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A Literature Review on Sustainability and 3D Printing within the Context of Smart Cities

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Abstract

In recent years, three-dimensional (3D) printing technology has emerged as a significant innovation in the construction industry, aligning with sustainability goals. As one of the key components of Industry 4.0, this technology offers advantages such as design flexibility, material efficiency, and reduced environmental impact. 3D printing (3DP) technology stands out as an innovative production method that supports sustainability goals within the context of smart cities. In order to evaluate the role of 3DP in sustainable construction practices, this study examines 100 publications in the Web of Science database through bibliometric analysis. 29% of the analyzed publications were published in 2024, which stands out as the year with the highest production in the literature. The majority of the publications are concentrated in the fields of engineering and building technologies. In addition, 72% of the 40 articles analyzed are research articles, and 75% are laboratory-based studies. The types of materials used in the studies show a significant diversity. In addition to traditional concrete, innovative and environmentally friendly alternatives such as recycled aggregates, fly ash, geopolymers, biobased fibres, salt-sand mixtures, high-density polymers and self-healing materials are used. This diversity demonstrates the potential that 3DP offers in terms of reducing environmental impacts, limiting waste generation and utilizing local resources. The study identifies trends in the literature and future research areas to strengthen the use of this technology in sustainable construction.

1. Introduction

The concept of sustainability was first defined by the World Commission on Environment and Development in 1987 as “development that meets the needs of the present generation without compromising the needs of future generations” (Vijayenthiran, Perera, & Kavirathna, 2025). This concept is based on three main dimensions: environmental, economic and social (Alami et al., 2023). According to the United Nations Sustainable Development Goals, smart cities aim to enhance the quality of life while ensuring sustainability, inclusivity, and resilience through the use of digital technologies and data-driven solutions (Arasteh et al., 2016). Sustainable development plays a crucial role, particularly in sectors with significant environmental impacts. In this context, reducing energy consumption, optimizing resource management, and minimizing environmental impacts are among the key objectives (Gracias, Parnell, Specking, Pohl, & Buchanan, 2023). The construction sector is responsible for around 33% of global greenhouse gas emissions and 40% of total energy consumption (Sizirici, Fseha, Cho, Yildiz, & Byon, 2021). It also generates 60% of global waste and consumes 32% of natural resources (Benachio, Freitas, & Tavares, 2020). These data underline the need for sustainable solutions in smart cities.

In recent years, 3-dimensional printing (3DP) technology has become an important tool supporting the vision of sustainability in smart cities (Kantaros, Petrescu, Brachos, Ganetsos, & Petrescu, 2024). As one of the key technologies of Industry 4.0, 3DP offers significant advantages in terms of customization, material efficiency and quality assurance in construction processes (El-Sayegh, Romdhane, & Manjikian, 2020; Gebel et al., 2024). In the literature, it is noted that 3D concrete printing (3DCP) systems are considered a promising method to advance sustainability, thanks to their fast production processes and structural durability (Alami et al., 2023; İlerisoy et al., 2025; Takva et al., 2024).

However, 3DP technology also has some challenges in terms of social and environmental sustainability. For example, automation-based production processes can lead to a reduction in labour employment and pose new risks in terms of occupational safety (Max Adaloudis & Jaime Bonnin Roca, 2021). Moreover, the amount of energy consumed during production is a crucial factor influencing environmental sustainability (Wu, Luo, Long, Zhang, & Geng, 2024).

On the other hand, the potential of 3DP technology in waste management and the use of environmentally friendly materials cannot be ignored. Construction waste is generated in significant quantities during both construction and demolition processes. 3DP technology reduces waste generation during the construction phase (Top & Ayçam, 2023). It makes it possible to use industrial waste (plastics, bricks, etc.) and recycled raw materials such as biomass in the production of concrete, insulation material or asphalt (Max Adaloudis & Jaime Bonnin Roca, 2021; Chen, Matar, Beatty, & Srubar III, 2021; Maafa et al., 2023; Murts, Ram, & Gebru, 2021; Pasupathy, Ramakrishnan, & Sanjayan, 2023; Tu et al., 2023). This approach not only reduces greenhouse gas emissions from waste disposal but also mitigates the environmental impact of producing new materials (Top, Cudzik, & İlerisoy, 2024). Furthermore, self-repairing materials that extend the building lifespan limit waste generation by reducing the need for refurbishment (Kanellopoulos, Giannaros, & Al-Tabbaa, 2016).

All these developments reveal that 3DP technology is a powerful tool for sustainability-oriented transformation within the context of smart cities. However, for this technology to be widely adopted, multifaceted elements such as environmental impacts, energy efficiency, material sustainability, and social dimensions need to be analyzed in greater depth. This study examines the role of 3DP technology in sustainable construction practices through bibliometric analysis methods, aiming to systematically reveal current trends, challenges, and future research potential in the field.

2. Material and Methods

This study aims to systematically analyze the literature on the sustainability of 3DP in the construction sector. Web of Science (WoS) was chosen as the database because its data are used to obtain an accurate and reliable bibliometric network. VOSviewer and Bibliometrix were chosen as software tools for acquiring and visualizing bibliometric datasets. The research criteria were restricted to keywords, language, and research area. To investigate the state of the art of sustainability of 3DP in the construction sector, the most frequently used keywords were used to describe the subject.

The results were retrieved from the given keywords ("Sustain*" OR "Eco") AND ("Architecture" OR "Building" OR "Construction" OR "Hous*") in the title, AND ("three dimensional print*" OR "3D Print*" OR "3DP" OR "Additive Manufactur*" OR ""Rapid Prototyping") in the title, abstract, and keywords. The language was selected as English. The selected document types, “Article” and “Review” were analyzed. Within the scope of this bibliometric analysis, 100 articles were found in the WoS database.

This scientific study identifies the most cited countries, the number of publications by year, total publications by country, research items, the number of publications, and the content of sustainability of 3DP within the context of smart cities (Figure 1). These analyses enable us to observe the expansion and prospects offered by the sustainability of 3DP in the construction sector. A comprehensive review of the selected publication analysis was conducted to summarize 3DP's previous research, focusing mainly.

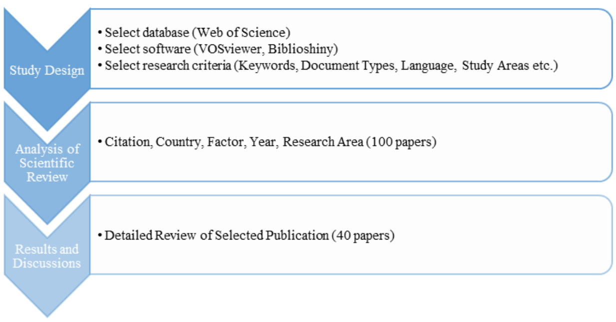

Figure 1. Methodology of the scientific review.

2.1 Annual Publication Analysis

A total of 100 publications were framed within the search criteria for the bibliometric analysis. The distribution of studies by years is an important parameter in evaluating a subject. Figure 2 shows the number of publications in the period between 2015 and 2025. Research on this subject increased slowly from 2015 to 2020. Between 2021 and 2025, the most substantial change in the slope of cumulative publications was observed. 29% of the publications took place in 2024, and this year was the period when academic production in the field reached its highest level. Interest in the sustainability of 3DP in the construction sector is increasing daily, as the concept of digitalization has gained importance in the construction sector, as it has in other sectors.

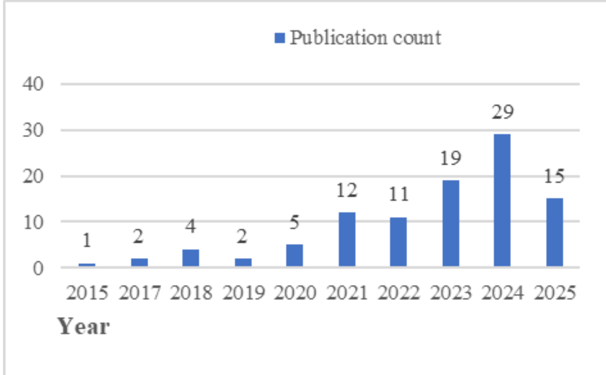

Figure 2. The number of publications by year.

2.2 Research Area Analysis

This study covers a total of 100 articles in the WoS database. All of these publications, 69 were research articles and 31 were review articles. According to the data presented in Figure 3, the distribution of the literature is focused under five main research areas. These areas are: *Engineering* (60%), *Construction Building Technology* (35%), *Science and Technology Other Topics* (27%), *Environmental Sciences Ecology* (25%) and *Materials Science* (22%). This distribution reveals that the themes of 3DP and sustainable construction have an interdisciplinary structure and are particularly concentrated in the fields of engineering and building technologies.

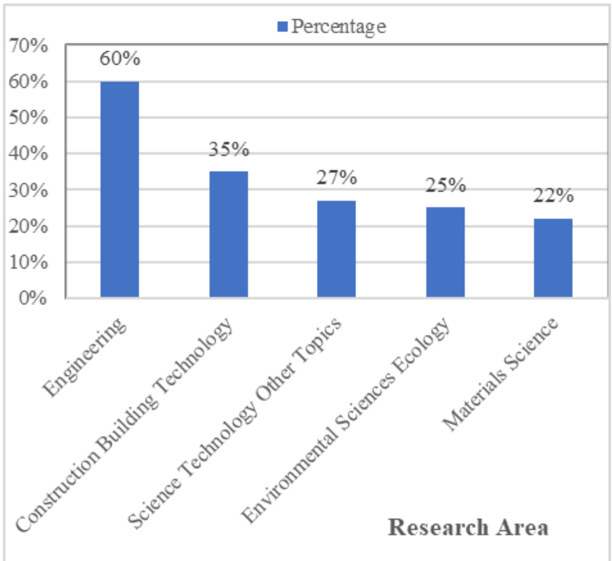

Figure 3. Publications’ research area.

2.3 Location Analysis

It is important to analyze the publications by country to understand the subject's importance in various countries. Scientific research is built on previous studies on the subject, and each study is a part of the literature on that subject. For this reason, giving and receiving citations is a critical issue in terms of ensuring the visibility of the research in the scientific environment and being a pioneer for future studies. Table 1 indicates the top 20 productive countries and the top 20 most cited countries in the field. While China leads the world in total articles (37), Singapore has generated the most citations (837).

Publication					
Rank	*Country*	*Publication*	*Rank*	*Country*	*Publication*
1	China	37	11	Poland	9
2	Australia	28	12	Italy	8
3	India	22	13	Saudi Arabia	8
4	USA	17	14	Egypt	6
5	UK	16	15	Pakistan	6
6	South Africa	14	16	Portugal	6
7	Brazil	10	17	Singapore	6
8	Malaysia	10	18	South Korea	6
9	Qatar	10	19	Denmark	5
10	Germany	9	20	France	5
Citation					
Rank	*Country*	*Citation*	*Rank*	*Country*	*Citation*
1	Singapore	837	11	USA	63
2	China	423	12	Netherlands	62
3	United Kingdom	369	13	Egypt	57
4	Australia	343	14	Saudi Arabia	54
5	U Arab Emirates	240	15	South Africa	54
6	Qatar	210	16	Ireland	40
7	Brazil	196	17	Italy	40
8	Sweden	140	18	Poland	40
9	India	77	19	Austria	31
10	Germany	67	20	Denmark	27

Table 1. Total publication and total citation by country and the most relevant countries.

2.4 Factor analysis

The multiple correspondence analysis methods were adapted for the analysis. Dendrogram diagrams are frequently shown in a variety of contexts. This diagram, for instance, displays the division of relationships between pieces in groups as a result of software analysis in a grouping hierarchy. The height of the coordination line between topics and clusters is also taken into account in this classification. Figure 4 presents a dendrogram tree diagram illustrating the relationship between the most frequently used topics in the literature and other topics. It shows the review topics that connect with the research on 3DP.
This diagram depicts two types of subject classifications: red topics and blue topics. Each of them is then broken into many clusters, each cluster into several sub-clusters, and so on until the topic is used, where several topics are part of one cluster, showing a relationship between the two in current research publications on the issue of 3DP. The red cluster shows the topics related to the 3DP technology, and the blue cluster shows the topics related to material properties (Figure 4).

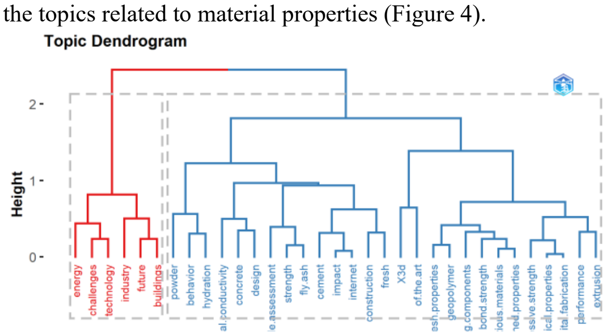

Figure 1. Dendrogram tree diagram of titles (Visualization: Biblioshiny)

2.5 Content Analysis of the Selected Publications

A content analysis of the research related to the construction sector is carried out to determine the prominent themes. Table 2 shows the content analysis of 40 documents on the sustainability of 3DP in the construction sector. The analysis of these articles revealed that 28% were literature reviews, while a significant 72% consisted of original research articles. In terms of methodologies employed, 10% of the articles utilized surveys, 15% were focused on simulations, and the predominant approach was laboratory experiments, which accounted for 75% of the total articles assessed (Table 2). This distribution highlights the diverse methodologies present in current research within this field. Potential building materials that can be printed in 3D printers, mechanical and rheological properties of 3D printable materials, 3DP technology in general construction, and the properties of 3D printers constitute the general framework of the articles.
Concrete and its derivatives, which are frequently encountered in studies, are still the most widely used group of materials, and their sustainable qualities are being increased with various additives. For example, the use of recycled aggregates and recycled concrete supports material circularity and reduces waste. Similarly, the carbon footprint of binders has been reduced by substituting fly ash and ground glass waste for cement.
Geopolymer-based materials stand out as cement-free alternatives; in some studies, structural strength is increased with fibre-reinforced geopolymers. Such materials are environmentally advantageous as they can be produced at low temperatures and can be obtained from industrial wastes. The use of local and natural raw materials such as clay, terracotta bricks, sand and biomaterials offers sustainable solutions that are low-cost and suitable for on-site production.
Innovative examples include materials with different physical properties such as SaltBlock, reactive magnesium oxide cement (RMC), high-density polyethene (HDPE) and fibre-reinforced PLA composites. In addition, energy-efficient materials such as phase change materials (PCMs) and smart bricks offer solutions to improve building performance.
In particular, biomaterials (e.g. palm fiber, wood particles, and local bio-mediated geomaterials) and innovative composites allow structures to be produced in an environmentally compatible way while reducing environmental impact. This diversity demonstrates the flexibility and potential that 3DP technology offers in sustainable building production.

Rank	Reference	Paper Type		Methodology			Material type
		R	LR	S	Q	LE	
1	Kim, Chang, Jo, Kim, and Lee (2025)		X				
2	Yu et al. (2025)	X				X	Polyurethane dispersion
3	Mohamed, Mishra, and Isam (2025)		X				
4	Yeşilata et al. (2025)	X				X	Phase change materials (PCMs) into 3D-printed polylactic acid (PLA)
5	Oladunni, Lee, Ibrahim, and Olanrewaju (2025)		X				
6	Maralapalle et al. (2025)		X				Geopolymer
7	Kallayil et al. (2025)	X				X	Smart bricks
8	Vijayenthiran et al. (2025)		X				
9	Mansouri, Wolde, and Joda (2025)	X				X	Sand
10	Abedi, Waris, Al-Alawi, Al-Jabri, and Al-Saidy (2025)		X				
11	Josa and De la Fuente (2025)	X					Concrete
12	Yousaf, Khan, and Koç (2024)	X				X	Soil and date palm fiber waste
13	Samrani, Cao, Fimbres-Weihs, Sanjaya, and Abbas (2024)	X				X	Fly ash and ground waste glass as cement
14	X. Liu et al. (2024)	X				X	Foam Concret
15	Zhang et al. (2024)	X				X	Recycled aggregate

16	El Aabbas et al. (2024)	X				X	Terracotta brick
17	Ye, Zhang, and Bi (2024)	X				X	Polylactic acid composites
18	Lacava, Cherrington, Corrado, Bigdellou, and Chen (2024)	X			X		
19	Zhang et al. (2024)	X		X			Recycled aggregate concrete
20	Moghayedi, Mahachi, Lediga, Mosiea, and Phalafala (2024)	X					Local bio-mediated geo-materials 3DCP
21	Małek et al. (2024)	X				X	Cement–Glass Composite Bricks
22	Mohsen et al. (2023)	X				X	Clay
23	A. Singh et al. (2023)	X				X	Fiber-reinforced 3D printed concrete
24	J. L. Liu et al. (2022)		X				
25	Batikha, Jotangia, Baaj, and Mousleh (2022)	X		X			Concrete
26	Kromoser, Reichenbach, Hellmayr, Myna, and Wimmer (2022)	X				X	Wood particles Biowall
27	R. Singh et al. (2021)		X				
28	Khan, Koc, and Al-Ghamdi (2021)		X				
29	Han, Yang, Ding, and Xiao (2021)	X		X			Recycled concrete
30	M. Adaloudis and J. B. Roca (2021)	X			X		Concrete
31	El-Mahdy, Gabr, and Abdelmohsen (2021)	X				X	SaltBlock (bonding salt and sand particles)
32	Souza, Ferreira, de Moraes, Senff, and de Oliveira (2020)		X				
33	Mohammad, Masad, and Al-Ghamdi (2020)	X		X			Concrete
34	Khalil, Wang, and Celik (2020)	X				X	Reactive magnesium oxide cement (RMC), Caustic magnesium oxide
35	Tahmasebinia et al. (2020)	X				X	Concrete; High-density polyethylene
36	Kaszynska, Skibicki, and Hoffmann (2020)	X					Sustainable concrete mix composition, Mineral additives; Limestone powder
37	Bong, Nematollahi, Nazari, Xia, and Sanjayan (2019)	X				X	Geopolymer
38	Ghaffar, Corker, and Fan (2018)		X				
39	Panda, Paul, and Tan (2017)	X				X	Fiber reinforced geopolymer
40	Panda, Paul, Hui, Tay, and Tan (2017)	X				X	Geopolymer

R: Research, **LR:** Literature Review, **S:** Simulation, **Q:** Questionary, **LE:** Laboratory Experiment

Table 2. Content analysis of selected papers.

3. Conclusion

This study evaluated the contribution of 3DP technology to sustainable applications within the context of smart cities through bibliometric analysis and literature review based on specific criteria. The findings from the 100 studies examined reveal that 3DP technology has garnered increasing academic interest in sustainable building production, peaking in the number of publications in 2024. The fact that 75% of the studies are experimental indicates the dominance of application-oriented studies in the field. In the country-based analysis, China leads in the total number of publications (37), while Singapore stands out in effective publication production with the highest number of citations (837). In terms of subject distribution, 60% of the studies focus on engineering and 35% on construction technologies. These data show that 3DP technology is approached in a multidisciplinary manner and offers a comprehensive research area centered on sustainability.

When examined on a material basis, concrete, geopolymers, recycled aggregates, bio-based additives, polymer compounds, salt-sand mixtures, and alternative binders obtained from industrial waste stand out. This diversity highlights the flexible structure of 3DP, which enables the use of sustainable materials and its contribution to environmentally friendly production processes. In particular, geopolymer concretes, waste-based materials such as fly ash, silica fume, recycled glass, and steel slag have significant potential in reducing carbon emissions and implementing circular economy principles.

However, there are some technical and systematic limitations hindering the widespread adoption of the technology. Technical obstacles, including interlayer adhesion issues, porosity, anisotropic behaviour, and inadequate assessment of long-term durability, are compounded by standard deficiencies, limited economic feasibility analyses, and a lack of Life Cycle Assessment (LCA) studies evaluating environmental impacts, thereby narrowing the scope of application. In addition, the socio-economic impacts of 3DP must also be carefully evaluated. Changes in the labour force structure, new skill requirements, and regional differences directly affect the adoption of the technology. In this context, policy support that considers local conditions, economic incentives, and the implementation of education programs are of critical importance.

In conclusion, 3DP technology has transformative potential to support environmental, economic, and social sustainability in the construction sector. However, for this potential to be fully realized, the following research areas must be prioritized:

- Experimental and field testing of the long-term mechanical and environmental performance of different waste and alternative material compositions,
- Developing durability, safety, and quality control standards for large-scale applications,
- Optimizing the formulations and applications of environmentally friendly materials such as geopolymers and bio-based additives,
- Comprehensively analyzing life cycle aspects such as energy consumption and carbon footprint in 3DP processes,
- Improving integration processes with digital production technologies (BIM, IoT, digital twins, artificial intelligence, etc.),
- Examining social impacts, workforce transformation, and technology adaptation processes at the regional and sectoral levels.

In conclusion, 3DP technology has significant potential for transformation in the construction sector in terms of reducing carbon emissions, increasing resource efficiency, providing flexibility in design processes, and minimizing environmental impacts. The effective utilization of this potential depends not only on technological advancements but also on strengthening interdisciplinary collaborations, establishing standard application protocols, and implementing sustainability-focused policy mechanisms.

This study systematically analyses the existing literature to comprehensively elucidate the role and importance of 3DP technology in sustainable construction applications. The findings show that the technology offers significant contributions, particularly in terms of material efficiency, production process optimization, and environmental performance. However, a holistic approach must be developed to overcome the technical, economic, and regulatory barriers encountered at the application level.

In future-oriented research, it is of great importance to develop innovative strategies that support integration between fields such as building physics, materials science, architecture, and engineering. In addition, education, legislation, and incentive systems must be restructured in line with this transformation in order to accelerate sectoral adaptation. Thus, 3DP technology will not only be a tool for sustainable building production but will also position itself as a pioneer in the digitalization of the context of smart cities. In this context, the development of 3DP technology will create a strategic turning point that will shape the future of the construction sector by making sustainable, environmentally conscious, and innovative building production processes more accessible and widespread.

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