictive design and structural optimization under complex marine conditions.

It is essential to have a sound theoretical basis to assess sustainable materials. The applicability of LCA, FEA, durability modelling, and performance-based design involved in the selection of materials and the optimization of structure are discussed in this section. These tools help engineers evaluate performance over the long term, minimize environmental impacts and design for infrastructure resilience.

3. Current Research on Concrete Alternatives

Sustainable alternatives to concrete are heavily investigated across a wide range of materials and methods which include supplementary cementitious materials, alternative binders and novel reinforcement approaches. The inclusion of supplementary cementitious materials, including fly ash, slag and silica fume, has been increasingly in use to lower cement content in the concrete mix, reducing the carbon footprint and improving durability. The **Figure 2** represents current research on concrete alternatives.

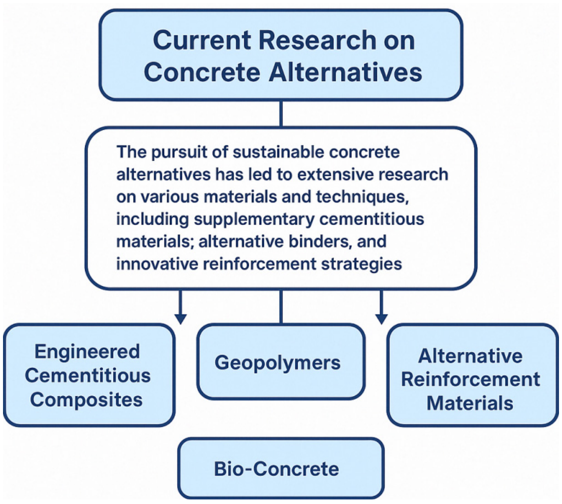

Figure 2. Research on concrete alternatives.

3.1. Engineered Cementitious Composites

ECC is a revolutionary concrete with increased ductility and crack resistance compared to normal concrete [1–5]. ECCs generally contains significant amounts of fly ash or other pozzolans, achieving an even lower environmental footprint. The addition of fibers, such as polyvinyl alcohol fibers, allows ECCs to sustain large deformations without fracturing, which renders them particularly suitable for demanding uses due to a high tensile and flexural strength.

3.2. Geopolymers

Geopolymer is a potential alternative to Portland cement-based concrete which is produced by the alkali activation of aluminosilicate precursors. These materials have a combination of really good mechanical properties, weather and chemical resistance, which makes them suitable for marine applications, as described in **Figure 3** [13].

Figure 3. Different material types used in sustainable concrete [13].

Geopolymer precursors based on waste products such as fly ash, slag, metakaolin, etc. add up to its sustainability. In addition, concrete based on geopolymer is reported to have enhanced chemical resistance and low water absorption with an ambient curing regime [14]. Geopolymer concrete made by using industrial waste products such as fly ash is being fabricated to lower CO_2 generation and thus an eco-friendly alternative to cement based concrete [15]. Preparation of Geopolymer Geopolymers production is manufactured by alkaline activation of aluminosilicate sources such as fly ash or metakaolin with the extract binder has good mechanical and durability (**Figure 4**) [16].

3.3. Bio-Concrete

The use of bio-concrete, where bacteria are used to precipitate calcium carbonate, is a novel way to improve the durability and self-healing properties of concrete structures. The integration of bacteria, typically from the *Bacillus* genus, into concrete mixes promotes the formation of limestone through metabolic processes, effectively sealing cracks and preventing the ingress of harmful substances. This self-healing mechanism enhances the longevity of structures, reducing maintenance needs. The incorporation of microorganisms into concrete can induce calcium carbonate precipitation, leading to self-healing of cracks and improved durability, representing an environmentally friendly and sustainable approach to concrete repair. To reduce the proportion of greenhouse gases in the atmosphere, researchers have explored using alternative materials to Portland cement, as well as recycling solid waste or by-product materials from iron manufacturing or power plants; geopolymer materials have emerged from this effort [17]. **Figure 5** shows the Geopolymer structure.

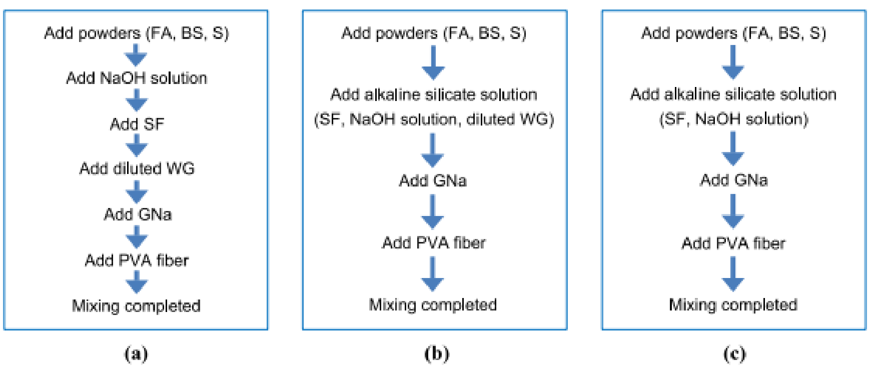

Figure 4. Three fiber-reinforced geopolymer (FRG) mixing methods (**a–c**) were conducted in Series A, including elements, such as fly ash (FA), blast furnace slag (BS), fine aggregate (S), sodium hydroxide (NaOH), silica fume (SF), sodium silicate (WG), sodium gluconate (GNa), and polyvinyl alcohol (PVA) [16].

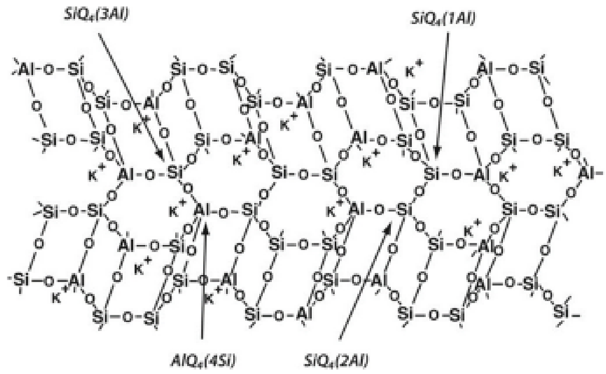

Figure 5. Geopolymer structure [17].

Geopolymers use industrial waste byproducts as precursors for the geopolymer binder; additive manufacturing with geopolymer composites offers easy fabrication, design freedom, and reduced expenses, time, waste, and labor [18]. Geopolymers not only possess outstanding mechanical qualities, but also a variety of superior qualities, including fire and corrosion resistance [19]. This positions them as a sustainable building material .The Composition of geopolymer concrete are shown in **Figure 6**.

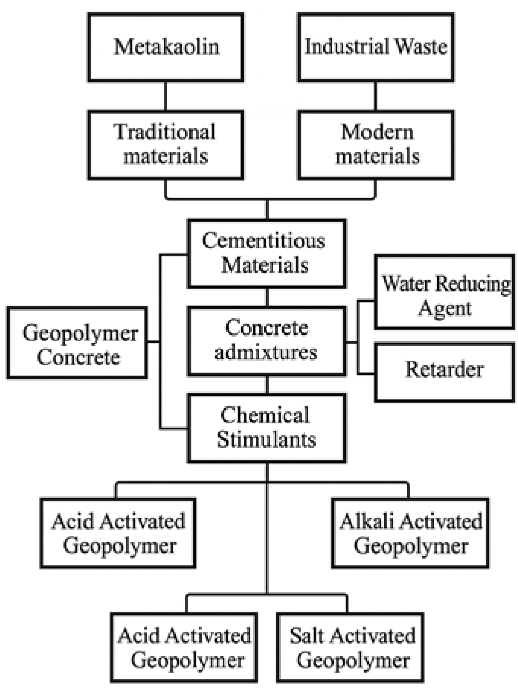

Figure 6. Composition of geopolymer concrete [17].

Bio-concrete is gaining traction as a sustainable and self-healing construction material, offering the potential to extend the service life of concrete structures and reduce maintenance costs. The ability of bio-concrete to autonomously repair cracks and resist aggressive environments makes it particularly appealing for marine infrastructure, where durability is paramount. Bio-concrete is a self-healing concrete that can automatically repair cracks using bacteria to produce limestone, reducing the need for manual repairs. Cracks in concrete can cause leakage and corrosion of steel reinforcement, but bio-concrete can seal these cracks and prevent waterborne ions from entering [20]. **Figure 7** represents the bio based concrete cubes and cylinder casting.

Figure 7. Bio-based concrete cubes and cylinder casting [20].

Conventional SCMs like blast furnace slag and fly ash have long been studied for their impact on cement hydration and concrete properties [21]. Due to supply issues, recent focus has shifted to alternative SCMs [22]. Replacing cement with SCMs helps lower concrete's carbon footprint [23]. Materials like silica fume, fly ash, and met kaolin improve workability, strength, and durability [24,25]. Their use offers economic and environmental benefits, enhancing long-term performance, and is growing globally in ready-mix concrete applications [22,26]. Supplementary cementitious materials enhance concrete's mechanical characteristics, manage alkali-silica reactions, and improve durability through chloride binding [27]. Concrete is at the forefront of total production among man-made engineering materials, but its fabrication, use, and demolition have contributed to CO_2 emissions, groundwater pollution, and damage to the natural riverbed [27].

3.4. Alternative Reinforcement Materials

Fiber-reinforced polymer (FRP) composites are strong, corrosion-resistant alternatives to steel in concrete, especially effective in marine environments by extending service life and reducing maintenance [3]. Common types include glass, carbon, aramid, and basalt FRPs—each offering specific benefits like high strength, light weight, and durability. Basalt FRP is cost-effective with better alkali and heat resistance. FRP degradation depends on material quality, manufacturing, matrix plasticization, and fiber–matrix bonding [3]. Due to steel's high cost and environmental impact, bamboo is being explored as a sustainable, low-cost reinforcement option [28]. The alternative reinforcement materials are explained in **Table 2**.

FRP composites are increasingly used in concrete to address steel corrosion issues [29]. While offering high tensile strength, light weight, and corrosion resistance [30], their durability may be compromised by UV radiation, moisture, chemical attacks, and high temperatures [3]. FRP rebars need less concrete cover and admixture and resist chloride ions and corrosion [30]. Fiber-reinforced concrete improves permeability under stress and enhances rebar bonding and corrosion control [31]. Glass FRP is especially suited for marine environments due to its strength and durability [32]. Bamboo is gaining attention as a low-cost, renewable, and biodegradable alternative to steel, especially in regions where it is abundant.

Table 2. Alternative reinforcement materials.

Reinforcement Material	Type/Variant	Key Advantages	Challenges/Limitations	Applications/Remarks
Fiber-Reinforced Polymer (FRP)	Glass FRP (GFRP)	High tensile strength, lightweight, corrosion-resistant	Susceptible to high temp, moisture, UV, alkaline attack	Widely used in marine structures; requires less cover and no corrosion protection
Fiber-Reinforced Polymer (FRP)	Carbon FRP (CFRP)	Very high strength, corrosion resistance, light weight	Expensive	Suitable for high-performance marine structures
Fiber-Reinforced Polymer (FRP)	Aramid FRP (AFRP)	Good impact resistance, corrosion resistance	UV sensitivity, higher cost	Used where high toughness is needed
Fiber-Reinforced Polymer (FRP)	Basalt FRP (BFRP)	Economical, good alkaline and temperature resistance	Less explored compared to GFRP/CFRP	Emerging as a cost-effective alternative
Bamboo	Natural composite	Renewable, low-cost, biodegradable, available in abundance	Biodegradable, lower strength than steel, durability issues	Sustainable alternative in low-cost applications, especially in developing regions
General FRP Composites	FRP grids/bars	Non-corrosive, high strength-to-weight ratio, reduced maintenance	Durability affected by environment, matrix plasticization, fiber-matrix interface degradation	Effective in extending service life of marine concrete structures
Fiber-Reinforced Concrete	With FRP or natural fibers	Improves stress permeability, rebar corrosion resistance, bond with old concrete	Dependent on mix design and placement method	Ideal for repair and marine environment use

3.5. Steel-CFRP Composite Bars

Steel-CFRP composite bars combine steel's tensile strength with CFRP's corrosion resistance, offering an effective reinforcement for marine concrete structures [33]. These bars have a steel core wrapped in CFRP, which enhances durability by blocking chloride ingress and preventing steel corrosion. They provide high strength, ductility, and corrosion protection—ideal for marine applications [33,2]. FRP bars, including glass, carbon, and hybrid types, are increasingly replacing steel due to their non-corrosive nature and durability [34,35]. Hybrid FRP rebars, combining different fibers, improve ductility and prevent brittle failure [36]. Though glass FRP is widely used [3], its non-biodegradability raises sustainability concerns, leading to interest in eco-friendlier options. Composite materials offer a revolutionary approach to enhancing the durability and lifespan of marine structures by combining the strengths of different materials. They hold immense potential for use in marine applications because of their light weight, high strength-to-weight ratio, and resistance to corrosion. The application of fiber-reinforced polymer composites in marine structures offers several benefits, including corrosion resistance, high strength-to-weight ratio, and design flexibility. The application to marine structures of the fiber reinforced polymer (FRP) composites opens the way to a reduction of the maintenance and repair, with obvious economic advantages for the entire life of the structure.

3.6. Geopolymer Concrete

Geopolymer concrete is a promising new sustainable material for building applications across the globe being a potential alternative for ordinary Portland cement concrete especially in construction of marine environment structures requiring a high service life. Geopolymer concrete is developed as a sustainable replacement of conventional Portland cement concrete, to reduce ecological impact caused by cement industry. Geopolymer concrete is a concrete that utilizes industrial waste products such as fly ash and slag as a binding agent instead of Portland cement. And not only is geopolymer concrete greener, as it doesn't need cement, it is also reduces carbon emissions. Geopolymer concrete is created using industrial by-products like fly ash or slag. This type of concrete is harder than ordinary concrete, and resists sea water and sulphates, so it lasts longer. The excellent chloride penetration resistance of geopolymer concrete also make it a great choice for marine structures where such structures are continuously exposed to sea water and subjected to chloride attack. It is highly immune to chemicals, heat and can be a long lasting option when in contrast to standard concrete. In particular, the performance of geopolymer concrete in marine environment is of special interest because of its excellent chloride resistive characteristics, and thus, the risk of steel corrosion is reduced [37]. Silica (and alumina) rich pozzolans are sustainable alternatives to similar functionality materials that have been conventionally used to date [38]. One of the significant benefits of the geopolymer concrete is its use of waste products such as fly ash and ground granulated blast furnace slag as a binding agent that reduces the requirement for Portland cement, which has high carbon footprints [39]. The manufacturing of ordinary Portland cements is quite energy consuming, and CO_2 gas (Green House Gas) is produced as a by-product, contrary, use of industrial by-products in geopolymers is more environment friendly.

The use of geopolymer concrete provides improved durability in marine, high chemical resistant environments, less permeable structures with a longer design service life. Geopolymer concrete has many advantages over conventional concrete when it comes to marine environments, it's more sustainable due to use of industrial by-products (reducing the carbon footprint) and it's extremely good to resist corrosion. Geopolymer concrete, which is early strength, chemical-resistant, and durable, is especially for marine structures application [40]. Geopolymer concrete stands up in the marine environment It works and is eco-friendly, so use it to develop sustainable marine infrastructure. The lower permeability of the geopolymer cement decreases the penetration of detrimental chemicals such as chlorides and sulphates which are present in marine environment and therefore protect the matrix concrete and steel bars from degradation [41,42]. Geopolymer concrete is an environmentally friendly and long life material which is suitable for marine structure. The low permeability of the geopolymeric concrete provides a barrier which slows the penetration of chloride ions into the concrete and thus helps to protect steel reinforcement from corrosion, increases the life expectancy of marine structures and reduces the amount of maintenance that is necessary [43,44].

Geopolymer Concrete is an emerging option to Portland cement concrete when a durable solution is required in marine environments. Geopolymer seawater concrete is expected to greatly decrease the carbon signature of the construction industry and enhance the life of marine structures. Constructing with geopolymer concrete can dramatically lower the carbon footprint of a construction project, as it requires less energy than typical cement to produce. The excellent resistance of geopolymer concrete is most beneficial in marine environment such as seawater and chlorides which can accelerate deterioration of ordinary concrete due to corrosive action. The reason is its resistance to both seawater and sulfates [45]. Geopolymers are emerging binders considered as a possible replacement for OPC binders [46]. Geopolymers have superior mechanical properties, and cure and solidify under room temperature with 80 to 90% less CO_2 emission than Portland cement [47]. The use of fly ash in geopolymer concrete provides the two-fold benefits such as a saving of natural resources and reduced environmental pollution due to waste disposal, and, positive effects on mechanical and durability properties of resulting concrete [48]. In addition, binding material of geopolymer concrete which is in the form of ground granulated blast furnace slag supports the increase in conservation as well as reduction in the waste, which in turn meets the objectives of sustainable development [49]. The application of fly ash, GGBS and metakaolin as ternary blend source materials in geopolymer concrete has been studied to optimize local waste materials efficiently [50]. **Table 3** represents the concrete alternatives with component, purpose and significance.

These recent developments such as ECC, geopolymer concrete and bio-concrete have the potential for positive sustainability implications. These materials improve mechanical properties, decrease CO_2 emission and prolong the life of the structure. The use of supplemental cementitious materials (SCMs) enhances durability and sustainability.

Table 3. Concrete alternatives: component, purpose, and significance.

Component	Purpose	Significance
Engineered Cementitious Composites (ECC)	Enhance concrete ductility and crack resistance using fibers and supplementary cementitious materials.	Improves structural resilience and reduces environmental impact in high-performance applications.
Geopolymers	Utilize industrial byproducts like fly ash and slag activated with alkaline solutions to replace traditional cement.	Reduces CO_2 emissions, enhances durability, and offers resistance to chemical and thermal attacks in marine environments.
Bio-Concrete	Employ bacteria (e.g., Bacillus) in concrete to induce self-healing through calcium carbonate precipitation.	Extends service life of structures, reduces maintenance, and enhances sustainability through autonomous crack repair.
Supplementary Cementitious Materials (SCMs)	Partially replace Portland cement in concrete using fly ash, slag, and silica fume to improve performance.	Boosts strength and durability while lowering the carbon footprint and conserving resources.
Alternative Reinforcement Materials (FRP, Bamboo)	Replace steel with corrosion-resistant FRPs or renewable bamboo in reinforcement applications.	Improves lifespan and sustainability of reinforced structures, especially in marine environments.
Steel-CFRP Composite Bars	Combine steel's tensile strength with CFRP's corrosion resistance to create hybrid reinforcement bars.	Enhances durability, reduces corrosion risk, and is ideal for marine infrastructure with long-term exposure.

4. Current Research on Steel Alternatives

4.1. Fiber-Reinforced Polymer Composites

Fiber reinforced polymer (FRP) composites are revolutionizing marine construction by providing lightweight and high-strength corrosion resistant replacements for steel [51]. They offer high strength-to-weight ratios, and can generally be moulded with more flexibility than one would expect from a common design material--thermoset fiberglass. FRPs minimize maintenance requirements and increase longevity of the structure, which makes it cost-effective in the long run. Unlike steel, FRPs provide resistance to seawater degradation and can be custom designed for specific structures. Furthermore, they minimize the environmental load through reduction of the dependence of resource-consuming materials and frequent repair with low carbon emission [51].

Fiber reinforced polymer (FRP) composites are environmentally benign as they are light weight, durable and can be designed to fit [52] (especially as to marine structures). Hybrid composites with multiple fibers further enhance performance for specific applications [52]. FRPs lower natural resource use, transport costs, and extend infrastructure lifespan, promoting sustainability, though glass fibers raise environmental concerns due to non-biodegradability [53]. Natural fiber composites offer a partially renewable alternative [51]. Despite being costlier than steel—up to 10 times more—FRPs offer high strength, corrosion resistance, and ease of maintenance, making them ideal for aging infrastructure [54,55]. Their adoption spans various fields beyond aerospace, but understanding of their mechanical behaviour is still evolving [56,57]. FRPs are widely used in marine construction for their high strength-to-weight ratio and corrosion resistance [58,59]. Ongoing research aims to optimize their performance and affordability. They improve structural integrity, reduce maintenance, and extend service life in marine environments [60]. FRPs are also useful for repairs and preventing chloride-induced corrosion in concrete [36,61]. Proper selection depends on fiber type, resin, and production methods. The Fiber-reinforced polymer composites in marine construction are explained in **Table 4.**

Table 4. Fiber-reinforced polymer composites in marine construction.

Aspect	Description	Advantages	Challenges/Considerations
Material Type	Fiber-Reinforced Polymer (FRP) Composites	High strength-to-weight ratio, corrosion resistance, customizable designs	Higher initial cost, requires specialized knowledge for design and use
Marine Suitability	Ideal for corrosive marine environments	Superior resistance to chloride-induced corrosion, long service life	Durability in harsh marine environments must be verified through long-term testing
Applications	Used in marine structures, floating platforms, retrofitting, and rehabilitation	Minimizes structural weight, allows tailored performance	Design not as well understood as steel, requires engineering expertise
Environmental Impact	Promotes sustainability by reducing need for resource-intensive materials	Lower carbon footprint, less need for repairs and heavy machinery	Glass fibers are non-biodegradable, potential toxicity to aquatic life
Design Flexibility	Customizable to project-specific requirements using hybrid composites	Optimized structural performance, tailored mechanical properties	Requires careful material selection and quality manufacturing processes
Economic Factors	Despite higher upfront costs, lower lifecycle costs	Reduced maintenance, fewer replacements, long-term savings	Initial cost can be up to 10x higher than steel
Sustainability Trends	Growing interest in natural fiber composites	Renewable and partially biodegradable, increased global awareness	May have lower mechanical performance compared to synthetic fibers

Table 4. *Cont.*

Aspect	Description	Advantages	Challenges/Considerations
Long-Term Use	Used in rehabilitation of aging infrastructure	Improves structural integrity, delays deterioration	Needs assessment of long-term performance in situ
Structural Benefits	Provides strong, durable reinforcement without corrosion	Increases safety and reliability of marine infrastructure	Proper selection of fiber and resin matrix is crucial
Research & Development	Continual improvements in cost-effectiveness and performance	Expanding applications from aerospace to marine and civil sectors	Requires ongoing innovation to address limitations and improve affordability

4.2. Stainless Steel

Stainless steel has emerged as a premium alternative to carbon steel in marine environments because of its exceptional corrosion resistance and durability, offering a long-term solution for structures exposed to harsh marine conditions. Using stainless steel in marine construction reduces maintenance costs and extends the life of structures, even though it costs more upfront. Stainless steel can withstand corrosion, making it ideal for use in marine environments, where it helps infrastructure last longer and reduces the need for repairs. Stainless steel's resistance to corrosion is due to its chromium content, which forms a passive layer of chromium oxide on the surface, protecting the underlying steel from corrosion. Stainless steel is particularly effective in splash and tidal zones, which are highly susceptible to corrosion because of constant exposure to seawater and oxygen. Stainless steel is frequently used in marine infrastructure projects because of its great strength, corrosion resistance, and low maintenance needs.

Different stainless steel types—such as austenitic, ferritic, and duplex—offer tailored mechanical and corrosion resistance for marine applications [62]. Duplex stainless steels, with combined austenitic-ferritic structures, provide superior strength and corrosion resistance, while lean duplex grades offer cost-effective solutions with sufficient durability [62]. Stainless steel rebars improve bond strength with concrete and reduce life cycle costs compared to carbon steel [63,64]. They help prevent corrosion-induced damage, preserving marine structure integrity [65]. Their effectiveness depends on chloride thresholds, chemical composition, and metallurgical factors [66,67]. Stainless steel rebars ensure long service life, reduced maintenance, and high corrosion resistance in chloride-rich environments [67,68]. Their increasing adoption reflects a shift toward durable, long-lasting marine infrastructure [64].

Stainless steel is used in marine infrastructure projects that require long-term durability and resistance to corrosion, and it is a reliable alternative to traditional carbon steel. The use of stainless steel can greatly improve the durability and lifespan of marine infrastructure because of its high resistance to corrosion in harsh environments [69]. Concrete structures in marine environments often suffer from steel reinforcement corrosion because chloride ions can penetrate the porous concrete and reach the steel [70]. Using galvanized reinforcement is one protective measure used to extend the life of concrete. Various techniques, including cathodic protection, inhibitor dosage, or coatings on the concrete surface or reinforcing steel, are frequently used to reduce the effects of rebar corrosion [71]. Introduction of stainless steel reinforcement in concrete structures provides for corrosion resistant solutions, especially in aggressive marine environment [72]. In fact, the application of Cr- bearing rebars in concrete structures has been found to have promising corrosion resistance for the extension of life-span in marine infrastructures [73].

In this section, the alternatives such as FRP, bamboo, stainless steel and steel-CFRP hybrid bars as reinforcements are examined. These products offer the best corrosion resistance, reduced weight, and a sleek style over traditional steel whilst providing superior strength and durability.

5. Gaps in the Literature

5.1. Durability and Long-Term Performance

Reliable and durable marine alternatives for concrete and steel exist and appear to possess potential for use in maritime infrastructure, but literature on their long-term performance and durability remains limited. Further work is required to gain a better understanding how these materials behave over the long term in a marine environment. Despite the potential of new age materials, there is a need for a comprehensive evaluation of the long-term performance of these materials in an open marine environment. Long-term performance data is necessary to assess the lifecycle cost and environmental benefits of sustainable materials. Prognosis in the performance of sustainable material in the long run is very important to evaluate sustainable materials for marine structures [74]. Further work is required to establish the long-term durability and performance of 'green' concrete and metal alternatives in the marine environment. This entails analyzing their resistance to corrosion, erosive, degradation, and other properties in different environmental scenarios. Despite an increasing interest in the application of green/sustainable concretes and steel alternatives for marine infrastructure, long-term performance and durability data are generally sparse. More studies are necessary to close these gaps for safe and economical design of marine structures.

5.2. Life Cycle Assessment and Cost Analysis

The life cycle assessment and cost analysis of sustainable alternatives to concrete and steel is essential to take the right decisions in the construction of maritime infrastructures. Environmental impacts are evaluated through a life-cycle assessment (LCA), from cradle to grave, whereas economic factors are analysed in a cost analysis to assess the economic feasibility of using sustainable materials as against conventional ones. Life cycle assessment and life cycle cost calculations are indispensable for assessing economic and ecological benefits of the utilization of sustainable alternatives into the marine infrastructure works. Life cycle analysis and cost-effective analysis are essential to assess the sustainable materials for long-term environmental and economic benefits in marine infrastructures.

Knowledge of the life cycle cost and environmental burden of the different materials used for sustainable marine structure is important for decision making purposes.

Public infrastructure owners demand longer service-life, less maintenance, repair and rehabilitation liability, resilience and sustainability motivations and it is now clear that traditional construction materials are not the solution to fulfil all the requirements with certainty [2].

Building performance is highly dependent on material choice, and sustainable materials need to be identified as early in the design phase as possible [75]. LCA assesses the total environmental impact of a material holistically [76] and cost analysis quantifies the economic competitiveness of a material [77]. Common materials need to be repaired often and are sensitive to marine environment e.g. corroding and crack propagation [2,78]. Preventive strategies such as cathodic protection are applied, but well-designed studies are needed to evaluate their long-term sustainability [2,77]. The assessment of laminated materials is very important because the degree of their ecological and structural approval could be estimated [75,79]. Considering that environmental and cost impact of the materials are some of the big concerns for the shift of trend in societal needs and desires caused by climate change and depletion of resources, it is necessary to evaluate both of environmental and economic inputs for materials [80]. LCA and cost analysis are useful instruments to support sustainability choices in the design of marine infrastructure [81,82], particularly the design phase [83], as the environmental situation is changing fast and strong assessments are required [84].

5.3. Standardization and Guidelines

Lack of universally agreed upon standards or guidelines for the application of environmentally sustainable alternatives of concrete and steel materials in marine infrastructure has potentially limited the large-scale use of these materials. Engineers and workers constructing with these materials must have a clear set of standards to follow to secure safe and effective use of all materials in marine applications. It is with no reference testing method and performance indexes comparatively between several materials, one could be able to compare different mediums to determine whether they can be applied in certain condition. Gaps in standardised criteria and specifications pose obstacles for the acceptance of sustainable materials in the marine works. A lack of consistent standards and guidance can be a barrier to the broad application of sustainable materials on marine infrastructure projects. Standardized testing methodologies and performance specifications are required in order to provide stakeholders with a rational means to evaluate and compare sustainability and performance attributes for different materials. Development of standardized testing protocols and performance reference levels will be important in order to allow consistent characterization and comparison of materials. Government agencies, industry groups, and research organizations must team up to facilitate the extensive use of sustainable non-concrete and non-steel alternatives in marine construction. To do so, it is necessary for all stakeholders to work together to develop comprehensive standards and guidelines that take the specific challenges of these materials in marine applications into account.

The establishment of industry standards for sustainable construction materials is paramount to inspire trust and ensure high quality control for sustainable materials used in marine infrastructures. "It is a must that industry standards are developed to instil confidence and to ensure quality control in marine infrastructure projects; this will naturally promote wide usage of environmentally friendly materials. It is important that standards of practice be established to assist uniformity in application and maintenance that will help to assure that sustainable materials perform as intended and continue to be of benefit to the environment. Such standardization of construction document forms may be beneficial to owners, contractors and architect/engineers [85]. The importance of this research will aid the construction sector with harmonized criteria on sustainable construction material [86]. It will also help architects and engineers to choose more sustainable materials effectively [86].

The future of the construction sector can rely upon the mass utilization of sustainable building materials due to the growing trend of sustainability and the circular economy in construction [87]. To support the principles of a circular economy in the construction sector, material passports and digital platforms should be adopted to scrutinize material flows and evaluate the level of circularity in buildings [88]. To fully exploit the promises of circular economy in sustainable construction these barriers need to be overcome, and industry players, policy makers and researchers should find structural partnership to work together [89]. The lack of unified standards and regulations is a barrier that prevents the broader use of sustainable materials in marine civil engineering works. In addition, education toward a sustainable society can help to raise awareness about principles of sustainable construction [90]. For the construction industry's pro-active move, there's the academic sector that should offer sustainable construction courses for project managers-wannabe. A construction-management workforce that is more well-versed in sustainable design practices and processes is expected in the twenty-first century [91].

5.4. Economic Viability and Market Readiness

The economic feasibility and market readiness of environmentally friendly concrete and steel alternatives are crucial for their adoption in marine infrastructure schemes. The higher initial costs of sustainable materials, if any, may not be very high when compared to conventional materials as the eventual benefits in terms of maintenance and service life may ultimately render them a cheaper alternative from economic perspectives over the lifecycle of the infrastructure [92]. LCC calculations are important to determine the economic feasibility of sustainable materials, including initial cost, ongoing cost, repair cost and end of life cost [93]. Government subsidies or tax credits for such materials can further increased the economic monopoly of green materials in marina construction project [94]. In addition, to aid long-term economic and climate competition, it is hot required to consider the embodied energy related to material production and transportation. In order to realize the economic and environmental advantages of these sustainable materials, However, the entire life cycle of the structure must be taken into account, from raw material extraction to end-of-life disposal or recycling. Moreover, design flexibility of the infrastructure can also extend design life. This requires system-wide approaches that consider indirect costs, as well as greenhouse gas emissions and other environmental consequences. A holistic approach consisting of carrot-and-stick incentives, some of which are publicly imposed and some are market-based, complemented with due attention to the industry cooperation, should be the key tool to unlock the full potential of these types of sustainable materials for the marine infrastructure, and the societal benefits arises thereof [95].

Albeit the recent progress, the knowledge on the long-term behavior of sustainable materials in a marine aggressive environment still lacks of appropriate attention. Uniform policies, full life cycle analyses, cost estimates and economic f easibility are still missing. It is imperative to fill these gaps for broad application and utilization.

6. Synthesis and Future Directions

6.1. Critical Synthesis and Comparative Framework

To assist in making a decision on which sustainable marine infrastructure materials should be used, the reviewed materials are examined according to the technical performance, environmental profile, economic viability, and marine service life. This synthesis will result in a complete comparison between all decision criteria considered for engineering and infrastructure development decision-makers. The Comparative Analysis of Sustainable Marine Infrastructure Materials Based on Technical, Environmental, and Economic Criteria represented in **Table 5**.

Table 5. Comparative Analysis of Sustainable Marine Infrastructure Materials.

Material Type	Durability in Marine Environment	Mechanical Strength	Corrosion Resistance	Environmental Impact	Cost Feasibility	Standardization Status
Geopolymer Concrete	High	High	Moderate	Very Low CO_2	Moderate	Limited
ECC	Very High	Very High	Moderate	Moderate	High	Moderate
Bio-Concrete	Moderate	Moderate	Self-healing	Low	Moderate	Experimental
SCM-Based Concrete	Moderate to High	Moderate	Improved vs. OPC	Lower CO_2	Low	High
FRP Reinforcement	Very High	Very High	Excellent	Moderate	High	Growing
Bamboo Reinforcement	Low to Moderate	Low	Low	Very Low	Very Low	Limited
Steel-CFRP Composite	High	Very High	Excellent	Moderate	High	Experimental
Stainless Steel	Very High	High	Excellent	High CO_2	Very High	High

6.2. Multi-Criteria Decision-Support Model (MC-DSM)

The **MC-DSM** applies weighted scoring across five performance dimensions:

1. **D**: Durability in marine conditions (weight = 0.30)
2. **S**: Structural/mechanical strength (weight = 0.25)
3. **C**: Corrosion resistance (weight = 0.20)
4. **E**: Environmental impact (weight = 0.15)
5. **F**: Financial cost and feasibility (weight = 0.10)

Each material is scored from 1 (low) to 5 (high), and a total weighted score (TWS) is calculated.

The weighted scoring of sustainable marine materials represented in **Table 6**. FRP reinforcement and geopolymer concrete rank highest due to their superior corrosion resistance and eco-friendliness. ECC and steel-CFRP composites also perform well but may require cost optimization. Bamboo and bio-concrete show promise for specific low-load or sustainable regional applications but are limited by structural reliability.

Table 6. Weighted Scoring of Sustainable Marine Materials Using the Multi-Criteria Decision-Support Model (MC-DSM).

Material	D	S	C	E	F	TWS
Geopolymer Concrete	5	4	3	5	3	4.20
ECC	5	5	3	3	2	4.05
Bio-Concrete	3	3	4	4	3	3.45
SCM Concrete	4	3	3	4	5	3.85
FRP Reinforcement	5	5	5	3	2	4.35
Bamboo	2	2	2	5	5	3.00
Steel-CFRP Composite	4	5	5	3	2	4.10
Stainless Steel	5	4	5	2	1	3.85

The application of sustainable building methods has been driven by growing environmental concerns, which have pushed the construction industry to look into environmentally friendly materials and techniques [96]. Construction is one of the environmental and resource consuming industries as it consumes much more material and energy and generates a huge number of trashes [97]. These impact are sought to be minimized through the adoption of green materials and efficient building technology, as principles of sustainable building practices [98]. Novel sustainable materials Recent work in research and development in the field of material development has aimed at developing sustainable alternatives to the traditional building materials such as concrete and steel, and in particular within the marine environment. The alternative is to reduce the environmental impact, add to the longevity of the system, and improve performance in marine conditions. It is therefore essential that the variables which affect choice of material are understood for sustainability to be encouraged in construction. In order to encourage more sustainable buildings, it is important to understand the variables that influence material selection, and decision-makers should understand the environmental and economic trade-offs associated with different materials used [95]. There is still a need for more research and the development of sustainable materials and construction methods for marine structures before we can use these materials and techniques to the fullest. More research and development is necessary to take advantage of the potential of sustainable materials and construction means on marine infrastructure (exploratory materials, construction procedures and design criteria). LCAs are becoming a key tool used for price-performance ratio of the built environment. The construction sector is critical to the achievement of sustainable goals and the choice of construction material is assuming ever greater significance as 44 it increasingly influences the ecological quality of construction over its The selection of construction materials is very critical with construction sector is crucial to contribute to sustainable development and choice of construction material is being seen as an idea whose time has come (115 more than 40 years) life cycle(including both embodied and operational energy/emission) [99,93]. Innovative materials, construction methods and design approaches must be researched in order to enhance the sustainability of marine infrastructure. This includes investigating new cementitious materials having lower carbon footprint (e.g. geopolymers and alkali-activated materials) and high performance concrete mixes with enhanced durability and life in severe marine exposure conditions. In this context, employing heterogeneous materials is a promising approach to reduce the environmental impact of the construction, which will lead to a more sustainable and environmentally friendly building industry [99].

In addition, the carbon emissions from the construction industry may be reduced if the building sectors adopts designs that prioritise resource efficiency, minimisation of waste and reuse or recycling of materials. Life cycle cost and environmental impact assessments of broad scope are crucial for selecting materials in an informed manner. Several investigations provide evidence that sustainable materials are advantageous for the environment and economy [75,100]. Regulations and incentives can also promote the use of green materials and methods in marine works. In addition to building performance, the environmental impact of construction activities itself is also important aspect of sustainability [101]. Sustainable building is the integration of environmentally friendly materials characterized by low environmental impact, recycle-ability, reusability [102]. These materials are also energy efficient and low maintenance [103]. It is crucial that stakeholders collaborate, share knowledge, and adopt a sustainable manner to drive sustainability and resilience in marine infrastructure projects. Sustainability and resilience of marine infrastructure require cooperation, knowledge sharing, and adopting sustainable best practices from stakeholders.

There are greater amounts of "greening" programs developed by governments across the globe, which push public authorities to already do something for developing government buildings to become sustainable [104]. Green building has been adopted by governments around the world as a strategic tool for improving the sustainability of the construction industry [105]. They institutionalize sustainability in projects through sustainable design standards, incentives to develop green building projects and laws that impose the use of sustainable materials [104]. Construction has a large impact on both the environment and on society, and it is both clients and governments in construction that realize this. Authorities and building clients are aware of the strong influence of design-construction-occupation of buildings in the environment and society [106]. The idea of sustainable building is taking hold as a response to the increasing demand for greener buildings. The growing demand for green building has driven the practice of sustainability in the construction industry. The construction industry is beginning to perceive the concept of the sustainability in order to take care of environment, to create more profits and competitiveness, and to produce buildings and structures with more satisfaction, safety, health and well-being of the consumer and user [94]. The industry sector can make a significant reduction of waste, conservation of natural resources, as well as contribution to more sustainability and resilience built environment by incorporating the use of these environmental friendly and recyclable materials in a construction by [107]. By encouraging the use of these environmentally friendly and recyclable materials in construction, the construction industry could save landfill space, protect natural resources, and contribute to a more sustainable and resilient built environment. The construction sector has sizeable effect on global sustainability targets; therefore selection of construction materials has been gaining increasing importance as it also has a significant effect on the eco-efficiency of construction during its service life.

Project performance is enhanced by the implementation of sustainable construction practices, including the use of sustainable materials, and this practice has great environmental, social, and economic value. The construction industry has embraced Green public procurement, which is purchasing procedures where a contracting authority seeks to buy goods and services that are environmentally friendly [108].

Innovations in the construction sector are essential for sustainable development, encompassing improvements in technical choices, new technologies, energy efficiency, and adherence to sustainable criteria [109]. Innovation in the construction sector can be made through improvements in technical choices, such as the use of better quality, the increase of new technologies and specialized personnel, improvement of processes, increase of energy efficiency, and increase of sustainable criteria [109]. To meet sustainable development standards, the construction industry is implementing creative technologies that emphasize energy and resource efficiency as well as circular economy principles [110]. Study [111] presented a deep learning-based approach for detecting and classifying moss and crack damage in rock structures for geo-mechanical preservation. Work [112] focused on improving heat transfer in micro-channel heat sinks through geometrical optimization. Research [113] explored the use of biodiesel blends to enhance diesel engine performance as a sustainable alternative. In continuation, study [114] analyzed the environmental impact and emission performance of biodiesel-fuelled engines. Experimental investigation [115] evaluated the performance of trapezoidal ducts with delta wing vortex generators. The heat transfer characteristics of these ducts were further analysed in [116]. Failure causes of the driving shaft in an industrial paddle mixer were identified in [117]. Thermal management of mobile devices using phase change materials was proposed in [118]. Design optimization and finite element analysis of a paddle mixer shaft were carried out in [119]. Review [120] summarized recent advancements in heat transfer using perforated twisted tapes. Finally, study [121] discussed the application of artificial intelligence in minimizing environmental impact in the mining sector.

A critical comparative framework and a multi-criteria decision-support model (MC-DSM) are introduced to assess materials based on durability, strength, corrosion resistance, environmental impact, and cost. This synthesis supports evidence-based decision-making and encourages further interdisciplinary research and policy development for scalable solutions.

Sustainable marine infrastructure demands the strategic selection of materials that offer durability, environmental compatibility, and long-term performance. Each material element contributes differently to the structural integrity, environmental impact, and life-cycle cost of marine constructions. Geopolymer concrete, developed from industrial by-products like fly ash and slag, significantly reduces CO_2 emissions while providing excellent chemical resistance in saline conditions. Engineered Cementitious Composites (ECC), known for their ductility and fine crack control, enhance structural resilience, especially under dynamic marine loading. Bio-concretes incorporate bacteria that autonomously heal cracks, reducing maintenance needs. Another reason for adding supplementary cementitious materials (SCMs) is to increase the durability and to decrease the clinker reliance, also to provide good chloride resistance in marine environments (Wolter, 2003). FRPs and other alternative reinforcement materials offer superior corrosion resistance, where GFRP, CFRP and BFRP, amongst others can be adjusted to specific application demands. Bamboo, which is a natural sustainable material, exhibits low embodied energy and cost, with a reduced strength and biodegradation promotions.

Stainless steel is water resistant in splash zones yet it's expensive and environmentally unfriendly to produce. Hybrid systems, such as Steel-CFRP bars, enable ductility of steel and corrosion resistance of composite, and are ideal for high seawater condition. Testing of these materials under marine loading (chloride penetration, cyclic wetting, and biological assault) serves to determine selection criteria. In the end, comprehension and analysis of material-specific performance help us achieve a more durable and environmentally-friendly marine infrastructure.

7. Conclusions

This review highlights the critical importance for alternative marine infrastructure materials to be developed, in part due to the environmental deterioration, high maintenance requirements, and limited durability of pervious maritime construction materials such as Portland cement and carbon steel. The paper provides an overall synthesis of the most recent of material developments and analysis methodologies by which to design durable and eco-efficient marine structures. Sustainable material developments such as geopolymer concrete, ECC (engineered cementitious composites) and bio-concrete based materials, with outstanding durability, reduced environmental impact, and ability to self-heal, have potential to be excellent alternatives to traditional concrete. In the category of reinforcement, fiber reinforced polymers (FRPs), bamboo, and steel-FRP jail hybrid bars have been gaining the next-generation alternatives to steel as they are adequately resistant to corrosion in tropical marine (saline) environment and the use of stainless steel, though very expensive, becomes a must for high value coastal areas. The use of tools such as Life Cycle Assessment (LCA), durability modeling, and performance based design provides an informed decision-making through optimization of structural performance, cost-effectiveness, and sustainability starting from the early design phases. Some specific material recommendation are presented such as Geopolymer concrete for chloride resistance, ECC for deformation or seismic prone areas, bio-concrete for reducing crack maintenance, FRP systems for the lightweight, non-load bearing applications, and Stainless steel in splash and tidal zone. Nevertheless, significant knowledge gaps still exist in terms of lasting performance as well as cost-benefit study and offering procedures for standard testing. Overcoming these gaps will demand methodological developments and life-cycle modeling of new materials. Generalization of the use of sustainable materials also relies on policies and incentives driving the chain of cooperation between academia, industry, and government for pilot and field validation. Finally, the work aims at adding a comparative approach and decision support model to the research community that provides a higher degree of fidelity of the gap between materials development and use in marine structures.

Author Contributions

K.N. conducted the literature review and drafted sections on sustainable materials. G.E.K. developed the theoretical framework and contributed to figures and tables. S.V.P. reviewed concrete alternatives and performed critical revisions. P.V.K. worked on bio-concrete and SCMs content. S.M.B. contributed to the comparative framework and conclusion. A.S.K. coordinated the research, edited the manuscript, and approved the final version. S.Y.W. supported in identifying research gaps and refining visual content. All authors have read and agreed to the published version of the manuscript.

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