

Review

A Review of Additive Manufacturing Techniques in Artificial Reef Construction: Materials, Processes, and Ecological Impact

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Featured Application: Advanced systems for water purification and ecosystem restoration.

Abstract: In recent years, additive manufacturing technologies have been employed for ecological projects, especially those connected with artificial reefs. This approach brings a lot of advantages, including the design of more complex structures, with surfaces fitted to the needs of water organisms. This technology can effectively support ecological design and engineering, especially in restoration efforts. The main aim of this article is to demonstrate the state of the art and further perspectives for the development of artificial coral reefs. This article is based on a critical analysis of the literature, supported by selected case studies. This article describes current technologies used in the creation of artificial reefs, putting emphasis on additive manufacturing, evaluates currently used materials, and summarizes the influence of this technology on ecosystems through the analysis of selected case studies. It also discusses the challenges and limitations of current technologies used in 3D printing artificial reefs as well as presents current trends and further directions. The most important findings show that the analyzed field is a promising interdisciplinary research area and practical implementations require collaboration between specialists from different branches.

Keywords: 3D printing; additive manufacturing; artificial reef; ecosystem restoration; material engineering



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1. Introduction

Artificial reefs are man-made structures that are intentionally submerged to mimic some of the features of natural reefs [1,2]. The first traces of artificial habitats in aquatic environments date back to the Neolithic period (9000–3000 BC), when coastal vegetation and rocks were intentionally submerged to create new fishing grounds off the coast of Africa [3]. Their use was also a common practice in traditional fishing communities, especially in Southeast Asia [4]. The main goal was to increase catches by creating additional structures that provided protection for fish. Research into the role of artificial underwater habitats in attracting, concentrating, and catching fish has been conducted since the 1930s [5,6]. However, the effectiveness of artificial reefs in this regard is controversial. On the one hand, there are studies showing the effectiveness of this method [5,7], but others negate the effectiveness of using artificial reefs for this purpose [8]. Currently, this kind

of solution obtains a wider meaning; the main aim of the application of artificial reefs is usually ecosystem restoration, particularly the improvement of biodiversity and support of the reproduction and habitation of underwater life [9–11].

3D printing technology brings a lot of benefits, including freedom of design—creating complex shapes without formwork, materials efficiency, and the possibility of working in harsh environments. In this article, the terms additive manufacturing and 3D printing, despite existing differences, are used as synonyms. This review is focused on the practical aspects of this technology. Currently, additive technology finds many applications in different areas, such as medicine, aerospace, automotive, and construction industries, and others [12–16]. Also, in recent years, this technology has been employed for ecological projects, especially those connected with artificial reefs. The usage of additive manufacturing for this purpose gives researchers the possibility to design surfaces with greater complexity and roughness, which is important for the settlement of water organisms, such as corals or mussels and other marine life [17,18]. Some research shows that this technology can effectively support ecological design and engineering, especially in restoration efforts [19,20]. It allows for the matching of artificial reef structures to specific requirements of local ecosystems [21]. Moreover, additive manufacturing can effectively support the shift toward ecological sustainability [19,22]. This technology is also scalable and cost-efficient [23].

The main aim of this article is to demonstrate the state of the art and further perspectives for the development of artificial coral reefs. This article is based on a critical analysis of the literature, supported by selected case studies. This article describes current technologies used in the creation of artificial reefs, putting emphasis on additive manufacturing, evaluates currently used materials, and summarizes the influence of this technology on ecosystems through the analysis of selected case studies. It also discusses the challenges and limitations of current technologies used in 3D printing artificial reefs as well as presents current trends and further directions. The main audience of this work is researchers and practitioners, and the presented knowledge can help them to acquire useful information to develop the research connected with artificial reefs.

2. Research Methodology

The presented work is based on a critical review. In the beginning, the basic literature for the defined problem was defined by using the Scopus database. The following two main keywords were used: “reef” and “3D printing”. This combination allowed us to obtain 52 results (Figure 1).

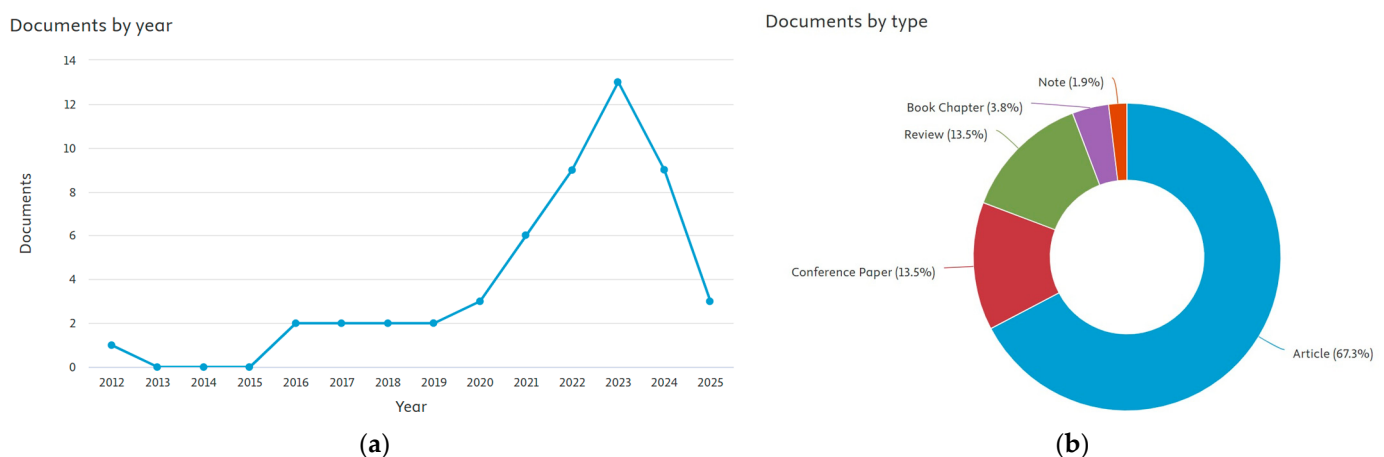
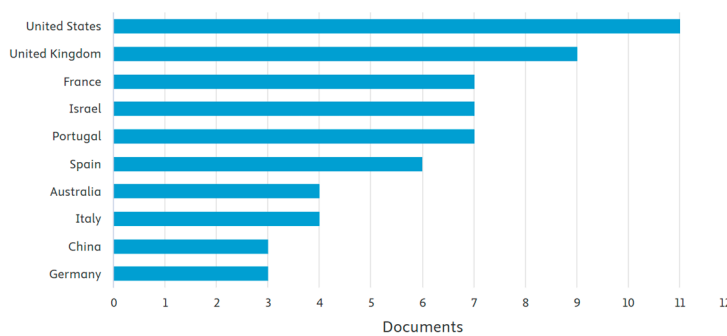


Figure 1. Cont.

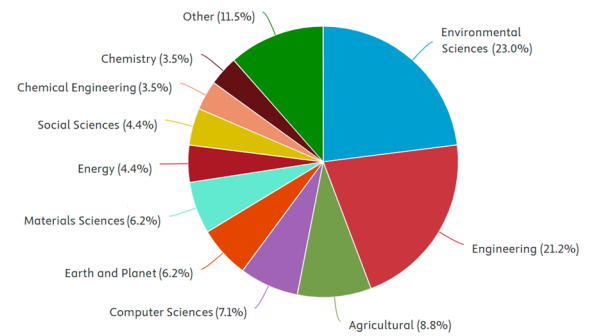
Documents by country or territory

Compare the document counts for up to 15 countries/territories.



(c)

Documents by subject area



(d)

Figure 1. Results of the analysis in the Scopus database, during the period from 2012 (first publication in the topic) to 2025 (March): (a) published documents by year; (b) published documents by type; (c) published documents by country/territory; and (d) published documents by subject area [24].

The first publication in the analyzed area was in 2012 (Figure 1b); however, up to 2020, there was a small number of documents connected with the usage of 3D printing technologies for designing and manufacturing artificial reefs. The development of interest in this topic was connected with the growing importance of the blue economy as well as the development of additive manufacturing technologies, especially for concrete-like materials. According to the structure of the types of publication, it is quite typical for newly developed topics, with about 67% consisting of original articles, 13% consisting of conference papers, and the same number of reviews (Figure 1b). The countries participating in research were taken into consideration. A large number of publications came from the USA and the UK. The great importance of this topic is also visible for developed EU countries, such as France, Portugal, and Spain. Also, some interesting research is visible in Israel and Australia (Figure 1c). These data show that the topic is a priority for developed countries. The characteristic issue is the far position of China or the lack of India in this ranking. Meanwhile, these two countries usually dominate in a large number of scientific topics, because of the significant number of publications. In Figure 1d, it is visible that the topic has a strongly interdisciplinary character, with the main share consisting of environmental sciences and engineering.

To visualize the obtained results in the Scopus database and receive more information about particular areas, a map of connection keywords was created. The selected limitations for keyword repetition was five, and the VOSviewer version 1.6.20 was applied (Centre for Science and Technology Studies, Leiden University, Leiden, The Netherlands). The visualization is shown in Figure 2.

The visualization shows three main networks (red, blue, and green). The keywords are connected mainly with areas of technology (3D printing, additive manufacturing), environmental issues (environment, climate change), and marine issues (coral, coral reef, cost, marine ecosystem). The graph confirms the interdisciplinary character of the provided investigations. There is a lack of words connected with freshwater, which may be a non-exploited area and suggest a research gap. The current research is focused on research on marine systems due to coral decline, but potential problems with freshwater ecosystems are ignored. This provides a chance for the development of new areas for research specializations. The scheme includes some overall keywords, such as paper and project, that can be suitable for many areas.

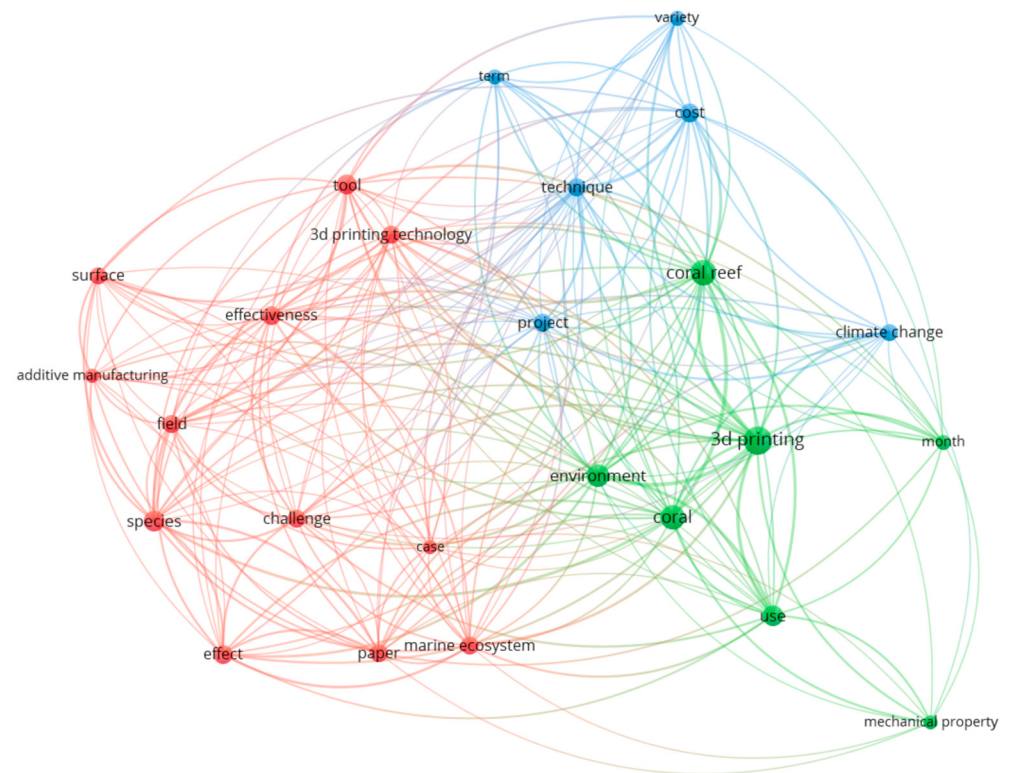


Figure 2. Visualization of network connection based on used keywords in analyzed articles.

3. Technologies Used for Artificial Reef Design and Manufacturing

3.1. Modeling and Design

Modeling artificial reefs can serve several purposes, especially in understanding their impact on coastal processes. It is a crucial element for the design of artificial reefs, especially if 3D printing is involved later in the process. The primary purpose of modeling is to design the artificial reef itself; other processes are connected with the optimization of the model for a particular environment and the simulation of behavior in underwater conditions.

The modeling allows for obtaining the complexity and diversity of shapes used for artificial coral reefs, including the proper surface roughness that is necessary for the further growth of organisms. An exemplary solution, designed using a parametric design tool using Rhino and Grasshopper software (v.7), is presented in

The design tool allowed for the generation using clay deposition trajectories; it was possible to create highly complex microfeatures, which increased the efficiency of colonization by different organisms [19].

In the case of simulation behavior in underwater environments, one primary use is to evaluate the effects of behavior on sediment transport and bed erosion. Numerical models can simulate how artificial reefs influence the movement of sediment and whether they help stabilize the seafloor under different conditions [25]. These models also help to assess how artificial reefs affect morphological changes in coastal areas, such as the formation of sandbars or the trapping of sediment in sheltered areas, which can contribute to beach stabilization [26].

Moreover, numerical modeling can be used to study the hydrodynamic effects of artificial reefs, such as wave attenuation and current modification. These simulations are crucial for understanding how reefs dissipate wave energy and reduce the intensity of currents, which can protect shorelines from erosion [27]. In areas where physical experimentation is challenging, modeling can provide detailed insights into the behavior of artificial reefs in various wave conditions [28], helping to refine designs for coastal protection projects.

By simulating different scenarios, models can also predict the long-term impacts of artificial reefs on beach profiles and the surrounding environment, guiding effective coastal management strategies. Figure 3 [19].

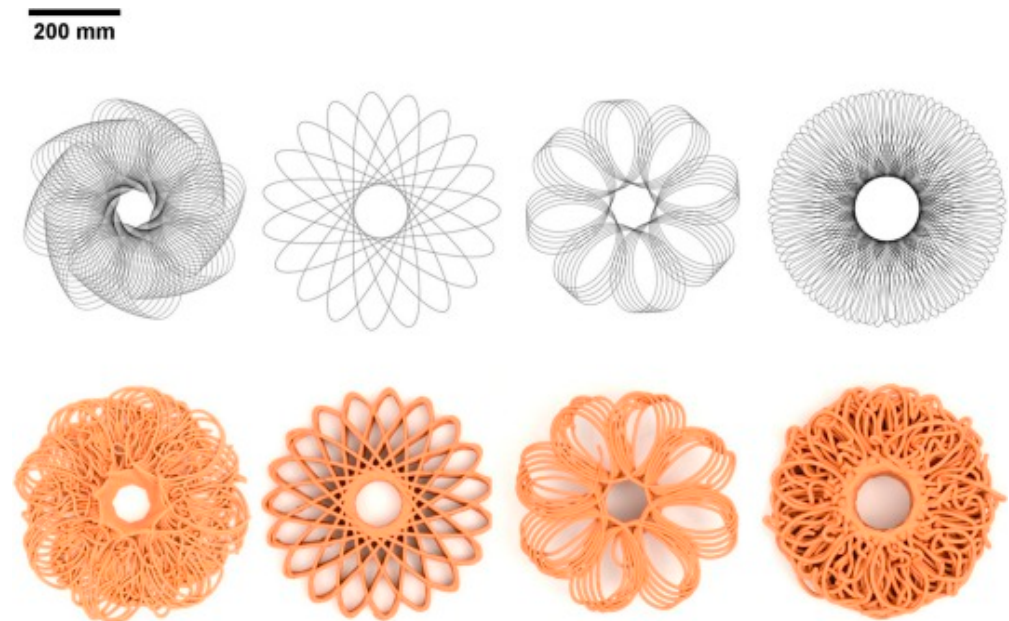


Figure 3. Samples of the elements used for the artificial reef creation—the trajectory of the printing path [19].

Traditionally, the complex morphological features and ocean forces at the field scale have been modeled using two-dimensional wave–current models (2DH) or three-dimensional (3D) wave–current models [29–31], with waves and mean currents typically coupled through radiation stresses, as introduced by Longuet-Higgins and Stewart [32]. For spectral wave transformation over realistic reefs, including infragravity waves, the XBEACH phase-averaged surfbeat model and phase-resolving non-hydrostatic models have been used more frequently in recent years [29,33]. At the laboratory scale, Boussinesq-type models, which are computationally efficient and phase-resolving, are the most commonly used. Boussinesq-type models such as FUNWAVE [34,35], COULWAVE [36–38], and others have been able to simulate the motion of monochromatic waves, spectral waves (including infragravity waves), and solitary waves over various reef profiles. Another popular group is the non-hydrostatic models, such as XBEACH [39,40] and NHWAVE [41,42], which have been used to model wave transformation over various laboratory reefs. However, both Boussinesq and non-hydrostatic models still face challenges in resolving detailed wave-breaking processes, such as wave overturning and breaking-induced turbulence over reefs. Meanwhile, bottom roughness in the above models is typically addressed using a quadratic friction law or Manning’s friction formula. Recently, some researchers have attempted to improve the friction parameterization by adding an additional drag term in the Boussinesq equations [43] or a porous media model in the non-hydrostatic XBEACH model [44].

The numerical modeling seems to be used only in limited areas. There is a lack of complex works with the prediction of ecosystem growth or correlation between some systems elements, for example, the complex geometry of reefs and the development of desired species. This area can probably be much more explored in the future to better understand the long-term mechanisms and designs for ecosystem development.

3.2. Traditional Manufacturing Technologies vs. Additive Manufacturing Technologies

The first artificial reefs were built with natural materials, such as stones. In the XX century, different components were tested as an artificial reef, including some kind of concrete cubic material, tire waste, materials from wrecks, and others [4]. Different kinds of cheap materials have gained popularity. The construction was rather simple, without necessary complications; mainly, concrete blocks and metal frames were applied [21]. Currently, additive manufacturing and reverse engineering have changed the rules. Technological progress allows for the use of 3D scanning and 3D printing as the background technology for the design of the coral reefs, in the same way as they are used for other applications [21,45,46]. Nowadays, there is a possibility to use scanned geometries of harvested corals to fabricate artificial coral skeletons [21] or design proper shapes dedicated to particular species, including the proper surface topology for settlements [23]. Alternatively, photogrammetric technologies can also be used to obtain 3D models [1]. Also, other advanced techniques are joined with additive manufacturing for customization, including eDNA metabarcoding, and lifecycle-based emergent traits [23]. The combination of these technologies gives the possibility to create biomimetic artificial structures with a high efficiency of restoration in selected ecosystems [23]. Thanks to modern additive technologies, it is possible to produce complicated shapes, potentially even in underwater conditions [47].

Various 3D printing technologies are used for manufacturing artificial coral reefs; the most popular seems to be Fused Deposition Modeling (FDM). However, other technologies are also used, including fused filament fabrication (FFF), binder jetting, and VAT polymerization [48,49]. Albalawi et al. [21], in reaction to coral bleaching, created artificial corals using two different technologies, FDM and stereolithography (SLA), as supplementary processes to build artificial reefs [21]. Jia et al. [49] applied digital light processing (DLP) for coral restoration projects. This technology was selected mainly because of the speed of production and model scalability [49]. In turn, Hitzegrad et al. [50] selected particle bed 3D printing with Selective Cement Activation (SCA) for artificial reef manufacturing [50]. This technology allows for the creation of greatly accurate surrogate surfaces with the desired high roughness [50]. The additional advantages were complex geometry with high porosity and large overhangs, as well as the independence of production time from the model complexity [50]. For the reef projects, various types of devices are used, starting from partly self-modified FDM 3D printers, through concrete laboratory machines, up to large semi-industrial devices. The usage of particular solutions is usually connected with the scale of the project and its budget.

The important aspect of each project is the costs. In comparison to the traditional approach, 3D printing is connected with higher efficiency in restoration, but also with higher costs. Albalawi et al. [21] prepared the cost simulation for coral reef restoration using 3D printing technology [21]. According to his estimation, the cost of a fully functional 3D printing facility was approximately EUR 300,000 in 2021 [21].

4. Materials Used in Construction

4.1. Development of Materials for Artificial Reefs

Development of the materials can be divided into several stages, as shown in Figure 4.

Together with the development of artificial reefs, new materials have been taken into consideration [9]. Traditionally, construction is mainly focused on materials such as wood and stone; next, various waste materials started to be used, including concrete, steel, and rubber [19,48,51]. Currently, together with the development of technologies, the design of materials also becomes important [52,53].

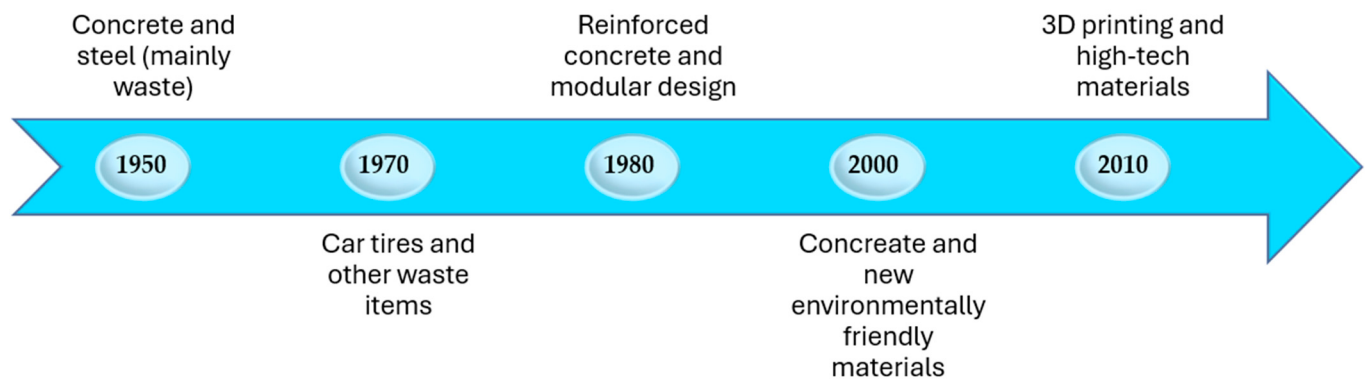


Figure 4. Development of technology and materials used for artificial reefs.

Regardless of the material used, there are important considerations when designing artificial reefs that should be considered in research. One of them is the long-term behavior of the material [9,51,54]. Some research shows the correlation between the artificial reef's age and its function [9,55]. This mechanism can be also connected with material deterioration as well as other factors [55,56]. As a result, together with material aging, the function of the ecological system can weaken, for instance, by an imbalance in biodiversity or deterioration of habitats [9]. In this case, long-term monitoring has a significant meaning for ensuring proper restoration functions as well as possible effective management, including reaction to changes [9].

4.2. Polymer-Based Solutions

Polymers and their composites are currently the most popular materials for additive manufacturing technology [57], and because of that, they also have a wide application in 3D printing artificial reefs [13,48]. Among the different types of polymers, particular attention was paid to biopolymers, such as celluloses, polylactic acid (PLA), and polyhydroxybutyrate (PHB) [21,58]. The usage of biopolymers improves the formation of coral species and effectively helps to restore marine habitats [21,58]. The efficiency of this system was investigated on oysters [59,60]. The main advantage in this case is the biodegradation of the material, which makes the growth of the organisms easier [61]. However, it could be stressed that biodegradation can potentially be a source of underutilized waste in the water. Also, some potential limitations with the usage of biopolymers in 3D printing artificial reefs are their poor rheological and mechanical properties [23,62]. This kind of material is suitable for the 3D printing process and very often requires modification.

PLA and PHA were employed by Ruhl and Dixon [63] to improve artificial reefs made using 3D printing technology for coral and mussel development [63]. The experiment confirms that the used material is proper for the settlement of reef-building corals, including *Porites astreoides*, and gives a better effect than limestone tiles made using traditional casting technology [63]. In other research, Temmink et al. [64] confirmed the possibility of using a 3D printing technique for the creation of proper growth conditions for blue mussel settlements [64]. Another research project with 3D-printed biodegradable artificial reefs shows the possibility of using the mineralized cellulose as a proper filament. The investigation was made on coral species (*Solenastrea bournoni*, *Orbicella faveolata*, and *Porites astreoides*) to confirm the proper growth [58] as well as the possibility of using these materials for CO₂ adsorption, which enhanced the ecological character of this composition [23].

One of the most interesting ideas is the usage of biopolymers from biomass waste [23]. This material has a lot of advantages, such as low price, possible marine degradability, and a lack of toxicity. However, there is a lack of long-term investigations into the influence of biodegradation products on marine ecosystems, which could potentially influence

increasing water eutrophication. Also, some research suggests that several biopolymers, such as PLS and PBH, can be characterized by ecotoxicity to the creation of microplastic waste [65,66]. Currently, two types of biopolymers, depending on their production strategy, can be employed: biomass directly extracted from waste and biomass synthesized from waste with the usage of additional processes, such as microbial fermentation or chemical conversion [23]. Nowadays, only a limited amount of materials from this group have been tested for their potential for the 3D printing of artificial reef creation, such as celluloses, PLA, and PHB [21,58]. However, they are not based on biomass waste. There is a large potential for providing complex research in this direction.

4.3. Cement, Geopolymers, and Similar Compositions

The results of studies conducted in different aquatic environments confirm that ceramic materials can be optimal for creating artificial reefs. The research found that ceramics and concrete were the most colonized by organisms compared with other materials such as metals or plastics, making them the most suitable habitats for a wide range of species, including fauna, flora, and microorganisms [6]. In addition, artificial structures made of ceramic materials are characterized by durability and the ability to form various types of reef structures. The complexity of the structure affects the associated fish communities, and the presence of holes and crevices provides shelter, breeding sites, and protection from predators [67]. The use of new technologies, in particular the use of 3D printing, is also of great importance.

It is not always clear which cementitious material is the best for applications on artificial reefs. Ly et al. [68] compared different cementitious materials, such as geopolymers and cement concrete, assessing their durability and biofouling (colonization of the structure by biological organisms) in seawater [68]. The results indicate that cement is a better material for building an artificial reef using 3D printing, due to its better mechanical properties and lower susceptibility to biofouling [68]. In turn, Yoris-Nobile et al. [69] showed that geopolymers have better biological receptivity compared to cement [69]. This indicates the need for further research on the selection of materials, depending on the purpose of remediation [68,69].

Selecting the right materials is crucial, as some of them can have undesirable effects. The two main problems associated with the use of Portland cement (OPC) or geopolymers are the increase in water alkalinity and the precipitation of calcium carbonate. The high pH value around the surface of the material inhibits the settlement of marine life [70,71]. OPC usually has pH of around 13, far exceeding the seawater pH of 8–9 [69,72]. Such a high value negatively impacts the surrounding environment, including the organism's settlement [72,73]. The process of neutralization in the natural environment typically takes 3–6 months to lower pH [73], where the colonization of the material is limited [74]. Therefore, during 3D printing, it is necessary to neutralize the print surface to ensure faster adjustment to the marine environment [75]. The second problem is mainly related to the use of OPC; in this case, we are dealing with carbonate formed as a result of the re-precipitation of soluble Ca^{2+} from alkaline cement. It tends to cover the surface and prevents the growth of marine life, resulting in poor colonization with microalgae [70].

A valuable trend is also the use of waste materials for artificial reef production, including industrial by-products, such as silica fume, which can result in lowering pH [72]. Alternative materials tested in artificial reefs manufacturing also include waste from machine-made sand production [76]. The investigation made by Kuand et al. [77] confirms the feasibility of applying this by-product in concrete for 3D-printed artificial reefs [76]. The replacement of 30% of sand with this waste does not influence the material's printability and only slightly decreases mechanical properties, while lowering carbon emissions [76].

The influence on the fish behavior was not observed [76]. There are even more possibilities if industrial by-products are used in the geopolymers. Martins et al. [77] investigated the material that was based on industrial waste–biomass of fly ash and red mud [77]. The 3D-printed samples confirm the printability of the created mixture and show that the mechanical properties are sufficient to create an artificial reef [77,78].

4.4. Other Materials

Among the other materials, the most popular are mineral-based, such as calcium carbonate, plasters, sandstone powder, ceramic clay, terracotta, and diatomite sand with magnesium oxide; these materials also show promising results in artificial reef research [13,20,79,80].

Most of them were used in extrusion technology as a paste, but it is not only possible to apply them; for example, calcium carbonate was successfully used as a photoinitiated ink [21]. It was also combined with soybean oil as an environmentally friendly composite, which was used in [49]. The other possibility is plant-based materials. Some of them have been tested using the vat-polymerization technique [48,49]. The investigation confirms the usefulness of these materials for coral restoration [49].

Other investigations show some advantages in using terracotta as a material for artificial reef construction [19]. These materials allow for the creation of highly mimicked natural reef habitats [20,71]. This ceramic material is composed of non-toxic oxides, is highly porous, and has a neutral pH, which is a clear advantage for artificial reef applications [19,71,81,82].

5. Case Studies, Including Impact on the Ecosystem

5.1. Marine Ecosystems

The influence of artificial ecosystems can be analyzed using several platforms, including positive aspects, such as increasing biodiversity, protection against erosion, and changes in the behavior of fish and other organisms, as well as potential challenges, including hazards related to the use of inappropriate materials or technologies.

The use of printing techniques allows for increased structural complexity and biodiversity by precisely adapting the structure to the needs of local ecosystems [68,83]. Artificial reefs created in this way provide additional space for organisms to settle and grow, which contributes to increasing local biodiversity and stimulating ecosystems [68,84]. It also plays an important role with fish populations by offering complex habitat structures [9,85]. 3D printing technology also allows for more effective environmental restoration compared to traditional solutions such as simple-shaped concrete structures [86]. Exemplary research was provided in the framework of the Interreg Atlantic project 3DPARE [87]. The activities in this project were connected with designing and testing different types of 3D-printed concrete reefs. The differences among the particular units were connected by the sizes of holes, tunnels, and overhangs. A total of eight solutions have been tested in the UK, France, Spain, and Portugal. The obtained results show clear differences recorded between the habitat features [87,88]. It confirms the necessity of the “personalization” of solutions, depending on local biodiversity.

Ruhl and Dixon [63] investigated the efficacy of using 3D-printed artificial reefs in comparison to natural coral reefs as habitats for blue-green chromis (*Chromis viridis*) and larval mustard hill coral (*Porites astreoides*) [63]. The provided behavior shows that both species did not discriminate or display modified behaviors between 3D-printed and natural coral skeletons. Moreover, larval mustard hill coral displayed a significantly higher settlement when provided with the artificial 3D-printed surfaces; meanwhile, the growth and mortality of the investigated species did not significantly differ [63]. This

confirms that this kind of artificial structure can be a valuable ecological tool for ecosystem restoration [63].

The other area of application for additive manufacturing is connected with the restoration of oyster reefs [59]. In this case, the advantage of 3D printing is connected with the possibility of designing irregular and intricate shapes of artificial structures resembling natural oyster reefs [21,69]. This kind of complex shape can ensure optimal substrates for oyster colonization and growth [59]. Another advantage of using additive manufacturing is the possibility to perform tailored structures according to specific environmental conditions, such as water flow and sediment composition in a short time [59,69]. The elements can be optimized for oyster survival and faster growth in a particular local ecosystem [22].

Also, it is important to monitor the efficiency of the artificial reefs and ecological succession [19,89]. The investigation provided by Oren et al. [19] confirms the efficacy of a 3D-printed terracotta artificial reef for the recruitment and settlement of fish, corals, and other marine organisms—Figure 5 [19].

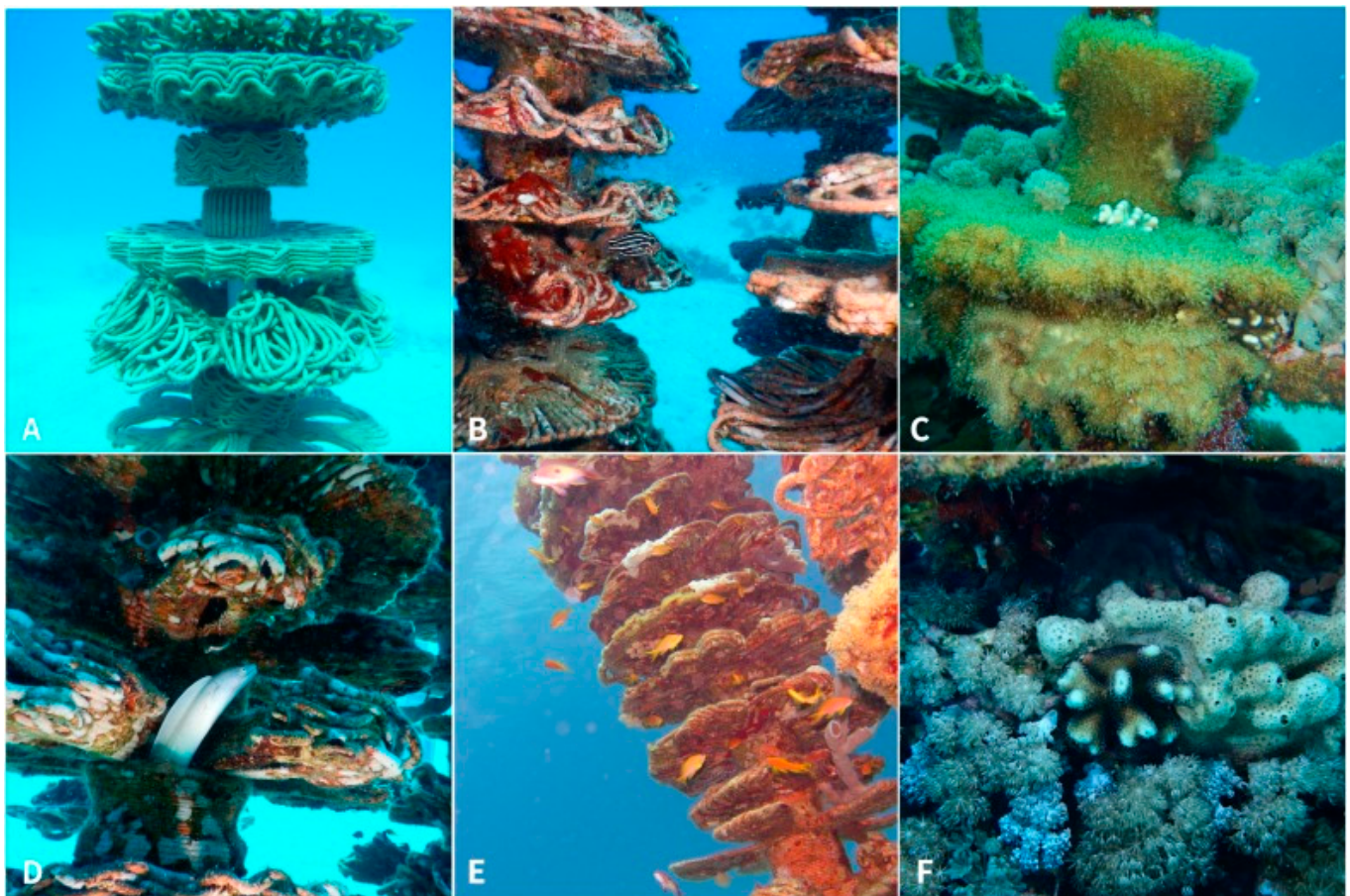


Figure 5. The ecological process of artificial reef colonization. (A) The first artificial reef structure a week after deployment (4 July 2019). (B) The artificial reef structures 6 months after unification (23 November 2020). (C) The top of the first deployed structure after 3.5 years (1 February 2023), completely covered with *Octocorallia Rhytisma fulvum* and *Xeniidae* sp. with two *Stylophora pistillata* colonies. (D) *Gymnothorax griseus* inhabiting the artificial reef structure in the inner spaces (23 November 2020). (E) The artificial reefs inhabited by around 60 *Pseudanthias squamipinnis*, together with various benthic organisms, two years after deployment (21 October 2021). (F) Interspecies interaction *Botryllus eilatensis*, *Stylophora pistillata*, and *Xeniidae* sp. covering the artificial reef (11 August 2022) [19].

The previous research confirms the usefulness of artificial reefs for the restoration of ecosystems; however, it is worth noticing that there is a lack of standardization in this kind of

research. Nowadays, the efficiency of artificial reefs is assessed mainly using comparisons to traditional methods [64]. Currently, there are no standardized methods for assessing biological invasions or “ecological services” (functioning of artificial reefs). There is a lack of effective methods for comparison and assessment that could take into account different phases of successional ecology [3]. It is necessary to develop such protocols in future studies. Artificial reefs, as a form of ecological engineering created by humans, have the potential to play a positive role in maintaining the stability and diversity of aquatic ecosystems over long time scales [90]. The condition, however, is their proper design, supported by comprehensive research and long-term monitoring. A similar problem is connected with monitoring the succession and biodiversity in artificial reefs, because of a lack of unified standards [9,91]. The most important thing in this area seems to be the long-term monitoring of the ecosystem-carrying capacity, which could potentially lead to unanticipated ecological consequences [9,91].

Artificial reefs can be also connected with some treatments for ecosystems. In the context of artificial reef planning, it is crucial to consider potential ecological threats. One important issue is the phenomenon known as “ocean sprawl”, i.e., the excessive spread of artificial structures along natural environments, which can pose a threat to ecosystems. The increased connectivity of systems caused by the proliferation of artificial reefs has the potential to facilitate biotic homogenization or introduce species outside their native ranges [3]. However, some research confirmed the reverse mechanism as a promotion of the settlement of coralline algae and discouraging invasive species in subtidal zones [17]; the problems connected with potential “ocean sprawl” and the wide spreading of invasive species should be taken into consideration during planning the research.

5.2. Development of Freshwater Systems

Nowadays, artificial reefs are commonly used in warm, salty waters. The benefits of their use include new habitats for organisms, from sessile forms to fish, protection of the shoreline, reduction in the effects of anthropogenic impacts by increasing spatial complexity, and development of tourism [1,8,92]. Artificial reefs mainly act at a local scale, acting as a refuge in the system and increasing spatial heterogeneity in the reservoir [4,8].

In this case, the use of these structures in inland reservoirs becomes particularly important. Despite the high demand, few studies have been conducted on the use of artificial reefs in freshwater lakes [3,93]—Table 1. Among them, there is a lack of additive manufacturing applications for this type of water.

The analysis of the research conducted to date, presented in Table 1, shows that the currently used solutions for artificial reefs in freshwater reservoirs are characterized by a high degree of primitivism, both in terms of the materials used and the technologies applied. There is a lack of previous research connected with the usage of 3D printing technologies for designing freshwater artificial reefs. Meanwhile, the need to optimize this kind of construction for freshwater ecosystems seems to be even larger than for marine ones.

Previous studies have shown the important role of microhabitats in the lifecycle of lake fauna, with particular emphasis on selected freshwater fish species. The artificial structures in these studies supported freshwater species, helping to reduce the negative impacts of environmental pressures and playing a key role in the successful colonization of these areas by several species. Additionally, these structures promoted the protection of juveniles, reducing the effectiveness of predators as the availability of shelters increased. The studies show that artificial reefs in freshwater can significantly support the maintenance of biodiversity by increasing the spatial complexity of the environment [8].

Table 1. Work to date on artificial reefs dedicated to freshwater.

No	Solution	Research Area	Source
1	Building a reef from piles of car tires placed on a wooden support—dimensions 2.45 m × 1.05 m × 1.25 m	A river in Brazil where the impact of introducing artificial reefs on fish communities in a tropical hypereutrophic reservoir was assessed	[4]
2	Reefs made of piles of car tires placed on a wooden support—dimensions 2.45 m × 1.05 m × 1.25 m	The impact of habitat complexity induced by artificial reef construction on fish communities in a reservoir in Brazil	[8]
3	Structure consisting of cement discs (weight: 25 g, diameter 39 mm, thickness: 13 mm). Cements enriched with silica (pozzolanic), blast furnace slag, and fly ash were used for the construction	Assessment of the suitability of different cements as substrates for the construction of artificial reefs based on the occurrence of microalgae populations on the structures in the USA	[94]
4	An artificial reef built of granite rubble	Impact on the number of different fish species in the USA	[7]
5	A round frame made of 19 mm diameter polyvinyl chloride (PVC) pipe with standard dimensions (diameter 1.8 m and surface area 2.5 m ²). Polyethylene ropes were attached radially to the rope to tie bunches of plants	Effects on the number of different fish species in the oligotrophic reservoir in Brazil	[5]
6	The artificial reefs were constructed from ceramics, concrete, and polyvinyl chloride (PVC) by arranging pipes of the individual materials with a length of 1.0 m and a diameter of 0.3 m in a pyramidal frame (10 pipes in a 4:3:2:1 arrangement from the base to the top)	Influence of reef material (ceramics, concrete, and PVC) on its colonization by fish in Itaipu Reservoir in Brazil	[6]
7	Two artificial structures: pipes and trees and two semi-natural rocks. The pipe structure was built from ceramic pipes 0.8 m long and 0.25 m in diameter. The structure is in the shape of a pyramid made of 10 pipes. The wooden structure was composed of four pine trees	Experimental verification of the use of artificial habitats by fish in two neotropical reservoirs (2 water reservoirs in Brazil). Determination of the relationship between the type of habitat and the impact on selected species	[95]
8	Artificial reef consisting of biomass modules, each measuring 900 mm × 900 mm × 120 mm. Raw materials were mainly derived from by-products of biomass energy production from crops and forest residues	Research on the structure of phytoplankton communities around an artificial reef and its adjacent waters in China	[93]
9	Four types of artificial reefs (cemented rope, brick, wood, and ceramic) were tested over a period of six months	Benthic species were studied. Colonization was faster and denser on bricks and ceramics. The study was conducted in a freshwater pond filled with water from a river in Iran	[96]

6. Challenges and Limitations

Artificial reefs bring a lot of potential benefits connected with their application, but there are still some challenges that limit their application. Some of the challenges and limitations were presented in previous sections. Here, we would like to summarize the most important among them. The existing challenges have been connected in four main areas, including materials, technologies, the ecosystem, and others. It is worth mentioning that these areas influence each other. The main groups of challenges are presented in Figure 6.

Despite the availability of many materials suitable for this purpose, there is a limited number of studies on the effects of their physical and chemical properties on different species of fauna and flora, especially over long periods [97]. Moreover, in the field research, the ecological impact on the ecosystems is not always easily predictable over a longer perspective [60]. Three-dimensional printing technology seems to be the best option for reef restoration, providing customized and sustainable solutions, but it should be mentioned that there is still a small amount of research that shows the influence of this kind of structure over a longer perspective [23]. Nowadays, the two more popular groups of materials for artificial reef creation using additive manufacturing are plastic-based materials and cement concrete. Both of them could potentially have a negative influence on the environment, such as the release of heavy metals or microplastic particles [23,98,99]. The challenges connected with the materials and technologies for artificial reef manufacturing are in several cases similar to challenges for additive manufacturing development in other areas, especially in terms of designing more environmentally friendly solutions [100–102] or optimizing the

material parameters [103,104]. Others are very specific, including the application of 3D printing technology in underwater environments [13,47].

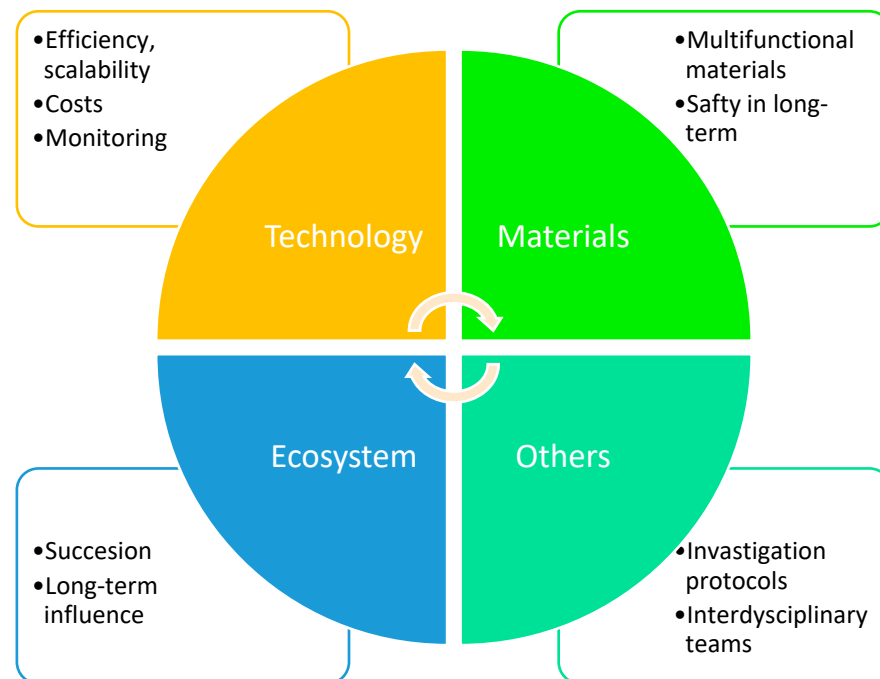


Figure 6. Selected challenges connected with artificial reefs.

An important group of limitations is also connected with current knowledge about different ecosystems and limitations in predicting the changes in the whole complex net of connections between the various organisms. Nowadays, our knowledge in this area is quite limited and we cannot always predict all the consequences of our activities. It can be especially important in the case of new perspectives that are offered by additive manufacturing [17,105].

The current limitations of provided projects are also connected with the scalability of the additive manufacturing technology. Providing research on a large scale is connected with increasing the size of the objects and with significant changes in the required time of production and cost of manufacturing [21]. A lot of publications mention additive manufacturing as a cost-effective approach to restoring coral reefs [21]. However, taking into consideration the huge size of the required scale of implementation, the overall implementation costs will be high. Moreover, the successful implementation requires close cooperation and the development of interdisciplinary teams, which are also challenging tasks [21].

7. Predicted Directions for the Development of Artificial Reefs

Nowadays, in scientific publications, there is a clearly visible trend connected with ensuring the multifunctionality of the reef structure and a more complex approach to investigating the interaction between particular components [88]. Bao et al. [9] predict that future research in the area of artificial coral reefs will be connected with the expansion and renewal of the effect range of these structures, including the influence of climate change [9]. Further research is needed on the impact of artificial reefs on ecosystems [93]. There is an urgent need for further research to better understand the role of artificial habitats, especially in the face of climate change scenarios [3]. This research is essential in the context of properly designing and planning artificial habitats that will support biodiversity conservation efforts in the case of lost or disturbed natural habitats [3].

The other specific problem is associated with decarbonization. The problem of decarbonization in the marine environment has gained its own terminology, most often referred to as “blue carbon ecosystems” or “organic blue carbon sequestration” [106,107]. So far, this issue has been mainly analyzed in the context of living organisms, especially in terms of the carbon dioxide storage capacity of mangrove forest ecosystems and aquatic plants in the coastal zone [108–110], and the role of other organisms in this process [111,112]. Only a few studies have been devoted to decarbonization in the context of lake and wetland ecosystems [113,114]. So far, this problem has not been considered in terms of using materials that could bind carbon dioxide underwater, in processes analogous to those occurring on the surface. The opposite situation applies to current solutions in construction, where the issues of carbon dioxide sequestration are implemented, e.g., in geopolymer materials [115–117]. However, these solutions have not been applied in underwater environments so far. The introduction of this technology will constitute a research challenge for the future development of artificial reefs. Research in this field should include the prediction of effects, especially considering interactions with other human activities, such as climate change [3].

Another important function of artificial reefs can be support in combating invasive species. Although artificial habitats can lead to an increase in the local abundance and diversity of fauna and flora species, it is necessary to consider the origin of these species (i.e., native or non-native). Previous studies indicate that artificial habitats can be effectively used to reduce the ability of invasive species [95]. Bao et al.’s [9] forecasts also employ molecular ecological regulation to create “active artificial reefs” [9]. This is possible by using specific natural chemicals integrated with reef materials [9]. However, this requires deepening knowledge and adapting the designed structures to specific local conditions and species occurring there. These activities can also be carried out on a micro scale. It is worth emphasizing that an artificial reef can promote the development of desirable microorganisms in a given water body. It can also limit the growth and reproduction of cyanobacteria, while significantly promoting the development of diatoms [93].

Another function of the reef can be connected with water treatment. The experiment in this area was provided by Mendirk et al. with microplastic trapping [118]. This team created mechanisms controlled by hydrodynamics for microplastic catching [118]. This kind of function can also be coupled with the controlled release of particular elements, oxides, or more complex components. Currently, one of the basic requirements for the materials is a lack of significant leaching of the elements from the material, but the controlled leaching of particular nutrients can be positive for the development of desired microorganisms.

Other areas of predictable development are digitalization and integration with smart technologies, including advanced materials. In this area, it is predicted that increasing importance will be given to smart monitoring systems that integrate sensors, self-regulating materials, and energy capture devices [9]. A beneficial idea concerns integrating the artificial reefs into existing and emerging marine infrastructure [9]. This allows for decreasing the investment costs. Concerning the design of new materials, the most promising seems to be symbiotic materials and self-healing materials [9,119]. Among the technological trends also worth considering are virtual reality and augmented reality technologies that have immense potential for marine research and conservation, and can help with spreading knowledge in this area [120–122].

8. Conclusions

The provided literature review allows us to formulate the following conclusions and identify the following areas for future development:

- Numerical modeling is used mainly for wave simulation. There is a large potential to also use the modeling process for other purposes, such as the prediction of development, particularly of species or ecosystem growth.
- Nowadays, different additive manufacturing technologies are used for designing and manufacturing coral reefs. The most effective seems to be joining several of them in one project, which gives new possibilities for reef restoration.
- Currently, the most reliable seems to be the use of cementitious materials for artificial reef production using additive manufacturing technology; however, the usage of other materials, including biopolymers from biomass waste, seems to be a valuable option for the future.
- A lot of research confirms the benefits connected with artificial reefs for the restoration of ecosystems; however, the problems connected with potential “ocean sprawl” and the wide spreading of invasive species should be taken into consideration during planning the research.
- Still, a lot of challenges exist in the area of artificial reefs, which are connected with materials, additive technology, investigated ecosystems, and other areas. The exemplary challenges are a lack of previous research connected with the usage of 3D printing technologies for designing freshwater artificial reefs and the small number of investigations about the long-term function of artificial reefs.
- There are several areas that seem to be crucial for the further development of artificial reefs, including multifunctionality, digitalization, and the design of advanced materials. This topic seems to have a huge potential in further research, but it also requires joining competences from several scientific disciplines.

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Abbreviations

The following abbreviations are used in this manuscript:

DLP	Digital Light Processing
FDM	Fused Deposition Modeling
FFF	Fused Filament Fabrication
PLA	polylactic acid
PHB	polyhydroxybutyrate
SCA	Selective Cement Activation
SLA	Stereolithography

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