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RESEARCH

# A COMPREHENSIVE REVIEW OF LIFE CYCLE ASSESSMENT AND ENERGY EFFICIENCY IN 3D PRINTING FOR CONSTRUCTION: CURRENT STATE, BENEFITS, LIMITATIONS, AND FUTURE OUTLOOK

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## ABSTRACT

The agenda of Industry 4.0 strongly affects design and construction at all its phases, and three-Dimensional Printing (3DP) is an essential part of it. The emerging technology has the potential to become a more valid and accepted form of construction. This research is based on a literature review regarding the relationships between the concepts of Life Cycle Assessment (LCA) and energy efficiency for 3DP in construction research to understand the developments. Systematic bibliometric and scientometric analyses are used as data analysis techniques to make a detailed comparison. The comparison allowed for assessing and determining the current state, benefits, limitations, and future outlook. Current research is based on insights examining materials first (80%), followed by walls (15%), buildings (11%), and 3DP technology (6%). The findings highlight that 3DP technology offers significant advantages in terms of time efficiency, reliability, ecological impact, and sustainability within the construction industry. However, several challenges, such as the complexity of material mixture content design, the lack of standardized 3DP materials and codes, and the limited availability of experts in the field, prevent its widespread adoption. Further advancement of 3DP requires the development of standards, policies, training and materials for its full implementation in the construction industry.

## KEYWORDS

3D printing (3DP); Bibliometric Analysis; Construction; Energy Efficiency; Life Cycle Assessment (LCA)

## 1. INTRODUCTION

Due to recent technological advancements, the construction sector faces challenges related to energy crises and Greenhouse Gas (GHG) emissions that significantly impact global

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environmental concerns (Alkhalidi and Hatuqay, 2020). With the construction industry accounting for 40% of the world's energy usage, 38% of its greenhouse gas emissions, 12% of its drinkable water consumption, and 40% of its solid waste generation in industrialized nations, there is a pressing need to address these issues (Sun et al., 2021). Despite substantially contributing to harmful environmental effects, the building industry holds great potential for reducing emissions and mitigating its impact.

The United Nations General Assembly established the 2030 Agenda for Sustainable Development, a framework consisting of 17 universal and 169 sustainable development goals, to guide global sustainable development efforts until 2030. However, the building sector has not fully achieved its sustainable development objectives, necessitating the continuous adoption of sustainable techniques and practices in construction (Cudzik and Kruk, 2022, Onososen and Musonda, 2022). To address this problem, factors such as national policies, ecological research, and energy and life cycle evaluations are crucial. Life Cycle Assessment (LCA), outlined in ISO 14040:2006 and ISO 14044:2006 standards, provides a methodology for quantifying and evaluating the environmental impact of a product or service (ISO14040, 2006; ISO14044, 2006). Buildings, being energy consumers throughout their life cycle, must be analyzed from a life cycle perspective (Ramesh et al., 2010). As the world increasingly seeks eco-friendly and energy-saving solutions, three-Dimensional Printing (3DP) has emerged as a sustainable construction method with the potential to reduce energy consumption and $CO_2$ emissions compared to traditional building methods (Kamel and Kazemian, 2023). The relationship between formwork and materials in the context of 3DP with cementitious materials in the construction industry has been a subject of significant interest in previous studies. Shakor et al., 2019; Mohan et al., 2021; Puzatova et al., 2022; Shakor et al., 2022 provided comprehensive studies of suitable materials for 3DP in the construction industry, considering the printing process, challenges, and post-processing stages, and emphasizing sustainability, suitability, and the achievement of desirable mechanical properties for various materials such as gypsum, cement and geopolymer mortar, clay, chipped wood, and sand. However, to understand the environmental sustainability of 3DP in the construction industry, further research on energy efficiency and LCA is necessary (Ingrao et al., 2016, Agustí-Juan and Habert, 2017). The interaction between energy and LCA is closely related to sustainability and ecology, highlighting the need for a comprehensive understanding of energy and LCA in the construction industry (Passer et al., 2012; European Parliament and Council, 2010).

In this context, this study aims to provide a comprehensive overview of the current research utilizing 3DP on energy and LCA in the construction industry. The study highlights these subjects' benefits, limitations, and future research perspectives. Furthermore, it will enable early adjustments and optimization of 3DP technology in the experimental and design stages.

## 2. BACKGROUND OF 3DP IN CONSTRUCTION

The reflection of Industry 4.0 on the construction sector is Construction 4.0, which defines the paradigm shift, especially for the Architecture, Engineering, and Construction (AEC) industry (Schönbeck et al., 2021). The term "Industry 4.0," often known as the "fourth industrial revolution," describes how cutting-edge digital technologies are used to convert conventional business procedures and manufacturing techniques into autonomous smart systems (Top et al., 2023; Takva and İlerisoy, 2023; Top et al, 2023). Construction 4.0 has the potential to speed up the construction sector's digital transition, producing vast volumes of data that can be efficiently used to increase operational effectiveness, inform choices, boost innovation and growth, and improve sustainability (Baduge et al., 2022). With digital technologies, simulations can be made on energy efficiency, LCA, fire, evacuation, thermal comfort, acoustics, and changes can be made in the design by taking printouts while still in the design phase (Top and Topraklı, 2019; Top and Topraklı, 2022; Top, 2023; Selmi and İlerisoy, 2023). One of the new technologies provided by Industry 4.0 or Construction 4.0 is the additive manufacturing method, which enables three-Dimensional (3D) output of the digitally designed product. 3DP is a type of automated additive manufacturing that produces 3D solid objects from digital (CAD) models (Bogue, 2013). Generating a 3D solid product from a digital model of any shape, known as Additive Manufacturing (AM), allows for the creation of new complicated geometric pieces that would be impossible or difficult to create using traditional methods (Monteiro et al., 2022). The advancement of this technology has been rapid since the creation of the first 3D printer in 1983 (Sakin and Kiroglu, 2017). This technology has become a part of daily and is now used in many sectors, such as healthcare, nanotechnology, food, aerospace, and automotive (Hager et al., 2016; Gibson et al., 2021). However, the use of this technology in construction is far more recent.

The use of 3DP technology in the Architecture, Engineering, and Construction (AEC) sector is still in its early phases; however, it is developing into an emergent technology that should be highlighted. The application potential of 3DP, on both a small and big scale, is becoming apparent in the building industry. The AEC sector should investigate the background and present the state of 3DP to promote the advancement and implementation of these technologies. The design of components suitable for the capacity of the printer and the raw material performance is essential in how the production will be carried out in building printing with a 3D printer. The use of 3DP in the construction sector has the potential to cut labor costs and allow for the manufacture of complex geometries, which results in cost savings. 3DP's continuous operating capacity reduces building deadlines, providing chances to improve design flexibility and product quality and increasing customization and affordability. Additionally, 3DP can potentially mitigate the environmental impact of construction by using fewer materials and less energy than traditional methods (Park and Ahn, 2018; Top and Ayçam, 2023).

The building sector has the potential to gain economically, environmentally, and in other ways from 3DP, which is an automated layer-by-layer production process (Ozeren et al, 2023). The accuracy of the printing tasks, the accessibility of printing materials, the price of the printing process, and the printing time, based on which pertinent 3DP technologies, are highly reliant on the usage of 3DP in the building and construction industry (Wu et al., 2016, Schuldt et al., 2021). In recent years, industrial and technological developments have allowed architects and engineers to realize construction projects that can be produced with a 3D printer as part of the ongoing digital revolution (De Schutter et al., 2018). The 3DP technology offers potentially different advantages for construction projects where it is applied (Wu et al., 2016). The positive attributes of 3D-printed structures can be assessed through various significant factors. These include evaluating material toxicity and emissions to gauge the environmental implications of the materials used. Minimizing risky tasks through 3DP could enhance productivity, occupational safety, and health by reducing reliance on human labor (Cai, et al., 2019). 3DP offers a unique prospect for significant cost savings across projects, owing to lower labor costs, material outlays, and building time. Regarding labor expenses, this technology can save 50–80% by automating manual operations (Craveiro et al., 2020; Shomberg, 2016).

Furthermore, by allowing the manufacture of sophisticated geometries that traditional technologies struggle with, 3DP reduces material costs by reducing waste formation. The process's efficiency extends to construction schedules since 3D printers may function constantly, saving building time up to 25% compared to traditional methods (Craveiro et al., 2020; Shomberg, 2016). 3DP's design flexibility allows for optimizing manufacturing processes and enhancing overall product quality and performance. The most important criterion for determining the environmental impact of 3DP technology in construction is whether it is sustainable and feasible.

Within the scope of this study, other literature reviews dealing with similar issues were also examined. By focusing on cement-based materials, de Brito and Kurda (2021) made conclusions regarding the past and future of sustainable concrete. Khan et al. (2021) focused on the sustainability assessment, potential, and limitations of 3D-printed concrete structures. Dey et al. (2022) conducted a detailed study on the usage of industrial waste in 3D concrete printing techniques. The research conducted by Samudrala et al. (2023) investigated and analyzed the rheological, physical, and mechanical aspects of 3D concrete printing in further detail. Tinoco et al. (2022) provided a review of the literature on the use of 3DP applications of cement-based materials in the context of environmental sustainability and the building industry. Samudrala et al. (2023) systematically reviewed the literature by screening the existing materials used for 3D concrete printing and using LCA to estimate its environmental effects. However, most investigations have concentrated on cement-based products or concrete. A comprehensive study of 3DP technology regarding energy efficiency and LCA is currently lacking.

## 3. MATERIAL AND METHODS

This study aims to systematically and comprehensively synthesize, identify, and analyze the literature on LCA and energy efficiency in 3DP for the construction industry. To achieve this, the conducted analyses encompass various perspectives, such as keywords, research areas, factor analysis, influential journals, leading authors, and country publications. These analyses enable us to observe the expansion and prospects offered by 3DP technology and research within the construction sector. Compared to traditional literature reviews, systematic review requires an additional dependency and exploratory approach (Higgins et al., 2019). Higgins et al. (2019) outline other advantages of utilizing a scientific research method, such as outlining the main points of existing evidence, identifying gaps, proposing new ideas and hypotheses, or assisting in their development. The goals of scoping reviews include providing a complete coverage of the existing literature. Furthermore, they involve assessing the scope, diversity, and types of research activities, determining the benefits of conducting a comprehensive systematic review, presenting and distributing research findings clearly, and identifying areas in the literature that need more investigation. This study aims to identify key points of research, identify gaps, and propose new ideas and hypotheses to build the scientific literature.

While determining the study design of systematic bibliometric and scientometric analyses, the database of the study is selected as Web of Science; the software program is selected as VOSviewer and Biblioshiny keywords, document types, language and fields of study as the research criteria. From a research perspective, the decision to use VOSviewer and Biblioshiny was motivated by their significance and application in the domain visualization field. VOSviewer, which Van Eck and Waltman developed in 2010, provides a dynamic platform for producing detailed maps based on network data, appealing to academic records and diverse network kinds. It allows for examining relationships via network, overlay, or density visualization. Bibliometrix, introduced by Aria and Cuccurullo (2017), is important within the R software environment, allowing for seamless data import and analysis in three stages and producing adaptable matrices that contribute to network analysis, multiple correspondence analysis, and domain visualization (Arruda et al., 2022). These decisions represent our dedication to thorough domain visualization analysis. ISI Web of Science (WoS), published by Thomson Reuters, is widely regarded as the primary data source for bibliometric analysis in the sciences (Van Leeuwen, 2006). In comparison to other databases like Scopus, its records are more consistent and standardized (Bettencourt and Kaur, 2011), allowing us to extract title texts, author names, and, more importantly, cited references for our systematic bibliometric and scientometric analyses. Additionally, WoS covers a wide range of journals related to LCA and encompasses various types of literature (Chen et al., 2014). This database is the most widely used in systematic bibliometric and scientometric research of LCA (Chen et al., 2014; Hou et al., 2015; Wang et al., 2014).

Since WoS is widely used in bibliometric research, the current study used this database and employs a dual methodology, combining bibliometric and systematic bibliometric analysis allowing us to embrace a wider spectrum of information processes. It identifies the most cited documents/countries/authors, the number of publications by year, total publications by country, research items, topics, journals by the number of publications, and the most frequently used keywords of LCA and energy efficiency research in the construction industry. Then the investigation is undertaken using data from evaluation and assessment perspectives (Figure 1).

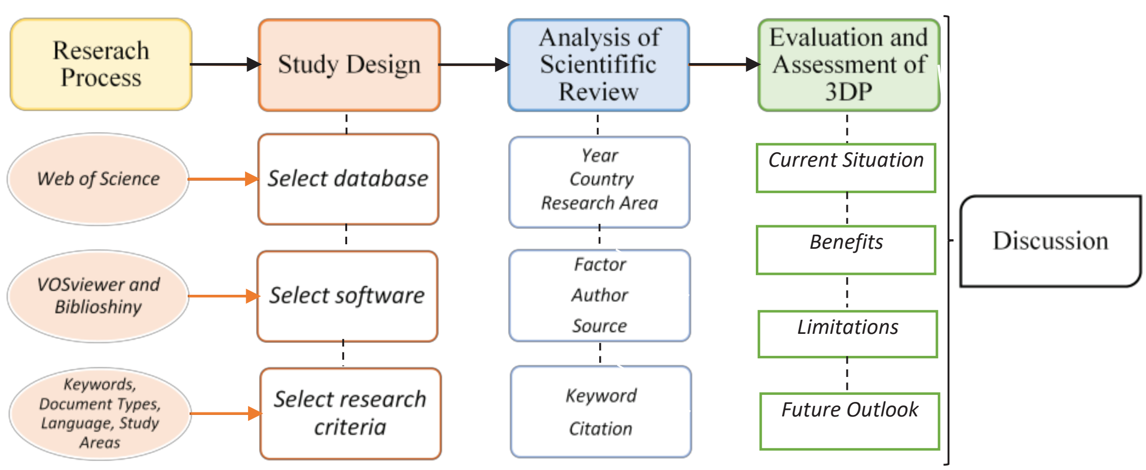
The search for the articles for this research was conducted in three distinct steps, namely:

1. Study design of systematic bibliometric and scientometric analyses,
2. Analysis of scientific review, and
3. Evaluation and assessment of 3DP.

### *3.1 Step 1: Study Design of Systematic Bibliometric and Scientometric Analyses*

Bibliometrics is defined as the application of mathematical and statistical methods in the evaluation of scientific communication environments (Pritchard, 1969). In bibliometric analysis, various findings related to scientific communication are reached by examining some features of publications. Nalimov and Mulchenko (1969) defined scientometrics as "the application of quantitative methods which deal with the analysis of science viewed as an information

**FIGURE 1.** Methodology of the scientific review.



process.” The bibliometric and scientometric analyses are highly preferred in scientific compilation studies as they are pioneers in forming such a discussion environment. Bibliometric analysis has been utilized in various studies, as demonstrated by the articles of Hu (2019), Wuni et al. (2020), Oguntona et al. (2021), Ranjbar et al. (2023), and Su and Hong (2022). In addition, Scientometric analysis is used in some studies such as Oguntona et al. (2021) and Adel et al. (2021). In this study, the literature was analyzed using systematic bibliometric and scientometric analysis together.

This review study design consists of three stages: selection of database, software, and research criteria (Figure 1). WoS was chosen for the database, and VOSviewer and Bibliometrix were selected as software tools for acquiring and visualizing datasets. The research criteria were restricted to keywords, language, and research area. In investigating the state of the art of energy efficiency and LCA analysis of 3DP in the building sector, the most frequently used keywords were used to describe the subject. The results were retrieved from the given keywords (“Energy” OR “Life Cycle Assessment” OR “LCA” OR “Sustain*” OR “Eco”) AND (“Architecture” OR “Building” OR “Construction” OR “Structure” OR “Wall” OR “Geometry” OR “Material”) in the title, AND (“3D Print*” OR “3DP” OR “Additive PRE/0 Manufacture*”) in the title, abstract, and keywords. The entire keywords were searched together. The language was selected as English. The selected document type “Article” OR “Review” was analyzed. The scope of the research has been defined to include areas related to the AEC industry while excluding fields unrelated to the subject, such as medicine and dentistry. Within the scope of this bibliometric analysis, 172 articles were found in the WoS database. They were SCI-Expanded and ESCI-indexed articles.

### 3.2 Step 2: Analysis of Scientific Review

In the analysis of the literature review, the most cited articles/countries/authors, the number of publications by years, the total number of publications by country, the research area, sources, factor analysis, the most used keywords, and content were examined on energy efficiency and LCA in 3DP technology.

### 3.3 Step 3: Evaluation and Assessment of 3DP.

The current state, benefits, limitations, and future outlook were obtained with the data obtained from 3DP’s energy efficiency and LCA analysis in the construction sector. A comprehensive analysis was conducted to summarize 3DP’s previous research, focusing mainly on energy efficiency and LCA in the construction sector. Thus, the general framework of 3DP technology was examined.

## 4. RESULTS

In this study, annual publication, position analysis, research area, conceptual structure, source, author, word, and citation analyses were conducted to interpret the trends and patterns in LCA research in the construction sector.

### 4.1 Annual Publication Analysis

A total of 172 publications were framed within the search criteria for the systematic bibliometric and scientometric analyses. The distribution of studies with respect to years is an essential parameter in evaluating a subject. Figure 2 shows the number of publications between 2014 and

June 2023. Research on this subject increased slowly from 2014 to 2017. In 2018–2022, the most substantial change in the slope of the cumulative publications was observed. The interest shown in energy efficiency and LCA of the construction industry for 3DP is increasing daily as the concept of digitalization is an issue that has gained importance in the construction sector, as it has in other sectors. The number of publications has already surpassed the numbers from the previous year in just the first half of 2023, indicating a promising trend of continuous growth in the years following. The growth shows a global reach and prevalence on a global scale.

### 4.2 Location Analysis

It is essential to analyze the publications by country to understand how important the subject is in these 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 significant issue in ensuring the visibility of the research in the scientific environment and being a pioneer for future studies. Table 1 indicates the field's top 20 productive and the top 20 most cited countries. While China tops the publication list with 80 articles, Australia tops the citation list with 971 citations. The number of publications and citations on energy efficiency and LCA in 3DP by countries displays their level of development and reflects their inclination towards this area. By expressing interest in this subject, countries not on the list highlight the need for worldwide research expansion in this field.

### 4.3 Research Area Analysis

The research area comprises 172 articles in the WoS database, consisting of 143 research and 29 review articles. As shown in Figure 3, this research consists of 10 primary research areas, including *Engineering* (48%), *Materials Science* (41% of papers), *Science Technology Other Topics* (25%), *Environmental Sciences Ecology* (19%), *Construction Building Technology* (13%),

**FIGURE 2.** The number of publications by year (Source: WOS).

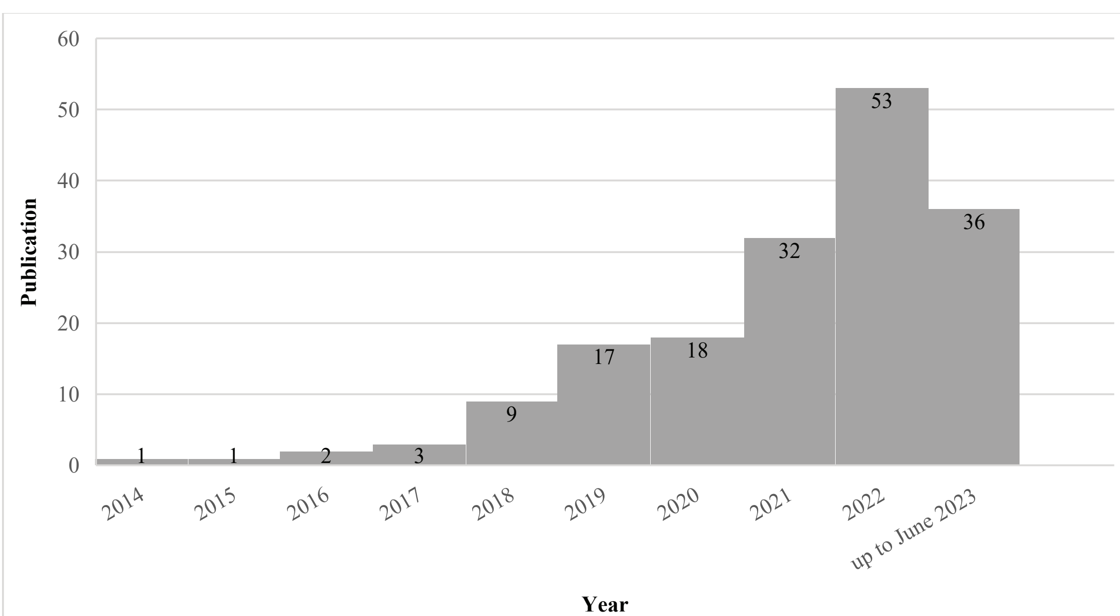


**TABLE1.** Total publication and total citation by country (Source: Biblioshiny).

| Publication | | | | | |
|---|---|---|---|---|---|
| Rank | Country | Publication | Rank | Country | Publication |
| 1 | China | 80 | 11 | Brazil | 9 |
| 2 | USA | 60 | 12 | Germany | 9 |
| 3 | India | 38 | 13 | Singapore | 8 |
| 4 | Australia | 26 | 14 | Egypt | 7 |
| 5 | Italy | 26 | 15 | France | 6 |
| 6 | UK | 26 | 16 | Netherlands | 6 |
| 7 | Canada | 19 | 17 | Poland | 6 |
| 8 | Iran | 17 | 18 | Korea | 6 |
| 9 | Portugal | 17 | 19 | Russia | 5 |
| 10 | Spain | 12 | 20 | Belgium | 4 |
| Citation | | | | | |
| Rank | Country | Citation | Rank | Country | Citation |
| 1 | Australia | 971 | 11 | Brazil | 86 |
| 2 | China | 776 | 12 | Iran | 78 |
| 3 | Germany | 437 | 13 | Korea | 77 |
| 4 | Singapore | 315 | 14 | Russia | 66 |
| 5 | United Kingdom | 304 | 15 | Netherlands | 61 |
| 6 | India | 225 | 16 | Qatar | 61 |
| 7 | USA | 216 | 17 | Portugal | 52 |
| 8 | Canada | 212 | 18 | United Arab Emirates | 51 |
| 9 | Iraq | 118 | 19 | Chile | 36 |
| 10 | Italy | 90 | 20 | Poland | 31 |

*Mechanics* (13%), *Energy Fuels* (9%), and other fields (8%). It is worth noting that engineering and material science issues received the most attention in the analyzed publications. It appears that architectural research should be expanded in the construction industry.

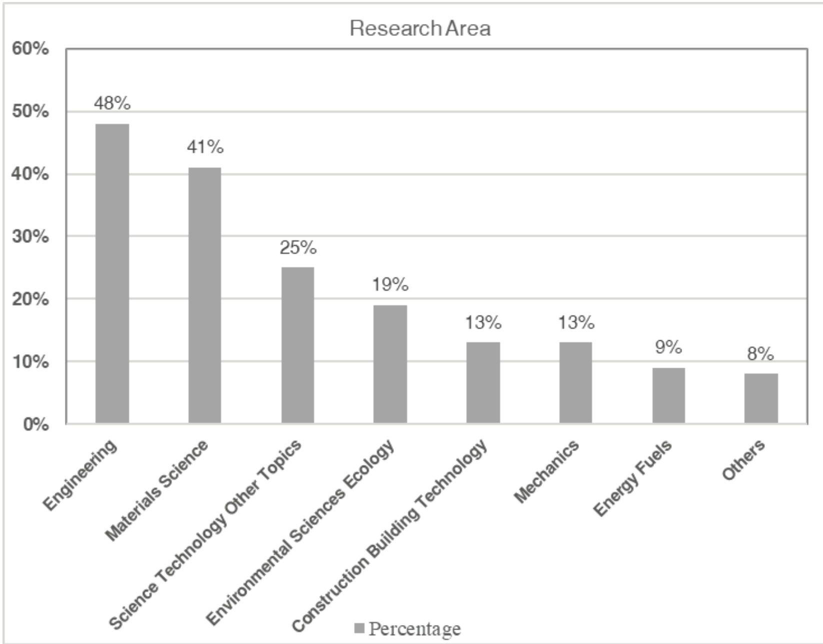
Some papers include one or more research areas, as shown in Figure 3. Since architecture is multidisciplinary, research in other fields can also contribute to architecture. However, when the title of architecture, which should be an essential and pioneering discipline in 3DP technologies, is examined, the absence of this subject shows the necessity of further research in architecture.

### 4.4 Conceptual structure analysis

The multiple correspondence analysis methods were adapted for the analysis. A dendrogram diagram is frequently shown in various contexts and displays the division of relationships between pieces in groups due to software analysis in a grouping hierarchy (Bedi et al., 2019). The height of the coordination line between topics and clusters is also considered in this classification. Figure 4 indicates a dendrogram tree diagram based on the literature titles of the most frequently used topics and their relation to 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, 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 LCA (environmental issues), and the blue cluster shows those related to 3DP (features of

**FIGURE 3.** Research areas (Source: WOS).




materials, building, technology, wall). It is seen that environmental issues and features of materials, buildings, technology, and walls are prominent in the reviewed articles examined.

### 4.5 Author analysis

The relationship between the authors refers to the citations they give to each other in the literature. When the authors of the studies are evaluated, Table 2 shows the top 10 most cited

**FIGURE 4.** Dendrogram tree diagram of titles (Visualization: Biblioshiny).

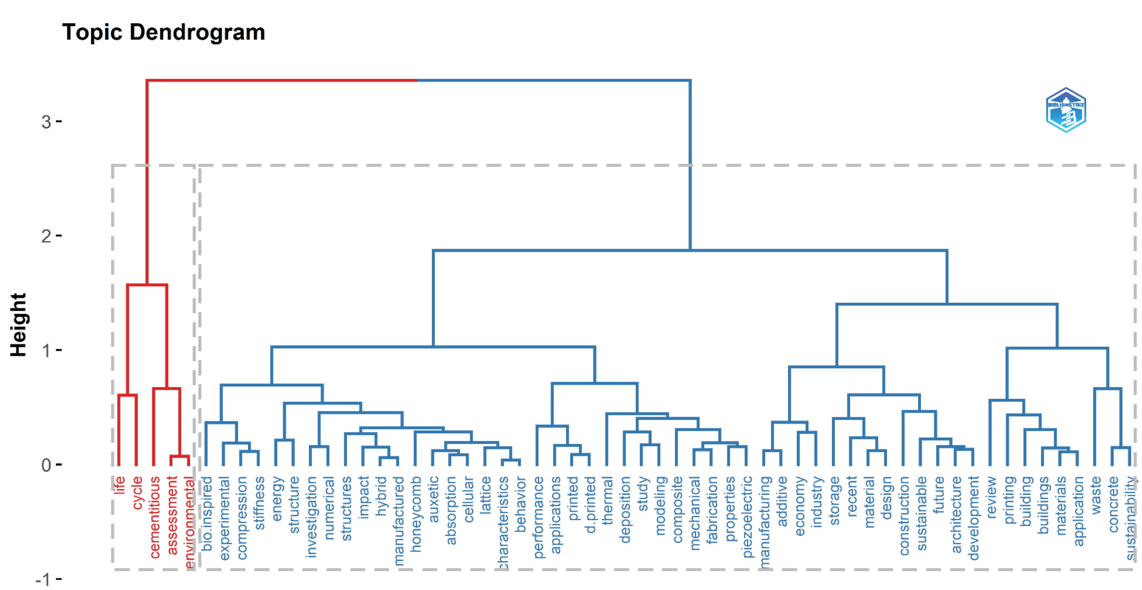


**TABLE 2.** Top 10 authors by the highest number of citations (Source: VOSviewer).

| Rank | Author | Total Document | Total Citation | Total Link Strength | H-index | Rank | Author | Total Document | Total Citation | Total Link Strength | H-index |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Lu Guoxing | 3 | 553 | 4 | 3 | 6 | Ngoc Sun Ha | 1 | 344 | 0 | 1 |
| 2 | Robin Kleer | 1 | 414 | 6 | 1 | 7 | Ming Jen Tan | 2 | 259 | 30 | 2 |
| 3 | Frank Piller | 1 | 414 | 6 | 1 | 8 | Lim Jian Hui | 1 | 234 | 27 | 1 |
| 4 | Christian Weller | 1 | 414 | 6 | 1 | 9 | Suvash Chandra Paul | 1 | 234 | 27 | 1 |
| 5 | Biranchi Panda | 4 | 358 | 30 | 4 | 10 | Yi Wei Daniel Tan | 1 | 234 | 27 | 1 |

authors and their connection strengths with other studies. *Lu Guoxing* is the most cited author (553) with a total link strength of 4 with three publications. Other most cited authors are *Robin Kleer* (414), *Frank Piller* (414), *Christian Weller* (414), and *Biranchi Panda* (358). Since 3DP technology is still a new technology, when we evaluate the authors of the reviewed publications, it is observed that the total number of documents and links is low. For this reason, it is thought that the number of authors working on this subject and the connections between them will increase over time.

### 4.6 Source Analysis

Examining the top 20 publishing platforms with the most publications in the reviewed literature is vital to understand which source is mentioned the most. Figure 5 includes the 20 journals by the number of publications. The highest number of publications (12) belongs to the *"Journal of Cleaner Production"* and *"Sustainability"* journals. It is followed by *"Materials & Design"* (9), *"Journal of Building Engineering"* (8), *"Additive Manufacturing"* (6), and *"Composite Structures."* The majority of the papers were published in high-impact journals.

### 4.7 Keyword analysis

The mapping of the keywords (repeated one or more times) that summarizes the researchers and shows the relationships with each other is given in Figure 6. VOSviewer visualized a co-occurrence keyword analysis of these 633 keywords to determine the relationship, frequency, and total link strength of these co-occurrences. Associating keywords with the main content of the articles shows trends in this research topic. The top three keyword clusters consist of green clusters related to *"3D printing,"* followed by yellow clusters concerning *"energy absorption,"* and red clusters associated with *"sustainability"* which are the most frequently occurring keywords. 3DP, sustainability, energy absorption, and mechanical properties" are the most popular key-words and are predicted to become more obvious trends.

**FIGURE 5.** Top 20 journals by the number of publications (Visualization: Biblioshiny).

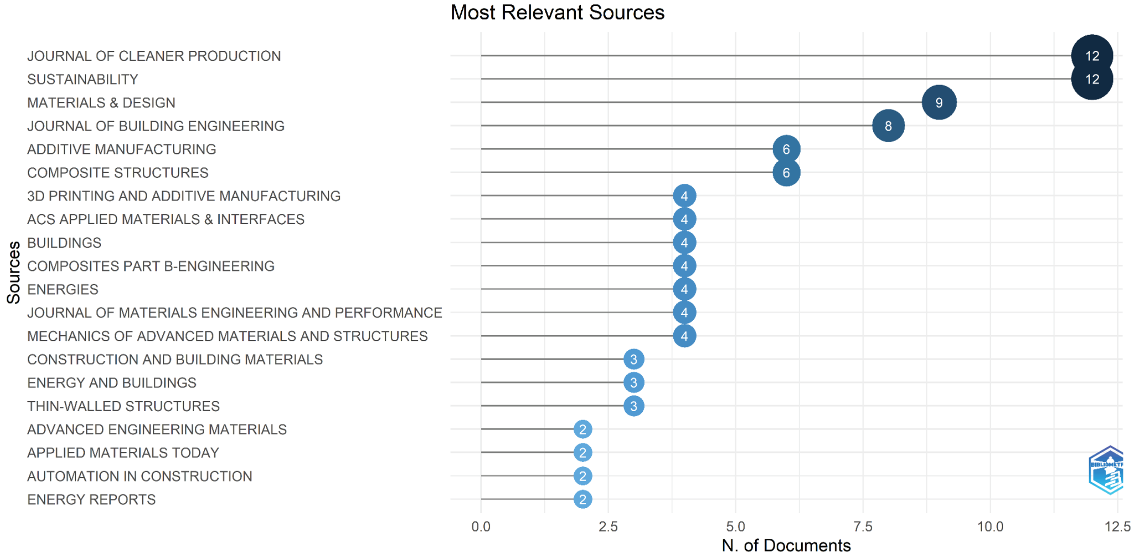
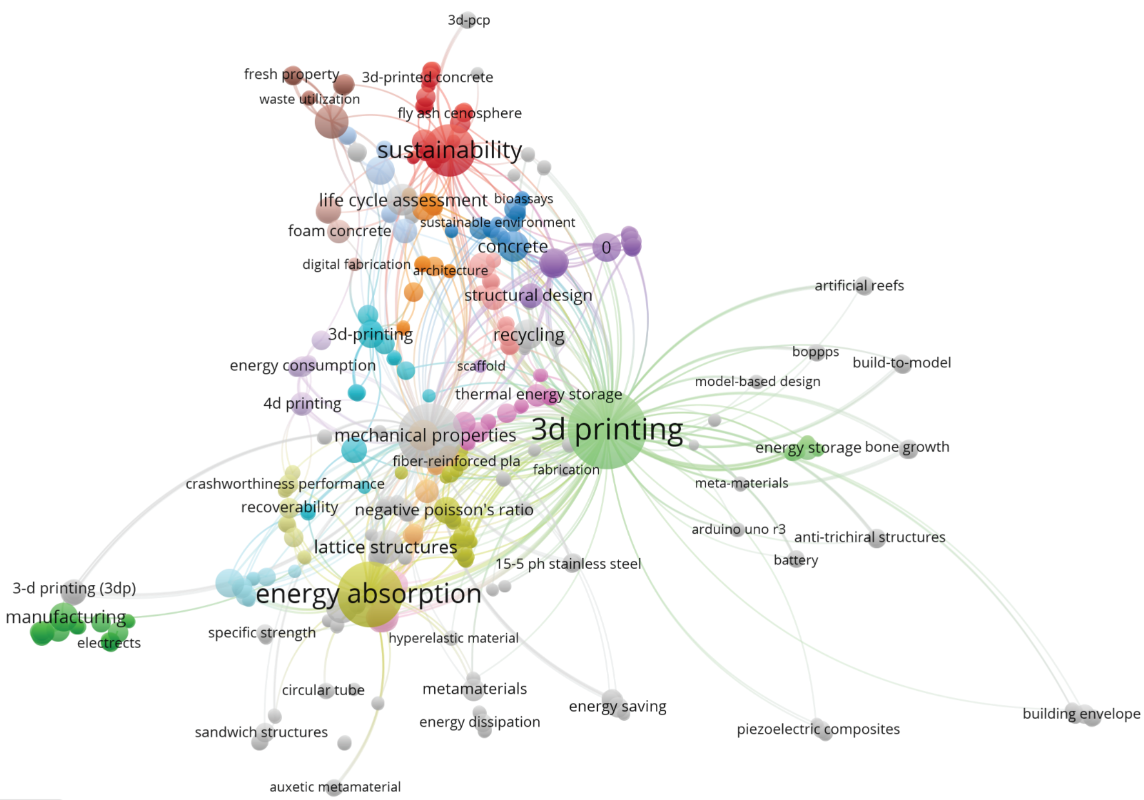



**FIGURE 6.** Co-occurrence of keywords (Visualization: VOSviewer).



## 5. DISCUSSION

In the article, the prominent themes were determined by analyzing the content of the research for the construction industry. Table 3 shows the main topics and methods used in 45 documents focusing on energy efficiency research and LCA for 3DP. The main focus of these articles are materials, walls, buildings, and 3DP technology. Of the 45 articles we reviewed, 80% were about materials, 15% focused on walls, 11% on buildings, and 6% on 3DP technology. Among the methods used in these studies, 38% preferred laboratory experiments, 29% preferred literature review, and 33% preferred simulation methods.

### *5.1 3DP Current State*

The reviewed articles highlight multiple benefits and limitations and propose future perspectives. Four main areas of interest were extracted from the authors, topics, keywords, and contents of the various articles analyzed in this paper: materials, walls, buildings, and 3DP technology. It is possible to assess the gaps and trends in the current state of 3DP, which is described in Figure 8. Studies about 3DP on walls are compared with the traditional construction method, 3DP building's energy-saving features, integration of architectural elements such as 3D-printed walls and facades into building design, 3D-printed concrete green wall systems, environmental impact, and LCA, 3DP wall configurations in different materials and sections, fire, energy and thermal performance by simulation method or laboratory experiments. Studies about 3DP in applying material solutions focus primarily on concrete and cement. However, there is also research on different materials, such as wood, plastic, soil-based materials, and polymers (Ali

**TABLE 3.** Main focus and method of selected documents (Laboratory Experiment: LE, Literature Review: LR, Simulation: S).

| Rank | Reference | Focus | | | | Method | Rank | Reference | Focus | | | | Method |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Material | Wall | Building | 3DP Technology | | | | Material | Wall | Building | 3DP Technology | |
| 1 | Panda, Paul and Tan (2017) | X | | | | LE | 24 | de Brito and Kurda (2021) | X | | | | LR |
| 2 | Panda, Paul, Hui, et al. (2017) | X | | | | LE | 25 | Bhattacherjee et al. (2021) | X | | | | LR |
| 3 | Biswas et al. (2017) | | | X | | LE | 26 | Kromoser et al. (2022) | X | | | | LE |
| 4 | Ghaffar et al. (2018) | X | | | | LR | 27 | Abu-Ennab et al. (2022) | X | | | | S |
| 5 | Bong et al. (2019) | X | | | | LE | 28 | Liu et al. (2022) | X | | | | LR |
| 6 | Chen et al. (2019) | X | | | | LE | 29 | Dey et al. (2022) | X | | | | LR |
| 7 | Alkhalidi and Hatuqay (2020) | X | X | | | S | 30 | Ebrahimi et al. (2022) | X | | X | | S |
| 8 | Mahadevan et al. (2020) | | | X | | S | 31 | Silva et al. (2022) | X | | | | LE |
| 9 | He et al. (2020) | | X | | | S | 32 | Ibrahim et al. (2022) | | | X | | LR |
| 10 | Colorado et al. (2020) | X | | | | LR | 33 | Munir et al. (2022) | X | | | | LE |
| 11 | Souza et al. (2020) | X | | | | LR | 34 | Tinoco et al. (2022) | X | | | | LR |
| 12 | Kaszynska et al. (2020) | X | | | | LE | 35 | Mir et al. (2022) | X | | | | S |
| 13 | Mohammad et al. (2020) | X | X | | | S | 36 | Mansour et al. (2023) | X | | | | LR |
| 14 | Khalil et al. (2020) | X | | | | LE | 37 | Samudrala et al. (2023) | X | | | | LE |
| 15 | Tahmasebinia et al. (2020) | X | | | | LE | 38 | Cuevas et al. (2023) | X | X | | | LE |
| 16 | Khan et al. (2021) | X | | | X | LR | 39 | Alsakka et al. (2023) | X | | | | S |
| 17 | Ciampi et al. (2021) | | X | | | S | 40 | Ibrahim et al. (2023) | X | | | | LE |
| 18 | Suntharalingam, Gatheeshgar, et al. (2021) | | X | | | S | 41 | Sambucci et al. (2023) | X | | | | S |
| 19 | Singh et al. (2021) | | | | X | LR | 42 | Taylor et al. (2023) | X | | X | | S |
| 20 | Suntharalingam, Upasiri, et al. (2021) | | X | | | S | 43 | Kamel and Kazemian (2023) | | | X | | S |
| 21 | Markin et al. (2021) | X | | | | LE | 44 | Ahmed (2023) | X | | | X | LR |
| 22 | El-Mahdy et al. (2021) | X | | | | LE | 45 | Mansour et al. (2023) | X | | | | LE |
| 23 | Han et al. (2021) | X | | | | S | | | | | | | |

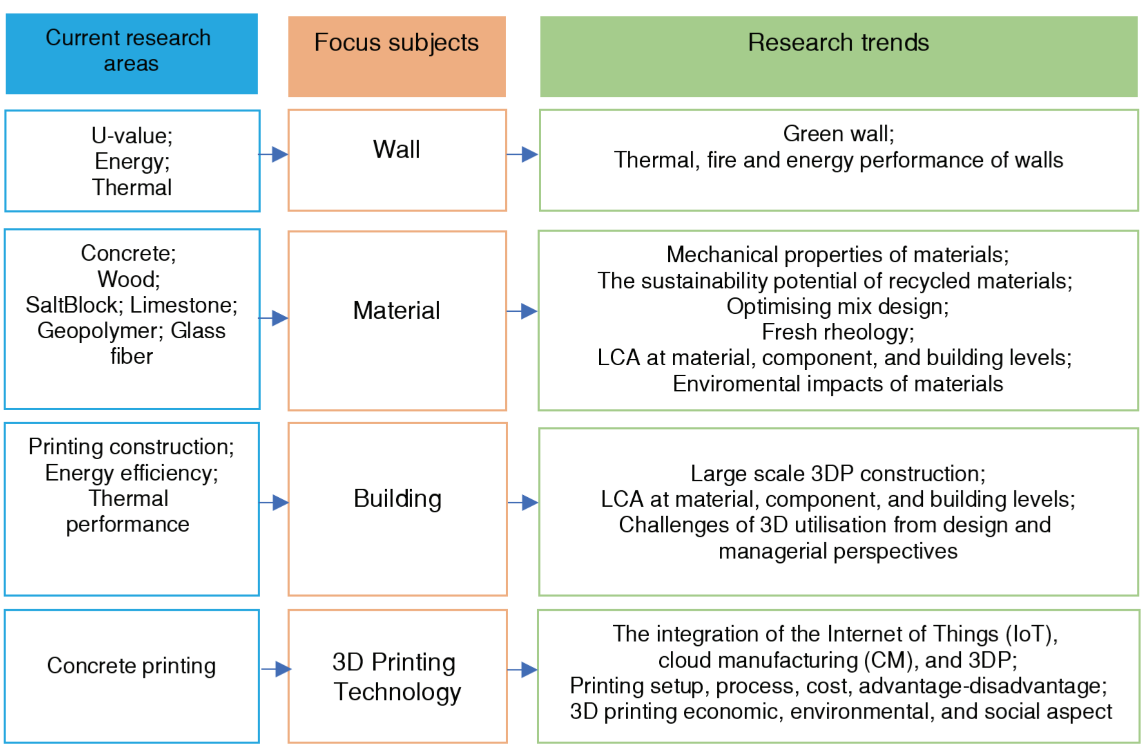
et al., 2019; Kaufhold et al., 2019; Rehman and Sglavo, 2020; Jemghili et al., 2021; Krčma et al., 2021; Ali et al., 2022). Experimental research about 3DP on the material is concerned with designing material components that reduce strength, mechanical properties, environmental impacts, and carbon emissions. Studies about 3DP on the building are energy saving, thermal comfort, environmental impact, 3DP on a large scale, materials, and components. Studies about 3DP technology discuss advantages, disadvantages, printing setup, cost, environmental, and social aspects.

### *5.2 3DP Benefits*

The benefits of 3DP in the construction industry can be categorized into two main areas. Firstly, 3DP offers time-saving and reliability benefits. By reducing reliance on manual labor, 3DP increases production speed in construction and enables mass customization. Compared to conventional construction methods, 3DP requires less time on average and eliminates the need for an extensive workforce, tools, and formwork (De Schutter et al., 2018). This automated process, driven by Computer-Aided Design (CAD) (Tay et al., 2017), ensures consistent quality and reliable delivery. However, conducting small-scale printing trials to evaluate models and parameters before embarking on full-size 3DP is essential to minimize the risk of errors (Zuo et al., 2019).

The second benefit of 3DP lies in its ecological and sustainable aspects. In traditional construction, the cost and labor associated with formwork often limit architectural design options, especially in concrete structures. Three-DP eliminates the need for formwork, enabling greater design freedom and complexity (Yang et al., 2019). This technology simplifies shape complexity,

**FIGURE 7.** The framework of 3DP's current status.



reduces material consumption, and minimizes waste, resulting in environmental benefits for LCA. Additionally, 3DP buildings use less material and generate less dust during construction, reducing logistics and transportation costs. The on-site printing of structures further lowers carbon emissions in production and transportation, reducing environmental impact.

## 5.3 3DP Limitations

On the other hand, there are several limitations associated with 3DP in the construction industry, which can be grouped into three main categories. The first limitation involves difficulty designing material mixtures and content for 3DP construction. Designing a material formulation with suitable rheological properties for 3DP is complex (Lucas and Barroso de Aguiar, 2019). The printable building materials currently available are relatively limited, and high-performance and durable materials, such as cement or earth-based materials, cannot be directly processed in the printing procedure due to poor rheological and stiffening qualities (Le et al., 2012; Robayo-Salazar et al., 2023; Yang et al., 2023). Printing errors, such as roughness, filament deformation, and filament tearing, can occur during the 3DP process. Integrating reinforcements into 3D-printed concrete parts is challenging and requires additional labor and energy (Buswell et al., 2018).

The second limitation pertains to the lack of construction standards and codes for 3DP. The absence of 3DP techniques in existing construction standards and codes creates challenges in adopting this new technology in the industry (Giesekam et al., 2016). The specific limitations and constraints of the production process still need to be discovered since 3DP technology has yet to be widely utilized in construction (Hossain et al., 2020). The third limitation is the need for more experts and professionals in 3DP. Establishing the robot's position and setting up the operational base for 3DP using a mobile robot can be highly challenging (Zhang et al., 2018). Physical separation between human activities and the moving elements of the 3D printer may be necessary to prevent unplanned collisions. Coordinating multiple mobile robots for printing large-scale structures requires careful planning and synchronized robot movements. Consequently, qualified individuals familiar with robotics, programming, and construction techniques are essential (Buchanan and Gardner, 2019). These professionals need to operate specialized equipment and software, possess knowledge of 3DP technology requirements, and be capable of performing complex computer analysis during the design and printing phases.

## 5.4 3DP Future Outlook

The findings of this study suggest three areas of research that can be further explored in the context of 3DP in the construction industry. Firstly, the development of policies and standards is crucial. Local governments should lead in establishing collaborations with stakeholders from the construction industry, government laboratories, and academia to define codes and standards for 3DP technology. Robust testing of large-scale 3DP structures is necessary to ensure public safety and facilitate changes in building codes. Global standards specific to materials and techniques in 3DP should be established, including regulations that address the performance aspects of 3DP production in terms of statics, mechanics, thermal properties, and energy efficiency. Local governments must prioritize the 3DP in their development goals and allocate resources and policies to support the transition. Public support, including funding for pilot initiatives and the establishment of a comprehensive database through public-private partnerships, may be required due to uncertainties surrounding the structural behavior and economic viability of 3DP in construction (Bonnín Roca et al., 2016; Seifi et al., 2017; Wiegmann et al., 2017; Adaloudis and Roca, 2021).

Secondly, there is a need to develop suitable materials for 3DP. The printability or buildability of materials depends on their rheological behavior, necessitating a holistic approach to material design (Roussel, 2018). Rigorous laboratory research and development should ensure step-by-step robustness and quality control. Furthermore, since 3D-printed materials are influenced by environmental factors such as temperature and humidity, research and development efforts should address the impact of ambient conditions on material mixture designs.

Thirdly, it is essential to provide education and training for 3DP professionals. The construction industry's shortage of skilled workers proficient in operating 3D printers underscores the need for specialized courses and educational programs integrated into university curricula (Qaidi et al., 2022). Proficiency in three key areas, digital components, machine operation, and material knowledge, is critical for successfully implementing 3DP projects. Institutions should offer courses and education encompassing these areas to equip professionals with the necessary skills and expertise.

## 6. CONCLUSION

The results of this article clearly show the importance of 3DP technology in the construction industry and the increasing interest of researchers. The research topic, started in 2014, has grown rapidly, especially since 2018. This growth is estimated at an annual rate of 48.91%, reflecting the wide acceptance of research in this area by the academic community. In addition, the main focus of studies on 3DP technology is materials, walls, buildings, and 3DP technology. Studies on materials have an extensive research percentage (80%), followed by walls (15%), buildings (11%), and 3DP technology (6%). These results highlight the importance of material-oriented studies for future research and the need for further work in the fields of building, wall, and 3DP technology. Laboratory experiments (38%) are the most common research method. However, different methods should be used more in the future.

Among the critical points examined in the research, issues such as the importance of research collaborations between countries and institutions, the necessity of life cycle analysis, and optimizing energy performance at different stages stand out. These results highlight the need for greater collaboration and policy development in energy performance and LCA. China, the USA, and India are leading countries in this field. In addition, the most frequently used keywords in publications are "3D printing", "energy absorption", and "sustainability".

However, several areas require further research and attention. Firstly, there is a need to explore materials, technologies, and design strategies associated with 3DP in construction to unlock its full potential. Additionally, the education and training of professionals, particularly architects and engineers, should be prioritized to introduce and adopt 3DP technologies in the industry effectively. Furthermore, the support of local governments through incentives, policies, and planning is crucial for facilitating the research, development, and production of 3DP technology in construction. Considerable capital investment is necessary to achieve widespread adoption of 3D printers, necessitating updates and the development of regulations, standards, and codes to accommodate this emerging technology. Effective collaboration between 3DP contractors and professional teams is essential to ensure successful implementation. This collaboration will enable the seamless integration of 3DP technology into construction projects.

All these findings highlight the need for more research and collaboration to contribute to the future development of 3DP technology in the construction industry and environmental sustainability. It is still unclear whether 3DP technology will bring about a revolutionary change in the construction industry. For the time being, this technology can be considered limited, especially in enhancing the artistic value of complex structures. Should be delted. ''However, from an environmental point of view, current studies do not point to a complete replacement of traditional production." The review highlights the need for greater energy efficiency and reduction of carbon emissions in construction processes, showing that 3DP technology can increase its environmental competitiveness. However, the adoption of 3DP in the construction industry depends on the environmental effects of the materials used, and factors such as reusability and recyclability need to be optimized in this area. Should be deleted ''In addition, the social and economic advantages offered by technology may not be fully measured by traditional environmental assessments, thus greater adoption of technology is required with environmental adequacy in mind." Overall, while industry and global organizations are turning to sustainable technologies, there is limited literature examining the environmental, economic, and social impacts of 3DP technology in the construction industry, and more research is needed in this area.

Future studies should address several shortcomings and areas of concern. These include evaluating the applicability of 3DP technology in both developing and developed countries, considering material content, fostering collaborations, shaping policies and regulations, assessing performance, evaluating environmental effects, and promoting sustainability. Moreover, there is a need for further research focused on reducing energy consumption, minimizing $CO_2$ emissions, and optimizing resource consumption to address concerns regarding the depletion of natural resources. A thorough investigation of the LCA of 3D-printed materials is necessary to comprehend their environmental impact throughout their life cycle from material preparation to building usage and eventual demolition.

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