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# Industrial Waste Utilization in 3D Printable Concrete for Artificial Reef Applications: A Bibliometric Analysis (2013–2023)

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**ABSTRACT**

The accelerating decline of coral reef ecosystems has intensified the search for sustainable restoration strategies. Artificial reefs (ARs) are widely recognized for their capacity to provide structural complexity and habitats for marine organisms. Recent advances in additive manufacturing, particularly 3D printable concrete (3DPC), create opportunities to design ARs with optimized geometries, tailored surface textures, and eco-friendly material blends. This review explores the role of industrial wastes in 3DPC for AR applications and examines global research progress between 2013 and 2023. By combining bibliometric mapping with qualitative synthesis, the study provides both a quantitative overview of research activity and thematic insights into material and ecological performance. The analysis highlights the rapid growth of interest in sustainable marine construction, the integration of industrial by-products such as fly ash and slag into 3DPC, and the emergence of interdisciplinary research bridging construction science and marine ecology. Beyond technical advantages such as improved strength and durability, these materials directly influence ecological outcomes by enhancing surface roughness, porosity, and long-term stability, which are critical for species colonization and biodiversity support. The findings reveal significant research gaps, particularly in standardized design protocols, ecological monitoring, and long-term performance evaluation. This study contributes a comprehensive perspective on how waste-based 3DPC can support sustainable reef restoration, while outlining future directions for advancing eco-friendly marine infrastructure.

## 1. Introduction

Over the past four decades, various factors have negatively impacted the complete coral reef ecosystem. In numerous regions, more than 70% of coral reefs have suffered from loss or deterioration. Coral coverage has declined, and numerous reef species have gone extinct. Presently, one of the most critical challenges we confront is the depletion of marine life, which is pushing species towards extinction. As a result, marine scientists have devised proactive strategies for restoration, such as the establishment of coral nurseries, coral transplantation, and the field of ARs[1–3]. According to Seaman's definition, artificial reefs are underwater structures formed of natural or artificial materials. They are deployed with the purpose of safeguarding, improving, or restoring various elements within ocean ecosystems. The presence of ARs in a reef habitat can lead to enhancements by introducing additional structural intricacy and reef substrate. This supports the colonization and survival of marine organisms, particularly in severely deteriorated natural reef environments[4], [5]. The utilization of ARs can play a role in assisting specific areas that require support. While ARs have the potential to restore various marine habitats, careful consideration is necessary before submerging any structures. An AR project should thoroughly address and justify various aspects, ensuring there are sound ecological grounds for undertaking such a project in accordance with ethical and responsible guidelines. OSPAR provides several guidelines that should be taken into account when ARs are associated with living marine resources[6]. To begin with, it is essential that the AR is constructed using non-reactive materials and does not include any waste or substances that are prohibited. Furthermore, the design and preparation of the AR should be robust and stable enough to withstand the physical pressures of the specific environment without causing any adverse effects on its surroundings. Ultimately, the AR should be designed in a way that allows for its potential removal if necessary[2], [5], [7–9].

For many years, the submergence of ARs along coastal areas has been practiced in different regions worldwide. This has involved the use of various objects, including old cars, shipwrecks, tires, stone or concrete blocks, and, more recently, specially designed elements that mimic natural environments[10–13]. Studies indicate that employing concrete as a construction material for ARs, combined with its rough surface texture, promotes more effective biological colonization [10]. The external configurations, dimensions, and arrangements of openings, surface roughness or texture, and the choice of materials utilized in the construction of ARs, among other attributes, directly influence the attraction and growth of marine organisms in a specific area[14–16].

Additive manufacturing or 3D printing (3DP) can have a significant impact on the production of ARs, as it enables the fabrication of tailor-made designs. This technology provides the opportunity to optimize the shapes and textures of ARs, aiming to attract a greater abundance of marine life by simulating natural environments[17], [18]. Creating ARs through 3DP is not a novel subject; numerous initiatives and projects have put forth various designs for shapes [7], [17–19]. However, there is a significant lack of information pertaining to the design, materials employed, and characterization of the deployment site. Additionally, there is an inadequate systematization of the monitoring process post-deployment, and the identification of correlations between shapes and/or materials with bio-colonization performance remains insufficient[20].

3DP is a technology that has been gradually integrated into the construction sector. Specifically, Extruded Material Systems (EMS)-based technology offers more flexibility compared to Powder Based Systems (PBS), aiding in the creation of larger three-dimensional components [21]. Another benefit of EMS over PBS systems is that in the former, mortar is pre-mixed, ensuring the proper hydration of the cement. In contrast, PBS systems involve spraying water onto a layer of dry mortar without subsequent mixing. This means that adequate cement hydration is not always assured, potentially resulting in a decrease in strength. Additional advantages of additive manufacturing include the elimination of formwork, decreased material wastage, and optimized resource utilization[22]. Nevertheless, EMS concrete printers often face limitations in terms of complexity, typically confined to the construction of vertical walls within an irregular flat configuration [23].

In existing construction practices, the combination of sustainable materials is regarded as a crucial prerequisite. This significance is further amplified in the case of ARs, given their distinctive environmental attributes[23]. Certain research directions advocate for the utilization of alternative or binders with lower clinker content, while others suggest substituting natural aggregates with recycled aggregates or industrial by-products. Several studies highlight the viability and advantages of incorporating recycled or alternative materials in the production of ARs. Examples include the successful use of materials like fluorogypsum, concrete with steel and blast furnace slag, sulphoaluminate cement, among others, in the construction of ARs[24–28].

Environmentally friendly cement blends often incorporate calcium aluminosilicate materials and various industrial by-products that have found application in infrastructure projects. Beyond contributing to sustainability, the incorporation of supplementary cementitious materials (SCMs) as substitutes for cement can enhance material rheology, as well as long-term strength and durability properties[29–31]. In this context, our emphasis is on exploring the suitability of different industrial wastes for incorporation into 3DPC. The utilization of these materials in 3D printed or digital concrete proves advantageous as it helps mitigate waste disposal issues, and these materials offer favorable effects on rheology and early age properties essential for printability. The concept of digitally fabricating concrete was initially introduced in 2004 by Behrokh Khoshnevis under the term 'Contour Crafting' [21]. Subsequently, in 2011, scientists at Loughborough University in the UK pioneered 3DPC, a technique that involves layering fresh concrete in accordance with the digital blueprint of a structure. The process flow of 3DPC involves several stages, typically starting from digital design and ending with the production of the final 3D printed structure. Here is a general overview of the process flow[32], [33]:

- **Digital Design:** The process begins with the creation of a digital model or design of the desired structure using computer-aided design (CAD) software. This digital model serves as the basis for the subsequent steps in the 3DP process.
- **Slicing:** The digital model is sliced into thin horizontal layers, creating a set of 2D cross-sectional plans. This step is crucial for the layer-by-layer printing process.
- **Printing Setup:** The 3D printer is set up with the necessary parameters, including the type of 3DP technology, the printing material, layer thickness, and other printing conditions. The printing material in the context of 3DPC is typically a specialized concrete mixture.
- **Printing:** The actual 3DP process begins. The 3D printer follows the sliced plans, depositing or extruding the concrete material layer by layer according to the digital design. Various 3DP technologies can be used, such as extrusion-based printing or powder-based printing.
- **Curing:** After each layer is deposited, the printed structure goes through a curing process. Curing allows the concrete to gain strength and solidify. The curing conditions, such as temperature and humidity, can impact the final properties of the printed structure.
- **Layer-by-Layer Buildup:** The printing and curing process is repeated layer by layer until the entire 3D printed structure is complete. The layer-by-layer buildup is a distinctive feature of 3DP and allows for the creation of complex geometries.
- **Post-Processing:** Once the printing is complete, there may be post-processing steps such as surface finishing, removal of support structures, or any additional treatments to enhance the final appearance and properties of the printed structure.
- **Quality Control:** Quality control measures are taken to ensure that the final 3D printed structure meets the required specifications and standards. This may involve checking dimensional accuracy, strength, and other relevant properties.

### 1.1. Objectives

This paper seeks to:

- Conduct a qualitative review of the literature on industrial waste utilization in 3D printable concrete.
- Perform a bibliometric analysis to identify key research themes, prolific authors, and influential journals.
- Synthesize qualitative and quantitative findings to present a comprehensive overview of the field.

## 2. Materials and Methods

### 2.1. Data Source and Search Strategy

The bibliometric dataset was retrieved from the Scopus database, which was selected due to its comprehensive coverage of peer-reviewed journals, conference proceedings, and review articles across engineering and environmental sciences. The search covered the period 2013–2023 and was performed using a combination of keywords related to “3D printable concrete,” “artificial reefs,” and “industrial waste.” The search fields included Title, Abstract, Author Keywords, and Keywords Plus.

### 2.2. Inclusion and Exclusion Criteria

To ensure relevance and quality, the following inclusion criteria were applied:

- Publications between January 2013 and December 2023.
- Articles, reviews, and conference papers written in English.
- Studies explicitly addressing industrial waste incorporation in concrete, 3D printing, or artificial reef applications.

Exclusion criteria included:

- Non-English publications.

- Editorials, book chapters, notes, or errata.
- Studies unrelated to either 3D printable concrete or artificial reef applications.

### 2.3. PRISMA Screening and Justification

The PRISMA framework was applied to enhance transparency and reproducibility in the selection process. Initial retrieval yielded 1,080 records. After removing duplicates and applying inclusion/exclusion criteria, 773 documents were retained for analysis. PRISMA ensures a systematic and replicable process for documenting database searches, screening steps, and final dataset selection, thereby enhancing methodological rigor [34]. **Fig. 1** shows the PRISMA framework for this study.

### 2.4. Limitations of Database Selection

This study relied solely on Scopus, which, while extensive, may not capture all relevant publications indexed in databases such as Web of Science or Google Scholar. This limitation was acknowledged to avoid overgeneralization. However, Scopus's broad multidisciplinary coverage and structured metadata make it suitable for bibliometric analysis, and its use aligns with standard practice in similar studies.

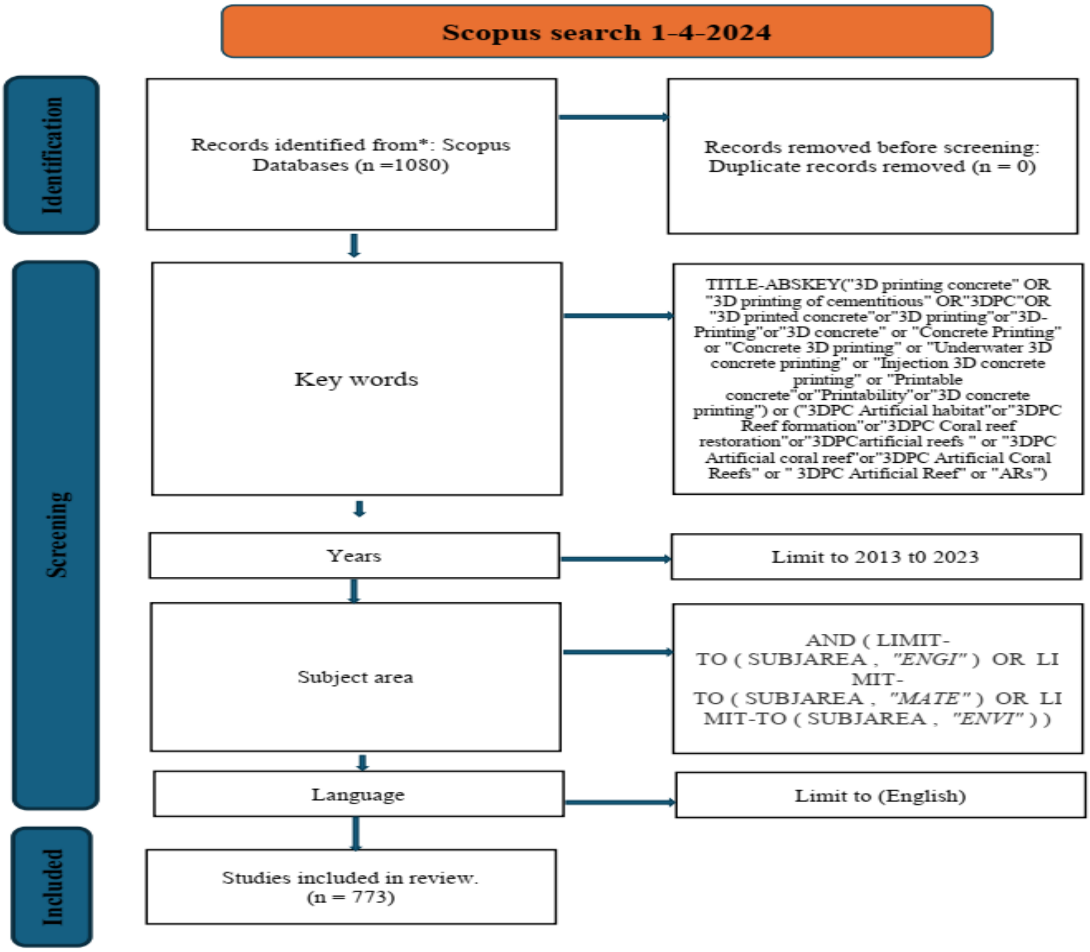


**Fig. 1: PRISMA Flow Diagram of the Study Selection Process.**

### 3. Bibliometric Analysis

Bibliometric analysis is a statistical approach used to quantify and evaluate the emerging trends within a particular field of study[27], [35]–[38]. Bibliometric analysis has been utilized to assess the academic outputs across various study disciplines[27], [39], [40]. The search, conducted on the Scopus database from 2013 to 2023, utilized various search fields such as Title, Abstract, Author Keywords, and Keywords Plus. The search employed a combination of keywords using AND/OR logic, including terms like ("3D printing concrete" OR "3D printing of cementitious" OR"3DPC" OR "3D printed concrete" or"3D printing" or"3D-Printing" or"3D concrete" or "Concrete Printing" or "Concrete 3D printing" or "Underwater 3D concrete printing" or "Injection 3D concrete printing" or "Printable concrete" or"Printability" or"3D concrete printing") or ("3DPC Artificial habitat" or"3DPC Reef formation" or"3DPC Coral reef restoration" or"3DPC artificial reefs " or "3DPC Artificial coral reef" or"3DPC Artificial Coral Reefs" or " 3DPC Artificial Reef" or "ARs"). The results were assessed based on titles and abstracts to ensure alignment with the theme and core topic of the article.

The research employed Scopus analysis and VOS viewer software, and graphs were generated using Microsoft Excel software along with the line graph maker tool on the website rabid tables. Various details were extracted for each document, including (1) the number of documents per year, (2) average citations of articles per year, (3) author keywords and frequently used words in titles, (4) journals of publication for each article, (5) science categories, (6) most cited articles, (7) authors and coauthors for each article, (8) H-index for top 10 authors, (9) affiliation details for authors and coauthors, (10) countries of the authors, and (11) H-index for top 10 journals,. Bibliographic maps were generated using VOS viewer software, covering co-occurrence between keywords, co-authorship maps for countries, and bibliographic coupling for countries and affiliations.

The total number of results that were initially found is 1080 documents, out of which 773 were found to be correlated with the theme of the study. Filtered results were categorized as follows: research articles, 436 review papers, 165 conference papers,176, and 5 for all other document categories. The total number of sources is 196, and the number of keywords is 1695. Retrieved publications had an average annual growth rate of 32.71% ;the most significant increase was between 2018 and 2023 as shown in **Fig. 2**. The most publications were in 2023, with 590 as shown in **Fig. 2**. The highest average citation per year was in 2023 ,with a mean total citation per year of 70.01 as shown in **Fig. 3**. This specific year had only 320 articles. **Fig. 3** shows journals' dynamics over the years. The journal "Sustainability (Switzerland)" was the most popular journal until the year 2023, when the journal" Journal of Cleaner Production" took its place with a cumulative number of articles of 48,515. As for the Cite Score (2022) of journals, "Journal of Cleaner Production" had the highest Cite Score with a score of 18.5, followed by "Additive Manufacturing" with a Cite Score of 17, and" Cement and Concrete Composites" also with a Cite Score of 15.5, as tabulated in **Table 1**.

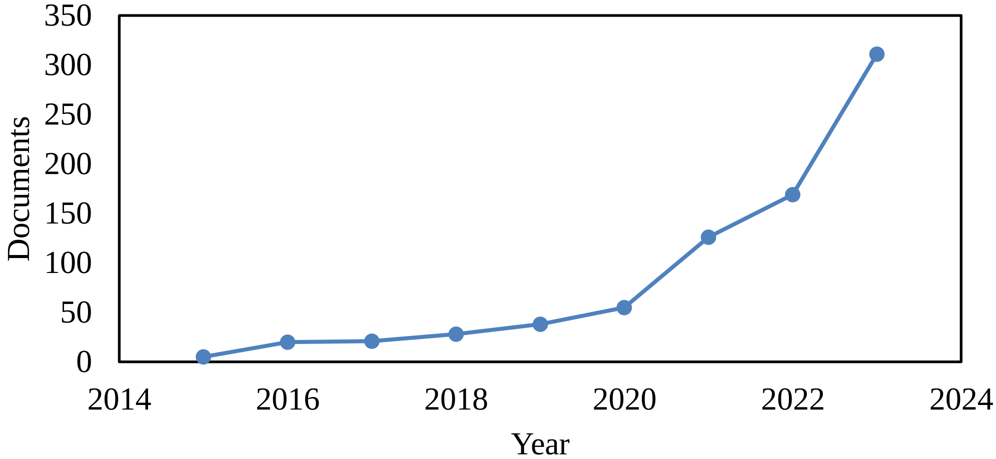


**Fig. 2: Annual Distribution of Publications (2013–2023).**

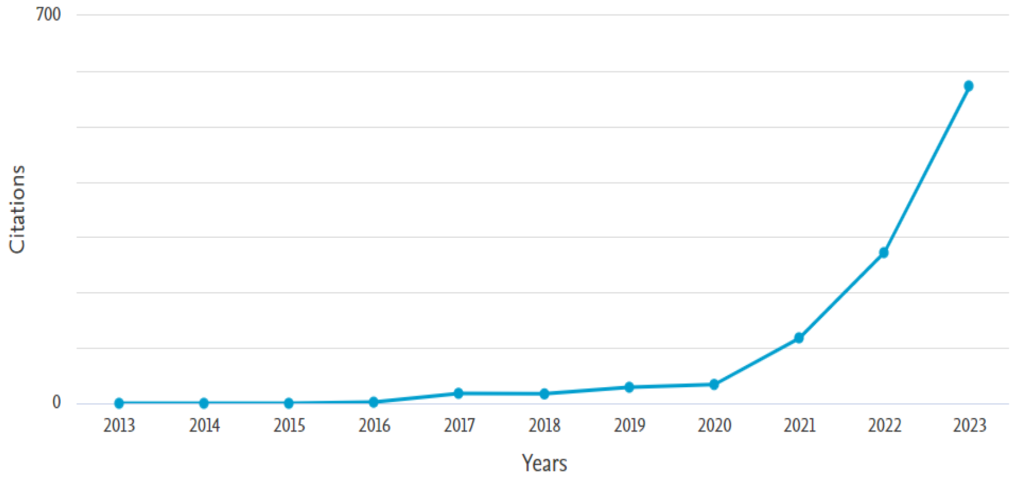


**Fig. 3: Average Citations per Article by Year (2013–2023).**

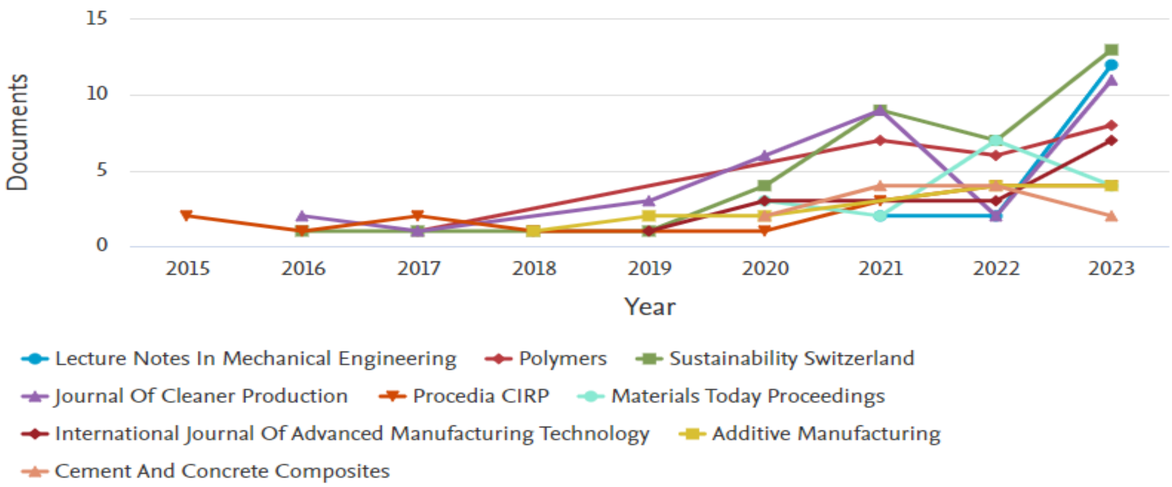


**Fig. 4: Annual Distribution of Publications by Journal (2013–2023).**

**Table 1: Top 10 Most Productive Journals on Industrial Wastes in 3D Printable Concrete Research.**

| Journal | TP | TC | Cite Score (2022) | Most cited publication | Times Cited | Publisher |
|---|---|---|---|---|---|---|
| Sustainability (Switzerland) | 48,515 | 281,271 | 5.8 | Aristovnik, Aleksander et al. (2020) | 958 | MDPI |
| Journal of Cleaner Production | 19,002 | 351,758 | 18.5 | Seuring, Stefan et al. (2008) | 4,013 | Elsevier |
| Polymers | 15,057 | 100,096 | 6.6 | Makadia, Hirenkumar K. et al.(2011) | 3,124 | MDPI |

| | | | | | | |
|---|---|---|---|---|---|---|
| Procedia CIRP | 4,625 | 16,348 | 3.5 | Lee, Jay et al. (2014) | 1,308 | Elsevier |
| Lecture Notes in Mechanical Engineering | 14,710 | 13,434 | 0.9 | Chalyj, Vasyl et al (2020) | 478 | Springer Science and Business Media Deutschland GmbH |
| Materials Today: Proceedings | 24,871 | 80,455 | 3.2 | Panwar, Vishwanath et al. (2020) | 399 | Elsevier Ltd |
| Construction and Building Materials | 13,865 | 171,966 | 12.4 | Sanchez, Florence et al. (2010) | 1,386 | Elsevier Ltd |
| International Journal of Advanced Manufacturing Technology | 7,465 | 46,142 | 6.2 | Tao, Fei et al (2018) | 1,687 | Springer London |
| Additive Manufacturing | 2,340 | 39,666 | 17 | Aboulkhair, Nesma T et al. (2014) | 1,077 | Elsevier B.V. |
| Cement and Concrete Composites | 1,396 | 21,652 | 15.5 | Meyer C. et al. (2009) | 1,101 | Elsevier |

TP= Total Publications, TC= Total Citation

Concerning scientific categories, 48.4% of total articles fell under the category of Engineering, followed by materials science with 17.8 % of total articles and environmental science with 9.6 % of total articles, as shown in **Fig. 5**. The articles had a total number of authors of 202. “Qian, S.” had the highest number of articles, with 7 articles, and “Bodaghi, M.”, “Mushtaq, R.T.”, “Tan, M.J.”, “Vidakis, N.”, “Wong, T.N.”, came in second with 6 articles, followed by “Lu, B.” with 5 articles as shown in **Fig. 6**. As listed in Table.2 the authors’ H-index, “Wong, T. N” had the highest H-index with a score of 42, followed by “Bodaghi, M” with an H-index of 39 and “Qian, Shunzhi”, and “Panda, Biranchi Narayan” with an H-index of 33.

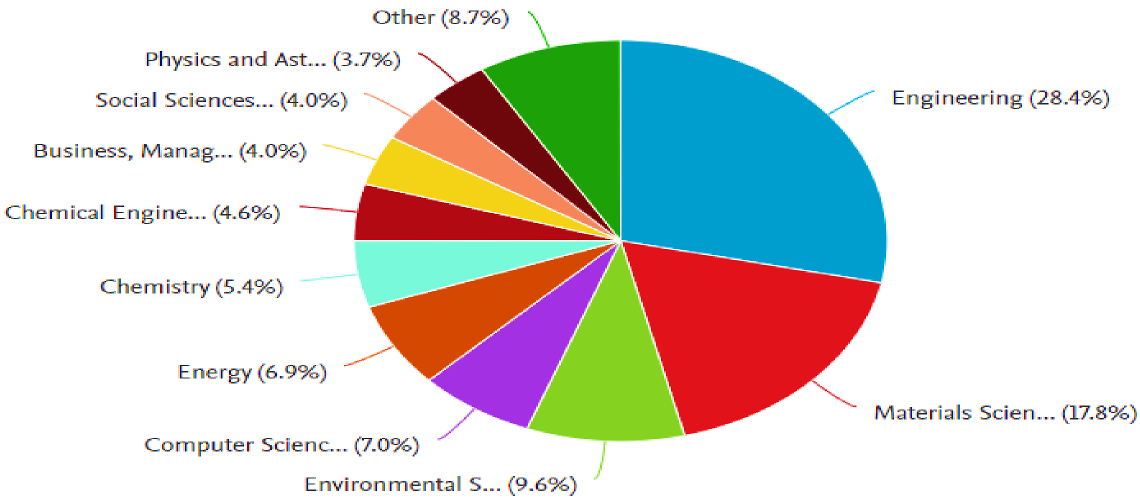


**Fig. 5: Publications by Research Field (2013–2023).**

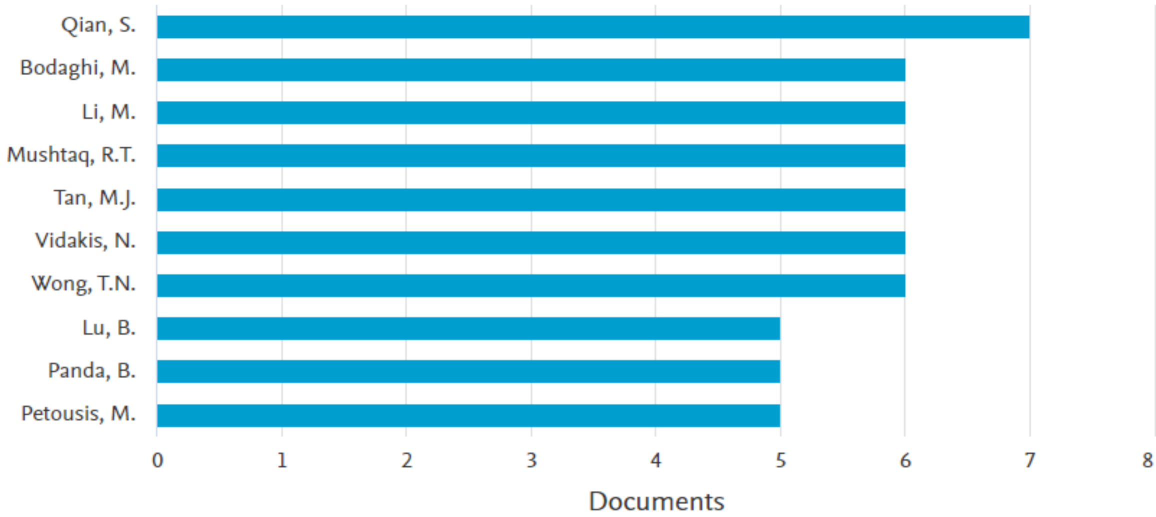


**Fig. 6: Top 10 Authors Ranked by Number of Publications.**

**Table 2: Top 10 Most Prolific Authors in Industrial Wastes for 3D Printable Concrete Research.**

| No | author | TP | h-index | Current affiliation | Country |
|---|---|---|---|---|---|
| 1 | Qian, Shunzhi | 99 | 33 | School of Civil and Environmental Engineering, Singapore City, Singapore | Singapore |
| 2 | Bodaghi, M. | 240 | 39 | Nottingham Trent University, Nottingham, United Kingdom | United Kingdom |
| 3 | Li, Mingyang | 67 | 19 | Northwestern Polytechnical University, Xi'an, China | China |
| 4 | Mushtaq, Ray Tahir | 30 | 8 | Northwestern Polytechnical University, Xi'an, China | China |
| 5 | Tan, Mingjen | 274 | 55 | Singapore Centre for 3D Printing, Singapore City, Singapore | Singapore |
| 6 | Vidakis, Nectarios | 153 | 33 | Info Hellenic Mediterranean University, Heraklion, Greece | Greece |
| 7 | Wong, T. N. | 239 | 42 | School of Mechanical and Aerospace Engineering, Singapore City, Singapore | Singapore |
| 8 | Lu, Bing | 18 | 9 | School of Civil and Environmental Engineering, Singapore City, Singapore | Singapore |

| | | | | | |
|---|---|---|---|---|---|
| 9 | Panda, Biranchi Narayan | 104 | 33 | Indian Institute of Technology Guwahati, Guwahati, India | India |
| 10 | Petousis, A. Markos | 131 | 28 | Hellenic Mediterranean University, Heraklion, Greece | Greece |

TP Total Publications.

The total number of keywords used in the articles was 1695. The most used keyword was “3D Printing,” which was used 441 times as shown in **Fig.7**, followed by “Sustainable Development” with 360 occurrences and “3D Printers” with 322 occurrences. The United States represented the most productive country with a total number of publications of 125, as shown in **Fig.8**; it had the strongest connections with other countries, as shown in **Fig. 9**. India came second with 87 publications, and the United Kingdom placed third with 79 publications, as listed in the **Table. 3**.

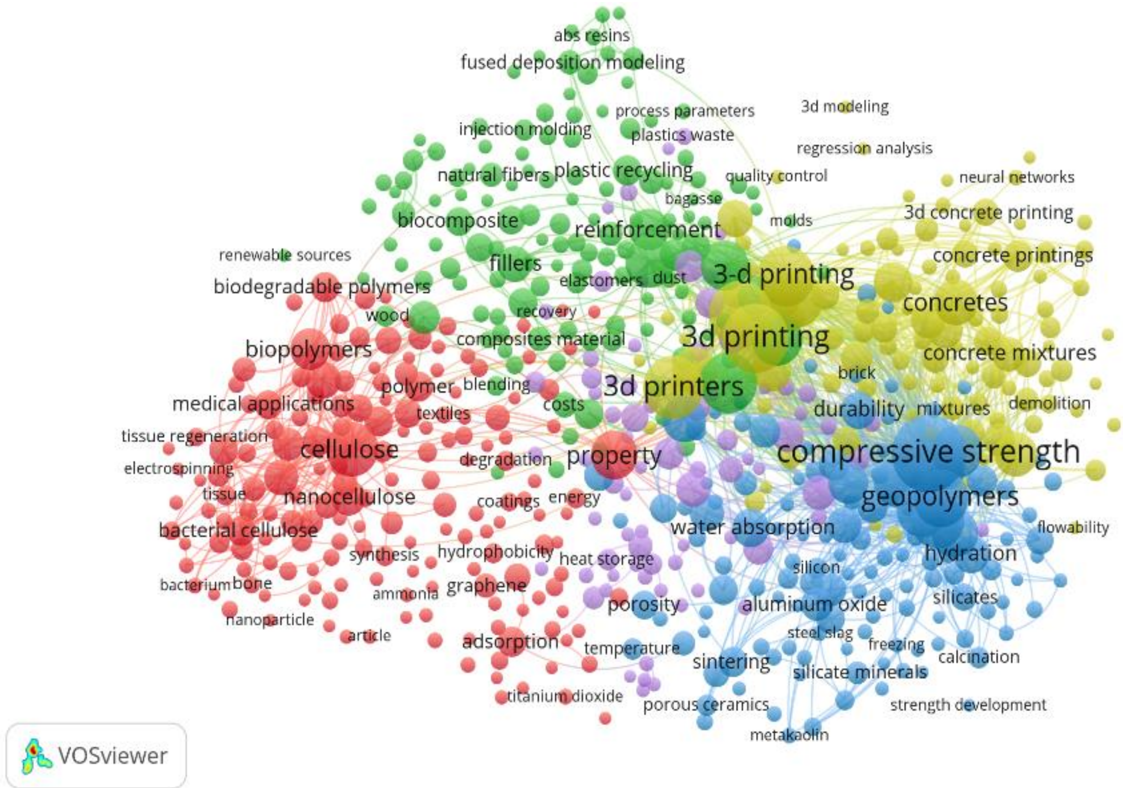


**Fig. 7: Publications by Author Keywords (2013–2023).**

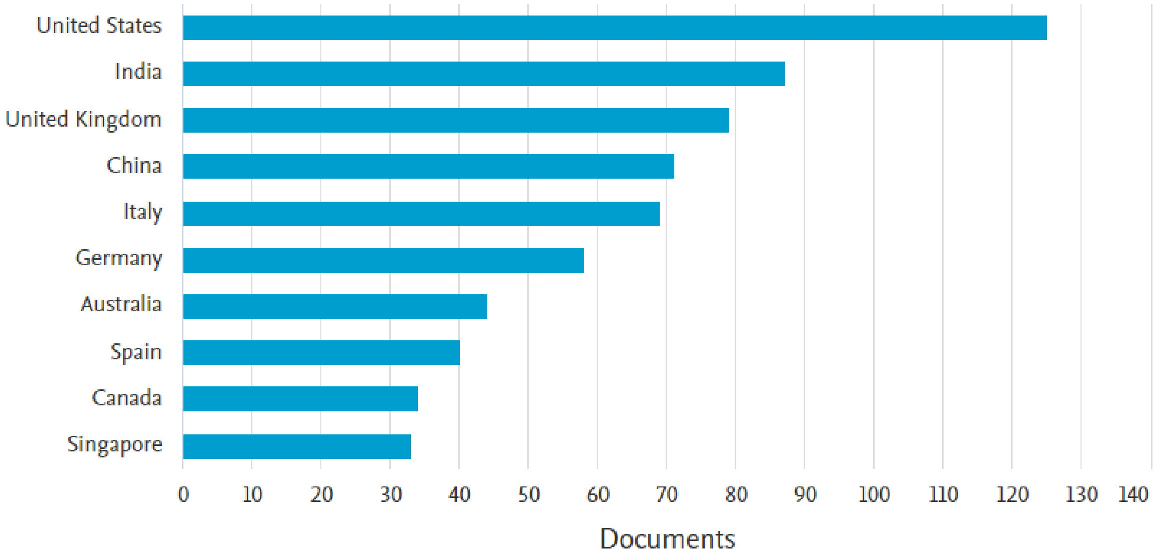


**Fig. 8: Most Productive Countries in 3D Printable Concrete Research (2013–2023).**

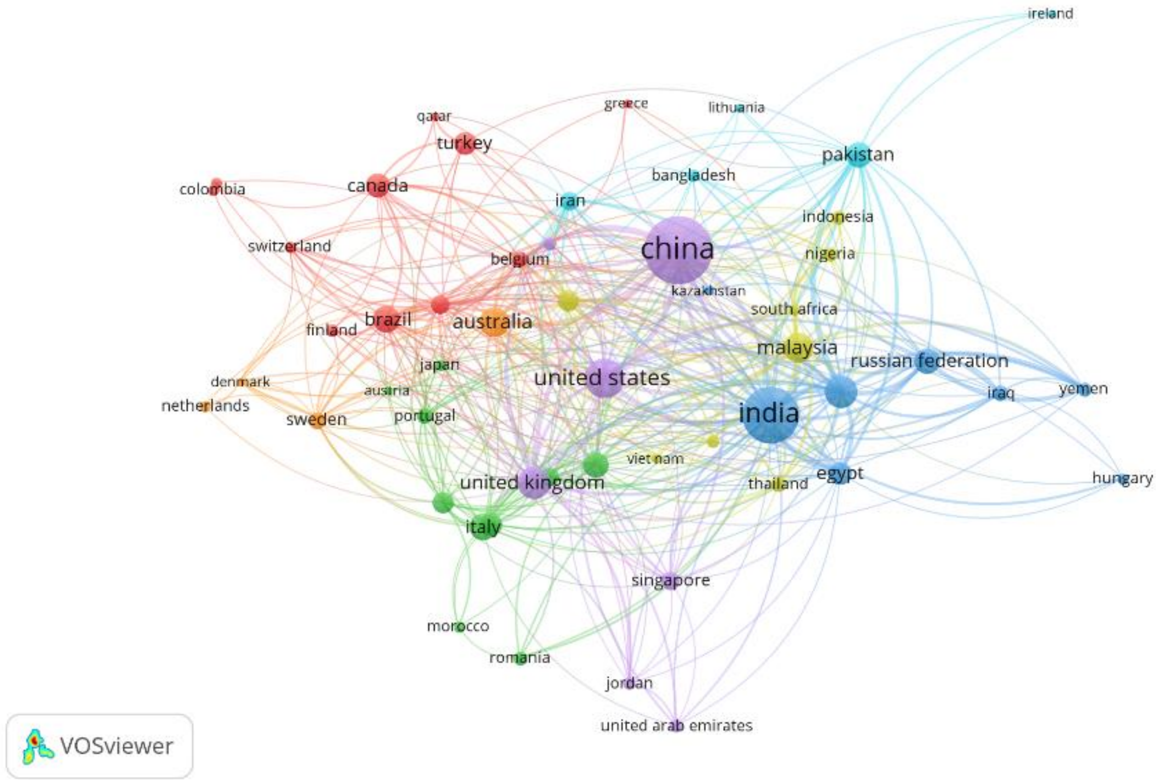


**Fig. 9: Co-Authorship Network of Countries (2013–2023).**

**Table 3: Most Productive Countries in 3D Printable Concrete Research (2013–2023).**

| COUNTRY | No of articles |
|---|---|
| United States | 125 |
| India | 87 |
| United Kingdom | 79 |
| China | 71 |
| Italy | 69 |
| Germany | 58 |
| Australia | 44 |
| Spain | 40 |
| Canada | 34 |
| Singapore | 33 |

The most productive affiliation was "Nanyang Technological University" with 18 articles, followed by "School of Mechanical and Aerospace Engineering" with 14 articles and "ETH Zürich" with 12 articles, as shown in **Fig. 10**.

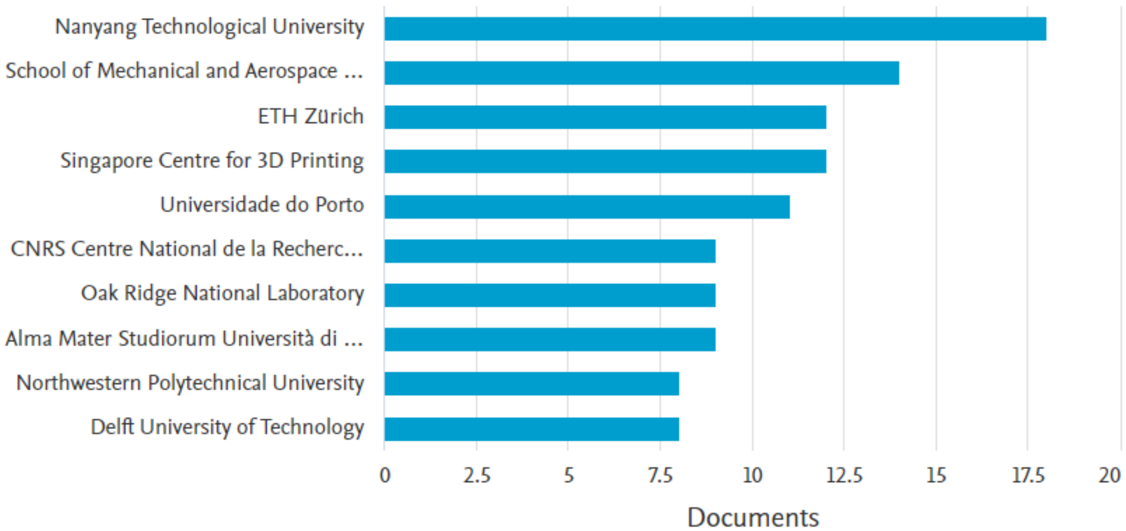


**Fig. 10: Top 10 Affiliations by Number of Publications (2013–2023).**

## 4. Discussion

The results of this bibliometric review demonstrate that the integration of industrial wastes into 3D printable concrete (3DPC) for artificial reef (AR) applications has become an increasingly important research theme, driven by the dual priorities of marine ecosystem restoration and sustainable construction practices. The steady increase in publications, with an average annual growth rate of 32.7% and a peak of 590 papers in 2023, reflects the rapid adoption of additive manufacturing technologies and the parallel shift toward low-carbon, resource-efficient cementitious systems.

### 4.1. Research Trends and Thematic Evolution

The dominance of keywords such as "3D printing", "sustainable development", and "printable concrete" highlights the transition of the field from early proof-of-concept studies to applied research focusing on eco-efficiency. This thematic evolution mirrors the global movement toward circular economy practices in construction, where industrial by-products such as blast furnace slag, fly ash, and recycled aggregates are increasingly valorized as alternatives to traditional cement and natural aggregates. The growing emphasis on sustainability suggests a recognition of ARs not only as ecological tools for reef restoration but also as demonstrators of sustainable construction practices.

### 4.2. Global Research Landscape

The geographical distribution of publications, led by the United States (125 papers), India (87), and the United Kingdom (79), reflects the globalized interest in combining digital fabrication and sustainable materials. The prominence of Singapore, despite its smaller research volume, is notable, as leading authors such as Qian, S., and Tan, M.J., are associated with the Singapore Centre for 3D Printing. This indicates that smaller but highly specialized hubs are shaping the direction of 3DPC for ARs, leveraging regional expertise in advanced manufacturing. In contrast, traditional construction research centers in China, Italy, and Germany are also emerging contributors, reflecting the interdisciplinary nature of the field.

### 4.3. Role of Industrial Wastes in 3DPC for ARs

The frequent use of industrial by-products in the reviewed literature illustrates their dual functionality: (1) reducing clinker content to mitigate carbon emissions, and (2) improving rheological and mechanical properties critical for printability. For example, blast furnace slag and fly ash are frequently employed as supplementary cementitious materials (SCMs), improving workability and long-term durability, while recycled aggregates contribute to resource circularity. However, limited studies address the marine-specific performance of these mixes, such as chloride resistance, biocompatibility, or surface bioactivity. This represents a critical research gap, as materials optimized for terrestrial applications may not perform equivalently in marine conditions.

### 4.4. Artificial Reefs and Ecological Implications

While bibliometric findings confirm strong growth in 3DPC-related research, only a subset of studies explicitly connect material development with ecological performance of ARs. Current literature often reports laboratory-scale results focusing on printability and compressive strength, yet few studies systematically evaluate how material composition, surface texture, and geometry influence colonization rates, biodiversity outcomes, or reef resilience. This disconnect indicates that material science research has advanced more rapidly than ecological performance assessments. The lack of standardized protocols for post-deployment monitoring further compounds this gap, leaving uncertainty about the long-term ecological efficacy of 3DPC reefs.

### 4.5. Journal and Citation Insights

The leading role of journals such as Sustainability (Switzerland) and Journal of Cleaner Production highlights the interdisciplinary positioning of the field at the interface of environmental science and construction engineering. The relatively high CiteScore values of specialized outlets like Additive Manufacturing (17.0) and Cement and Concrete Composites (15.5) further reflect the technical sophistication of the research. However, the dispersion of publications across 196 sources also suggests that the field remains fragmented, without a dedicated journal that consolidates research on 3DPC for AR applications.

### 4.6. Research Gaps and Challenges

Three key challenges emerge from this analysis:

- Standardization: The absence of unified guidelines for design geometry, material mix, and surface characteristics of 3DPC reefs limits comparability across studies.
- Ecological validation: Limited field-scale deployment and monitoring reduce the ability to draw robust conclusions about biodiversity outcomes.

- Interdisciplinary integration: The separation between construction-focused studies (materials, rheology, printability) and marine-focused studies (habitat suitability, colonization) creates a research divide that hinders holistic solutions.

### 4.7. Implications for Future Research and Practice

The findings underscore the importance of interdisciplinary collaboration between material scientists, structural engineers, and marine biologists to bridge the gap between laboratory innovation and ecological impact. Future studies should integrate life cycle assessment (LCA) to quantify environmental benefits and employ digital monitoring technologies (e.g., IoT sensors, AI-based species recognition) for post-deployment evaluation. Such approaches would strengthen the scientific basis for deploying 3DPC ARs and ensure that sustainability claims are validated in real-world marine ecosystems.

### 4.8. Comparison with Prior Reviews in Adjacent Fields

The bibliometric trends observed in this study resonate with findings from prior reviews in adjacent domains such as sustainable construction and marine ecology. For instance, reviews on sustainable construction materials have consistently emphasized the rising role of industrial by-products like fly ash, blast furnace slag, and silica fume in reducing the carbon footprint of cementitious composites[41], [42]. Similarly, bibliometric analyses in sustainable construction have shown a steep increase in publications during the past decade, driven by global policy directives and industry demand for greener materials[43], [44]. In comparison, the research trajectory for 3D printable concrete in artificial reef applications appears more recent but follows a similar exponential growth pattern, indicating the transfer of sustainability-driven material innovations into the marine engineering context. Parallel to this, reviews in marine ecology have highlighted artificial reefs as effective tools for habitat creation and biodiversity restoration[45], [46]. By integrating these perspectives, the present study demonstrates how knowledge from construction science and ecological engineering is converging to advance environmentally responsible marine restoration strategies.

### 4.9. Integration of Material Science Outcomes with Ecological Performance

A key finding of this review is the extensive use of industrial wastes such as fly ash, slag, and recycled aggregates in 3DPC formulations, with demonstrated improvements in mechanical strength, durability, and printability. While these properties are critical from a structural perspective, their ecological implications are equally significant. Enhanced durability and resistance to degradation contribute to the long-term stability of artificial reefs, reducing maintenance needs and ensuring consistent habitat provision for marine organisms. Additionally, the surface roughness and porosity influenced by material composition directly affect larval settlement, species colonization, and biodiversity enhancement[47]. Prior ecological studies have underscored the importance of microstructural characteristics in determining reef performance[48–50]. By bridging material science outcomes with ecological performance metrics, this review highlights the dual function of industrial waste–based 3DPC: advancing sustainable waste management while simultaneously improving the ecological effectiveness of artificial reefs.

## 5. Conclusion

This study has demonstrated the growing importance of industrial waste utilization in 3D printable concrete (3DPC) for artificial reef (AR) applications, where both ecological restoration and sustainable construction intersect. The bibliometric analysis of 773 relevant publications (2013–2023) revealed an annual growth rate of 32.7%, with the United States, India, and the United Kingdom identified as the most productive contributors. “Sustainability (Switzerland)” and “Journal of Cleaner Production” were the most influential journals, while the keywords “3D printing,” “sustainable development,” and “printable concrete” highlighted the field’s research priorities. Results confirm increasing attention to industrial by-products such as blast furnace slag, fly ash, and recycled aggregates for enhancing printability and durability in 3DPC. Despite significant advances, research gaps remain in establishing standardized design protocols, site-specific ecological performance assessments, and systematic post-deployment monitoring of ARs. Overall, this study provides a consolidated overview of the field, offering guidance for both scientific inquiry and practical implementation of eco-efficient AR construction.

### 5.1. Study Contribution

1. Provides the first integrated bibliometric and qualitative review on industrial waste utilization in 3DPC for AR applications.
2. Maps global research trends (2013–2023), including prolific authors, institutions, countries, and leading journals.
3. Highlights the most frequently investigated industrial wastes (e.g., blast furnace slag, fly ash, recycled aggregates) and their role in printability and durability.
4. Identifies research gaps in standardized design, ecological monitoring, and performance evaluation of 3DPC-based ARs.
5. Serves as a reference framework for future researchers and practitioners seeking to integrate sustainable materials into additive manufacturing for marine habitat restoration.

### 5.2. Limitations of the Study

1. The analysis is based solely on the Scopus database; inclusion of other databases (e.g., Web of Science, Google Scholar) may provide a broader perspective.
2. Bibliometric tools capture quantitative patterns (publications, citations, keywords) but do not fully assess the qualitative ecological performance of 3DPC in AR applications.
3. The study period (2013–2023) may exclude very recent publications not yet indexed.
4. Variations in terminology and keyword usage may have led to the exclusion of some relevant articles.
5. Practical insights from field deployment and long-term monitoring are limited in the literature, restricting the ability to link material innovations with real-world ecological outcomes.

## 6. Future Research Directions

Building on the findings of this review, several avenues for future research are recommended:

1. Standardized design protocols: Develop unified guidelines for the geometry, porosity, and surface texture of 3DPC-based artificial reefs to ensure consistency in ecological outcomes.
2. Material innovation: Expand the use of industrial by-products such as fly ash, slag, recycled aggregates, and alternative binders while investigating their effects on rheology, printability, and long-term durability in marine environments.
3. Eco-performance assessment: Implement systematic post-deployment monitoring to evaluate colonization, biodiversity enhancement, and long-term ecological impacts of 3DPC reefs.
4. Life cycle assessment (LCA): Conduct full environmental and economic assessments to compare 3DPC-based ARs with traditional reef restoration methods.
5. Integration with marine engineering: Explore hybrid systems that combine 3DPC ARs with renewable energy devices, coastal protection structures, or carbon sequestration functions.
6. Cross-disciplinary collaboration: Strengthen partnerships between materials scientists, marine biologists, and civil engineers to bridge the gap between laboratory-scale material development and large-scale ecological restoration.
7. Advanced monitoring technologies: Employ AI-driven image recognition, remote sensing, and IoT-enabled underwater sensors for real-time assessment of reef colonization and performance.

These directions underscore the need for multidisciplinary approaches that integrate material science, environmental engineering, and marine ecology to advance the sustainable application of 3D printing in artificial reef construction.

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