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MINI REVIEW **Open Access**

Choosing the right substrate to restore coral reefs through artificial reef construction: a mini-review

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Abstract
Coral reefs are among the most valuable ecosystems on Earth, providing major benefits to human societies and hosting a wide variety of species. Today, these ecosystems are threatened by a combination of local and global factors that overcome the natural capacity of coral reefs for regeneration. Therefore, active restoration methods have been developed and conducted to help coral reefs recover faster than before. The construction of artificial reefs, which are artificial structures that are deliberately submerged in aquatic environments and whose characteristics mimic those of natural reefs, is a marine restoration strategy. These strategies have the potential to increase the ecological value of degraded sites in both the short term and long term by providing additional habitats for coral growth and acting as future hubs for coral larval dispersal. However, the success of artificial reefs in achieving these objectives depends largely on the materials used to construct them. Concrete, plastics, metals and wood, which are the major materials found in modern reefs, suffer from substantial drawbacks that limit the ability to reach restoration goals. In this short study, we discuss innovations that have been developed to overcome the drawbacks of modern artificial reefs to encourage the creation of a new generation of artificial reefs that can substantially contribute to active coral reef restoration.

Keywords Coral reefs, Artificial reefs, Active restoration, Engineered substrates, Innovative materials

Introduction

Coral reefs are among the most economically and ecologically valuable ecosystems on Earth. While coral reefs account for no more than 0.1% of the oceanic surface, they host 25% of the global marine biodiversity [1]. This finding suggests that approximately 100,000 species depend on coral reefs to various degrees to complete their life cycles [2]. Coral reefs provide important ecosystem benefits. These reefs provide coastal protection, ensure food security for coastal communities in developing countries, and represent a major source of income through fishing activities, tourism, and pharmacological research [3, 4]. Some studies have estimated that coral reefs provide ecosystem services worth $9.9 trillion to the global economy each year [5, 6]. Although there is considerable variation in the economic valuation of coral reefs due to the use of different variables (e.g., valuation methods, site studied, and a growing understanding of the extent of the services provided), these studies raise awareness of the magnitude of the services provided by coral reef ecosystems [5].

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Unfortunately, coral reef ecosystems have been in decline for decades because of a combination of global and local factors. More than 60% of the world's reefs are affected by local pressures, such as overfishing, coastal development and watershed-based pollution [1]. Furthermore, the effects of these local stressors are exacerbated by climate change, which has become the greatest threat to reefs worldwide [7]. These pressures have led to the loss of approximately half of global tropical coral reefs in the past 30 years, and this dynamic process is expected to continue [3]. The Intergovernmental Panel on Climate Change [8] has estimated that 70–90% of modern coral reefs may disappear if the temperatures increase to 1.5 °C above preindustrial levels. If the degree of global warming exceeds 2 °C above preindustrial levels, more than 99% of the reefs will be destroyed [8].

Restoring coral reefs through artificial reef construction

The natural capacity of coral reefs to regenerate is overcome by the intensity of the factors affecting them. To help reefs recover, active restoration methods—such as coral transplantation, algae removal, larval propagation, acoustic enrichment, artificial reefs—have been employed [3, 9–11]. According to the International Convention on the Protection of the Marine Environment [12], artificial reefs are defined as submerged structures deliberately immersed on a seabed, and their purpose is to mimic the characteristics of a natural seabed to allow benthic species to thrive. Their ability to enhance local marine resources has been demonstrated when they have been correctly implemented in sediment-affected environments [13]. Artificial reefs can help recruit coral larvae and be used as a culture substrate for transplanting colonies grown in nurseries or taken from other reefs [14]. In the long term, artificial reefs can act as intermediate platforms that help disperse coral larvae when established colonies reach sexual maturity [13].

However, from both ecological and economic perspectives, the successful deployment of such structures is highly dependent on the materials used to build them [15, 16]. Materials that encourage biological colonization by corals without inadvertently polluting the environment and that are as cost efficient as possible should be used to restore as many reefs as possible [17, 18]. Various structures made from different materials have been tested around the world, ranging from specifically designed structures to materials of opportunity, with varying degrees of success in terms of achieving restoration objectives [19].The OSPAR convention states that artificial reefs must be made of inert materials that can withstand the harsh conditions of the marine environment to avoid pollution events that can be provoked by biological, physical or chemical alteration processes. Stable materials are preferred to encourage biotic development [17]. Notably, active restoration efforts are highly constrained financially [20, 21]. Because the median cost for the setting of artificial reefs is US$3,341,754, working with affordable materials is necessary [15, 22]. Considering this context, a good material can be defined as one that is cost-effective, sustainable, and biocompatible and that does not pollute the environment into which it is introduced.

Substrates used in modern artificial reefs

Concrete

Concrete is one of the most common material used in the design of artificial reefs due to its high resistance, high adaptability, and properties that are similar to those of natural rock [19, 23, 24]. Concrete is an easily malleable substrate that can be molded into any desired shape, so it is used in a variety of forms [23]. A wide variety of epifaunal organisms can settle and grow on its surface, and its characteristics can be easily modified by adding various elements, such as coarse sand, to adjust the surface roughness [25]. Nevertheless, concrete has several major drawbacks. Once immersed, some cements have a surface pH of 10–11 [26], and these cements require 3–12 months of aging in sea water for the surface pH of the material to reach a similar pH to that of sea water [25, 27]. During this time, pH-resistant organisms, such as barnacles, can colonize structural surfaces and block the settlement of corals [28]. Finally, the cement industry accounts for approximately 6% of global carbon emissions [29]. Although most of the concrete produced is not used to construct artificial reefs for coral conservation, the use of a material whose production technique contributes directly to climate change, which is a primary threat to corals, is paradoxical [17].

Tires and plastics

To minimize the need for new materials to be produced for coral restoration projects and to reduce their carbon footprint, recycled materials can be utilized. Old tires are a perfect example of how materials can be reused for marine conservation through the construction of artificial reefs [25, 27]. The main advantages of their use lie in their very low cost and high potential for colonization by marine benthic organisms, such as corals [23, 27]. However, artificial reefs built with recycled tires are not very stable, as they can be easily moved by currents, potentially harming the surrounding coral reefs [27]. Moreover, there are major concerns about tire leachates and the pollution that they produce [23, 30]. Once immersed, toxic compounds such as zinc, copper, formaldehyde and acetone products are released into the environment, preventing the development of marine biota [23]. For these reasons, the large-scale deployment of tires is, to our knowledge, no longer considered a viable strategy for artificial reef projects. Instead, other plastic structures are preferred, such as PVC tubes, which are recognized for being low-cost and lightweight. These can be incorporated into artificial reefs made from substrates such as concrete to help structure the systems [31] or to build entire rearing systems, such as the Coral Tree Nursery developed by the Coral Restoration Foundation [32]. The tree consists of a central PVC column and PVC or fiberglass arms on which corals can be hung or attached to be grown in situ. The entire system is anchored to the seabed using steel rebar or cables, which minimizes impacts on the substrate. At the top of the structure, a floating device, typically made of polystyrene balls or plastic bottles, remains upright in the water column. Despite its advantages of portability, low cost, low maintenance, and minimal disturbance to sensitive seafloor habitats, the Coral Tree Nursery is a temporary structure designed to rear corals before their final transplantation onto degraded reefs [32, 33]. Furthermore, because its plastic components are vulnerable to degradation under harsh marine conditions, the Coral Tree Nursery may release microplastics into the environment [27]. Microplastics can impact coral directly through ingestion and indirectly via pathogen transmission. According to Allen et al., plastic particles release phagostimulants that cause the particles to appear as prey [34]. The consumption of plastics is energetically expensive because it replaces actual food and gives corals a false sense of satiation. Consumed plastics can also clog the digestive system. Moreover, plastic consumption can lead to the death of polyps [35, 36]. In addition to these direct effects, plastic can serve as a host of pathogens that can trigger disease outbreaks on coral reefs. Once an individual is exposed to plastic debris, the likelihood of disease occurrence increases significantly from 4% to 89.1% [37].

Metal

Metal structures can be used to construct artificial reefs. Project developers appreciate its light weight and the fact that it can be used to create complex shapes [27]. For example, Mars Incorporated used metal rebar to develop and deploy hexagonal, modular ‘spider’ structures on degraded reefs in Indonesia [38]. Coated with coarse beach sand, the structures provide a substrate that is suitable for coral recruitment and the rapid recovery of the damaged reefs [39, 40]. Moreover, their low cost (US$15 per spider) makes them an affordable option for practitioners [38]. However, substances released during oxidation can be used by algae to grow once immersed, which can limit the growth and recruitment of corals to their surface [23]. In a comparative study of the colonization of reefs made with concrete, tires and metal plates by corals, R. C. Fitzhardinge and J. H. Bailey-Brock [25] observed lower amounts of coral on metal plates than on concrete structures. This could be due to the textural characteristics and rougher surface creating a more ideal environment for marine larvae [41] and to the thinness of the plates that were used, as they disintegrated within 17 months, which was not enough time for the corals to grow [25]. Metal structures from decommissioned ships can be repurposed for artificial reef construction by submersion. This method is economically appealing, as sunken ships can be good diving locations and provide large areas for coral colonization [27]. However, their use poses major pollution issues, as they can be contaminated by various pollutants, including PCBs, radioactive control dials, petroleum products, lead, mercury, zinc, TBT and asbestos [27, 42, 43]. These pollutants can be removed, but this represents an additional expense, leading to an inflated budget.

Wood

Wood is a cheap material characterized by good compatibility with marine organisms because of its lack of toxicity. Moreover, it is a low-to-no carbon emission material for artificial reef construction. These benefits explain why wood has been widely utilized in artificial reef projects [44]. Muthukrishnan and his colleagues investigated the development of fouling communities and reported that among 4 substrates, wood hosts the greatest total biomass [45]. In another experiment, Dickson et al. constructed tree–reef structures made of felled pear trees and observed their colonization by sessile organisms [44]. Researchers demonstrated that within 6 months, the reefs became hotspots of sessile epibenthic organism biodiversity in which habitat-forming species, such as mussels, were found. Paradoxically, however, the downside of this material is this same property that allows it to be quickly colonized. Depending on the type of wood used, the lifespans of structures made of this material vary and can be degraded in 18 months or less [46]. However, wood used in marine environments can be chemically treated to increase its longevity, which raises potential pollution issues associated with the leaching of toxins such as copper, arsenic and chrome [27, 47]. Another problem is that wood is a very light material that must be ballasted to keep it on the seafloor when placed underwater [27]. Finally, to our knowledge, artificial reefs made of wood have never been used in a project aimed at restoring coral reef ecosystems. If generalist corals, such as *Tubastrea* spp., have been observed colonizing and growing on wood tree fragments in the Atlantic Ocean [48], we do not know how reef-building coral species can settle on this kind of substrate.

Table 1 Summary of the advantages and disadvantages of each modern material in terms of the environmental, biological and economic criteria

	Benefits	Drawbacks
Concrete	Highly resistant and adaptable surface characteristics close to those of natural rocks	Basic surface pH, incompatible with marine life for several months, large carbon emissions of the cement industry
Tires and Plastics	Low cost, high potential for coral colonization, lightweight, easily transportable, readily deployable onto target sites	Leaching of toxic compounds, sources of microplastics pollution, can ultimately increase disease occurrence
Metal	Light material, enormous flexibility, can help with creating complex forms	Leaching of toxic compounds (especially for decommissioned ships), expensive substrate for pollutant removal
Wood	Low cost, lack of toxicity, low-to-no carbon emissions, compatible with diverse marine sessile organisms	Short lifespan, may contain toxic compounds when chemically treated, need to be ballasted, little-to-no data for coral settlement

Next-generation substrates for coral reef restoration

A brief review of the principal substrates actually used to construct artificial reefs demonstrates that there is a need to develop and deploy materials that combine reasonable cost with biocompatibility, durability, and little-to-no risk of pollution. Concrete, metals, plastics and wood struggle to meet all of those criteria (Table 1).

One method for addressing these limitations may be to address the issues associated with the types of each material. For example, the density of each tree species varies, with hardwood being much denser, more durable, and heavier. Selecting and testing different hardwood species should enable the development of an artificial tree–reef system that can last for decades [44]. However, sourcing of such dense hardwood should be rigorously monitored to ensure that it comes from sustainable sources and does not contribute to other negative externalities. In addition, it is interesting to study whether habitat-forming species, such as coral, can develop properly on wood and how the resulting reef might react in the event of collapse from degradation. Researchers have proposed innovative concrete mix designs that can help increase the colonization of marine organisms while being less carbon intensive and expensive. Rupasinghe et al. tested various concrete mixes that incorporated recycled oyster shells that were crushed and sieved [28]. Researchers reported that their inclusion creates highly porous concrete with a highly complex surface texture compared with that of conventional concrete. Larvae preferential tests performed with blue mussel larvae (*Mytilus galloprovincialis*) have revealed that concrete with oyster shells increases attachment numbers. Similarly, Wilding and Sayer produced cost-effective and robust concrete blocks using fly ash and granitic dust [21]. The utilization of these industrial byproducts with standard concrete resulted in the production of a material that is between 25% and 40% cheaper than commercially available concrete. In addition, the inclusion of fly ash did not result in a high level of leaching. This process supports the production of a cheap, more environmentally friendly material for the construction of artificial reefs to restore coral reefs. Artists such as Jason deCaires Taylor are already using low-carbon, pH-neutral concrete to create submerged statues designed to be colonized by marine life, including corals [49].

Another approach to address the limitations is to design and deploy smaller structures that use less material and have lower deployment costs. Guided by this philosophy, Chamberland and his colleagues developed a concrete tetrapod structure that can be placed efficiently using the natural complexity of the seabed. Each seeding unit costs just US$1, including deployment [50, 51]. Numerous studies have shown that the surface of deployed structures can be altered, in terms of color, topography, biofouling or the addition of antifouling coating, to increase coral colonization and growth [41, 52, 53]. A structural design that takes advantage of the chemical, biological and physical characteristics that attract coral larvae could improve the effectiveness of artificial reefs. Mason et al. showed that coral larvae settle more frequently on red surfaces [52], whereas Whalan et al. [54] found that larvae of *Acropora millepora* and *Ctenactis crassa* preferentially settle on surfaces whose microtopography matches their size. Therefore, increasing the roughness of submerged surfaces can improve the colonization of submerged structures, as is the case with the spider structures of Mars Incorporated [25, 38]. Additionally, chemical cues can be used to support coral settlement, either by attracting larvae or limiting algal competition. Crustose coralline algae (CCA) play a key role, as their extracts and natural colonization of substrates can provide biochemical signals that guide larval settlement [41]. Complementary approaches, such as non-biocidal FRC coatings, have shown promise in reducing algal fouling and promoting coral colonization, although further validation is needed to confirm their effectiveness and assess potential side effects [55].

In addition to these improvements, alternative materials are in development. In particular, biosourced materials are the subject of great interest. Some experimental structures built with biosourced materials have already been designed for bivalve reef recovery and tested in the Netherlands and Florida [56]. These structures, which are made from biodegradable potato-waste-derived Solanyl C1104M and fibrous coir ropes that mimic mussel byssal threads, successfully facilitate reef formation.

Furthermore, we anticipate that biosourced reefs can benefit stony corals [57]. The temporary nature of biodegradable reefs can meet another important criterion. OSPAR guidelines state that artificial reefs should be designed for removal if necessary. The degradable nature of biodegradable artificial reefs meets this criterion, as the structure can be removed over time at a pace that allows corals to develop.

As more biodegradable options become available in coral restoration projects, quantifying their effectiveness and monitoring their probable impacts will become essential [58]. Alternative materials also include composite inorganic substrates. Levenstein et al. developed a material made from lime mortar and different additives, such as quartz-rich sand and strontianite [41]. Ions released into the water column attracted the coral larvae of two Caribbean species and promoted their settlement. Following this work, Yus et al. [53] confirmed the influence of inorganic additives on coral larval survival and settlement. The search for other mixtures using those additives could create opportunities for material scientists to develop more efficient sustainable materials for artificial reef projects.

Ceramic materials are noteworthy, with high rates of coral settlement. The advantages of ceramic include its chemical inertness, which makes it nontoxic to the environment, and its long-term durability [59]. Antink et al. [59] confirmed the potential of this material by producing different substrates with specific pore sizes and by observing the settlement success of *Pocillopora damicornis* coral larvae. Bioinspired materials with close morphological similarities to the coral skeleton are good surfaces for larval settlement. Furthermore, 3D printing techniques can be used with ceramic materials; the use of 3D printing techniques is emerging as a strategy for creating complex morphologies that are extremely difficult to obtain through conventional design approaches. 3D printing methods have the ability to (i) produce complex structures characterized by heterogeneous features favored by coral species, (ii) reduce costs, (iii) reduce environmental impacts and (iv) improve the scalability of restoration projects [60]. In the Red Sea, 3D-printed terracotta structures were deployed next to natural coral patches to test their ability to host complex communities of fish and benthic organisms [61, 62]. After 3 years of monitoring, Oren et al. observed the settlement of dozens of coral colonies along with 15 species of sponges and ascidians. Additionally, Archireef started to print and test their own clay reef tiles, which demonstrates the enthusiasm of the community towards this approach to artificial reef design. Low-voltage mineral deposition (LVMD) technology is another method for producing complex, highly porous structures. The resulting material, known as Biorock, is a promising substrate that can be stronger than concrete and that allows corals to grow up to 3.17 times faster than under control conditions [63]. From a global perspective, engineering methods that draw on biomimicry—using nature as inspiration—have shown great potential for generating innovative materials that satisfy criteria for both economic and technical success [64]. Nevertheless, for both Biorock and 3D-printed ceramic structures, larger-scale deployment is needed to properly assess the scalability of these techniques for reef restoration.

Conclusions

In summary, a wide range of initiatives are being undertaken to correct the negative characteristics of the materials currently being used to construct artificial reefs, particularly for coral restoration. New materials are being developed and studied. The development of new concrete mixes and more durable woods represents an intermediate step toward the next generation of artificial reefs that support coral ecosystems and upscale restoration efforts. Conversely, the cost of these new materials (e.g., biosourced substrates or porous ceramics) needs to be clearly evaluated to meet the accessibility criteria that constrain active coral restoration programs. Finally, we believe that future research should focus on upgraded production technology, such as 3D printing, along with innovative substrates, such as ceramics and biodegradable, bioinspired materials. This combination will provide novel insights for the future of coral restoration by providing stakeholders and conservationists with new strategies for actively restoring reefs.

However, improvements in the materials used for artificial reefs should not be considered a silver bullet. While artificial reefs can be valuable tools for supporting reef recovery and resilience on limited scales, their success depends on mitigating direct human stressors (eutrophication, pollution, overfishing and destructive fishing) and reducing global emissions.

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Author contributions

Baptiste Ozanam, Pascal Romans and Raphaël Lami conceived the idea for this mini-review. Baptiste Ozanam wrote the manuscript. All the authors listed made substantial contributions to the discussion of the ideas outlined in the work and the development of the manuscript. All the authors contributed to the article and approved the submitted version.

Data availability

No datasets were generated or analysed during the current study.

Declarations

Competing interests

The authors declare no competing interests.

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