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Material Used in 3-Dimensional Printing Technology in the Construction Industry

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Abstract

3-dimensional (3D) printing technology, a core technology of Industry 4.0, is increasingly being applied in the construction industry. Scientific research and deployment of this technology in the building industry have both significantly contributed to its widespread use. The aim of this research is to evaluate the material used in 3D printing technologies in the construction sector to understand its development and future research in the industry and scientific community. The evaluation included 74 research publications from the Web of Science database and 25 building applications from the construction sector. The VOSviewer and Bibliometrix package for R software were used to visualize the results of the bibliometric analysis graphically. The literature was examined and it was found that cement-based materials, polymer, concrete, recycled or waste materials, and new material mixtures are being investigated, with concrete receiving the most attention. The 25 3D-printed constructions were predominantly houses (76%), and these construction printing materials primarily used concrete (88%). 3D printing material design mixes must provide rheological properties such as printability, extrudability, and manufacturability. The properties of materials used in 3D printing, such as fire resistance, durability, thermal properties, and acoustics, are examined in very few studies. However, further research should characterize and improve the material properties associated with 3D printing buildings.

1. INTRODUCTION

As a part of computer-aided systems, 3D printing in the construction sector is mostly in technological progress. After 3D printing was introduced into the construction industry as part of Industry 4.0, architects and engineers have been able to utilize construction projects with a high level of complexity and digitalization [1]. In the process of digitalization, computer-assisted systems such as numerical simulation in architecture (e.g., energy, fire, thermal comfort, acoustic, and evacuation simulations) and adjustments to the design can be made while still in the design phase [2-4]. Additionally, artificial intelligence (AI) systems have been implemented in the digitalization of construction projects. The ability of AI to analyze vast amounts of data, identify trends, and create broad statistical models has significantly aided the "Construction Industry 4.0". AI, which was first coined in the 1940s, refers to the field of creating intelligent robots or computer programs that emulate human cognition. Artificial intelligence has been applied to a variety of applications, such as biomedical diagnosis [5-7], computer vision [8, 9], text classification [10-12] speech recognition [13, 14], and the construction industry [15-17]. Construction 4.0, which incorporates advanced technologies within the construction industry, has the potential to accelerate the sector's digital transformation. This transformation can generate significant amounts of data that can be effectively utilized to enhance operational efficiency, inform decision-making, stimulate innovation and growth, and improve sustainability [16].

The increasing number of buildings or structures with complex geometry built or planned in various countries recently represents the result of technological progress that has led to the transformation of

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traditional building materials, design approaches, and production methods [18-23]. It is important to research materials (such as concrete, polymer, steel, wood, clay, etc.) in 3D printing production [24].

Currently, 3D printing is more commonly used in construction projects. The 3D printing production technique is becoming prevalent in the construction industry because it can print with various materials, reduce construction time, and decrease the need for human labor [25]. 3D printing is essentially an additive manufacturing process that can produce complex form shapes from a 3D model on a layer-by-layer basis. It can reduce material waste, lower labor costs, and speed up manufacturing [26, 27]. In comparison to 3D printing construction and traditional construction processes, traditional construction is time-consuming, expensive, generates more construction waste, and requires human labor at various stages, while 3D printing is mostly automated, requires less human involvement, and does not need a framework [27-29].

Several review articles have investigated 3D printing in construction. Currently, wood, steel, polymers, and concrete are the most commonly used materials in 3D-printed projects [30]. Polymers are the least common among them, and their use in the construction of structural components is limited due to their high production costs and low rigidity [31]. Concrete and cement-based materials have been progressively used in digital production techniques in the past 5-10 years, in addition to wood and steel [30]. Bedarf et al. [32] reviewed the area of foam 3D printing in construction and determined an outline of relevant developments. Lim et al. [33] reviewed the latest developments in 3D printing, focusing on concrete as a printing material. Labonnote et al. [34] investigated the challenges and opportunities of 3D printing in construction and classified them into material science, building design, engineering, and market analysis. Bos et al. [35] identified the key difficulties and advantages of 3D printing concrete. Shakor et al. [36] examined the technique of 3D printing of cementitious material. Hamidi et al. [37] investigated the literature on cementitious composites. Ma et al. [38] investigated the printable properties of an environmentally friendly waste material mixture compatible with an extrusion-based printing process.

These review articles have discussed significant and recent developments in 3D printing in the building industry. Each has provided an analysis of a specific subject, such as 3D printing technologies, materials, advantages, and disadvantages. However, the materials and applications of 3D printing in the construction industry need to be further explored. The aim of this review is to both reveal the current state of 3D printing in terms of materials in the construction industry and to determine whether 3D-printed construction is currently or could be a viable alternative to traditional construction methods. To this end, 3D printing applications and literature are reviewed. This article provides a current review of material-related 3D printing applications and construction research. 3D printing identifies trends in material processes and the development of materials in construction and examines potential issues. This research will serve as a foundation for understanding what is currently being done and what needs to be done in the future.

This research reviews the use of materials in 3D printing in the construction industry. The method for researching materials used in 3D printing technology in the construction industry and the investigations are presented in section two. Section three of this paper presents the results of the review, and finally, with a view to the future, research gaps and possible future research topics are discussed in section four.

2. METHOD

Data from the literature review of materials used in 3D printing technologies in the construction sector, bibliometric analysis, and scanning methods were employed. In this research, 74 research papers in the literature and 25 applications of 3D printing technology in the construction sector were extensively examined.

The search for papers for this review was divided into three stages (Figure 1):

(1) Study design of the bibliometric analysis,

(2) Analysis of the scientific review, and

(3) Analysis of applications of 3D printing technology.

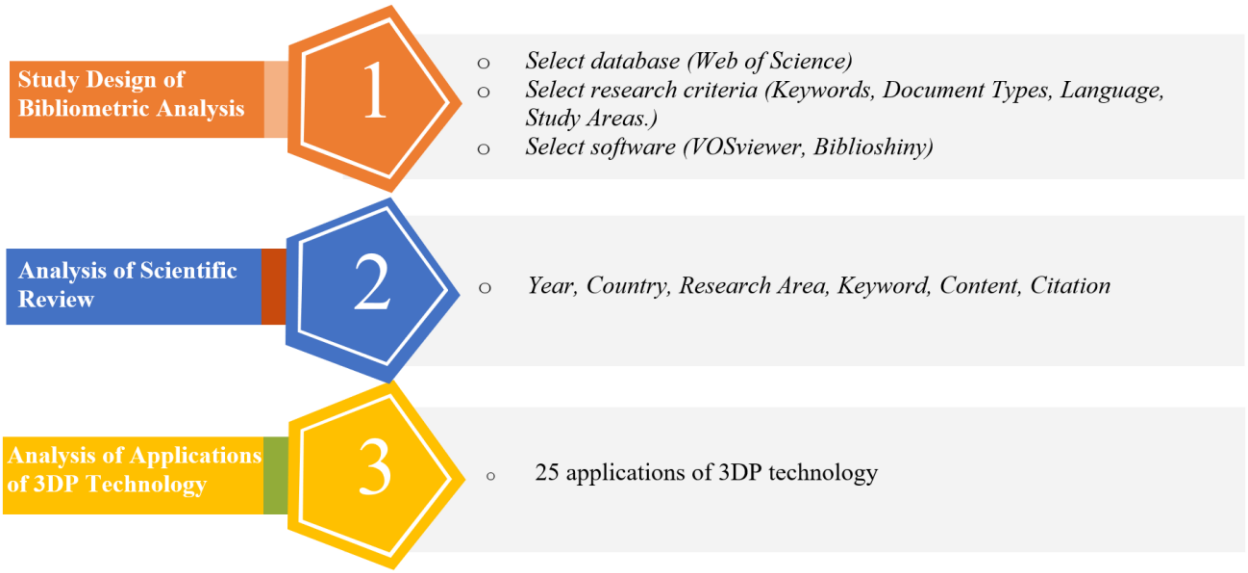


Figure 1. *Method of material used in 3D* printing *technology in the construction industry*

2.1. Study Design of Bibliometric Analysis

Bibliometrics refers to the use of mathematical and statistical approaches to assess scientific communication settings [39]. Various conclusions can be drawn using this quantitative research approach by evaluating items such as citations, keywords, publication year, and language of the study in the literature [40]. With these findings, the state of the literature is exposed, which aids in identifying developments and challenges and preparing the ground for problem resolution in future investigations. The Web of Science (WOS) Core Collection database is the most widely used database in bibliometric research due to its broad nature and numerous scientific publications. This database was chosen for this study.

The most frequently used keywords were used to examine the current status of material analysis in the construction industry of 3D printing technologies in the literature. In the research, *"Materials"* and *"3D printing"* or *"3DP"* and *"Architecture"* or *"Building"* or *"Construction"* or *"Structure"* or "*Wall"* or *"Geometry"* which includes 74 research papers in the field of architecture and engineering in the WOS database, or research and review articles published in English with these words in the title were reviewed These papers were analyzed using VOSviewer and Bibliometrix, software tools that acquire and visualize bibliometric datasets.

2.2. Analysis of the Scientific Review

The total number of citation analyses by country, the number of articles by year, the total number of papers by country, the study field, the most used keywords, and content on the material of 3D printing technology production in construction were reviewed in this study.

Keyword

Keywords refer to the main subject of the studies. Figure 2 shows the 20 most used keywords in the reviewed publications. *"3d printing"* were used as keywords in 38% of publications, *"additive manufacturing"* in 15%, *"mechanical properties"*, *"pla"* and *"yield stress"* in 4% of publications. The *"pla"* and *"concrete"* keywords were highlighted in terms of materials.

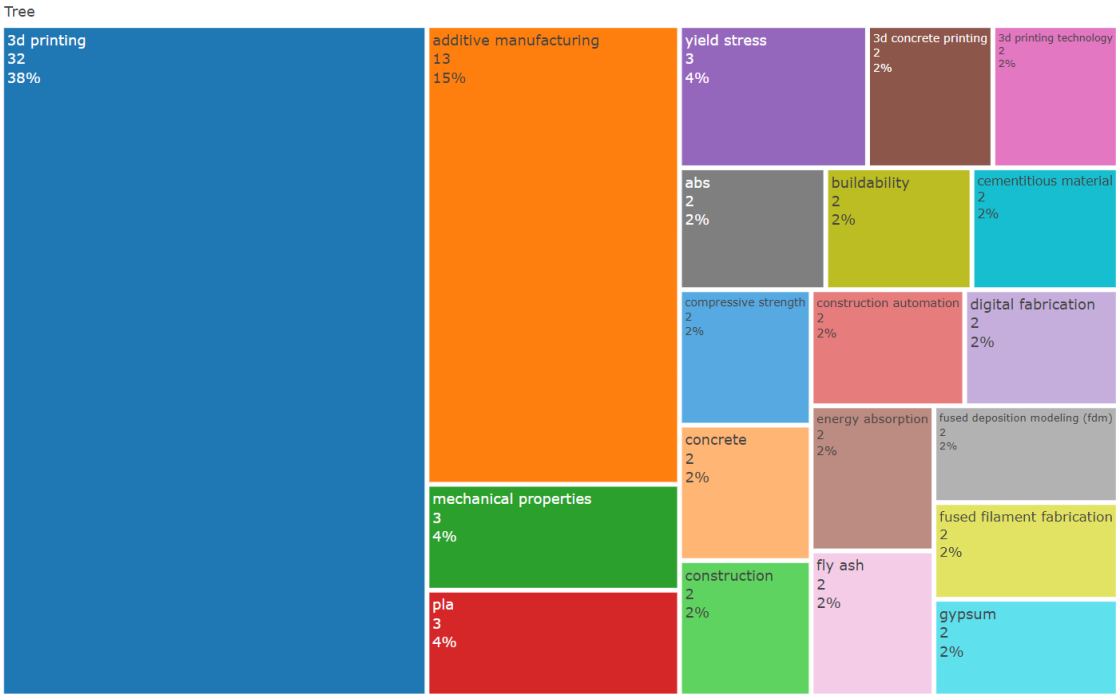


Figure 2. *The 20 most used keywords (Source: Biblioshiny)*

The mapping created with keywords summarizing the studies and showing their relationships with each other is given in Figure 3. In the mapping of this study, the analysis of the keywords used in the reviewed publications was visualized using VOSviewer to determine the relationship, frequency, and total link strength of the keywords. It was seen that 2 clusters dominate around *"3d printing"* and *"additive manufacturing"*. The *"3D printing"* keyword is used in almost all articles and has a strong connection.

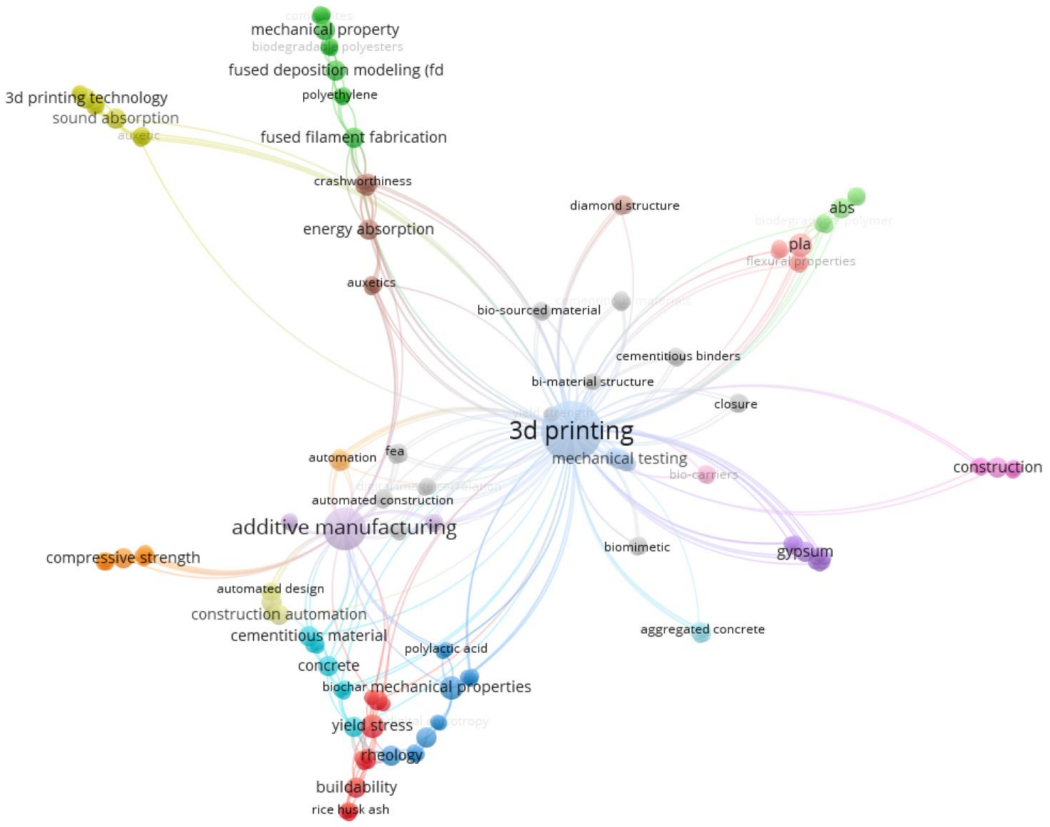


Figure 3. *The relationship of keywords with each other. (Source: VOSviewer)*

Year

The number of publications published per year is important for assessing a subject. Figure 4 shows the number of publications in the 2013-2022 period. There will be a significant increase in research on this subject after 2020. Recently, it has been observed that material research in 3D printing technology has gained great momentum and attracted more attention.

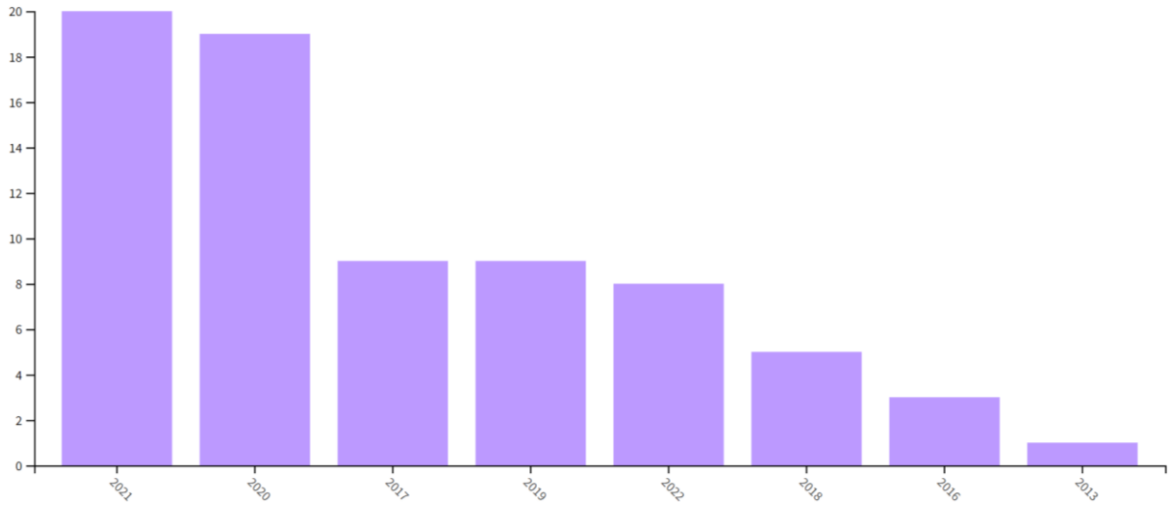
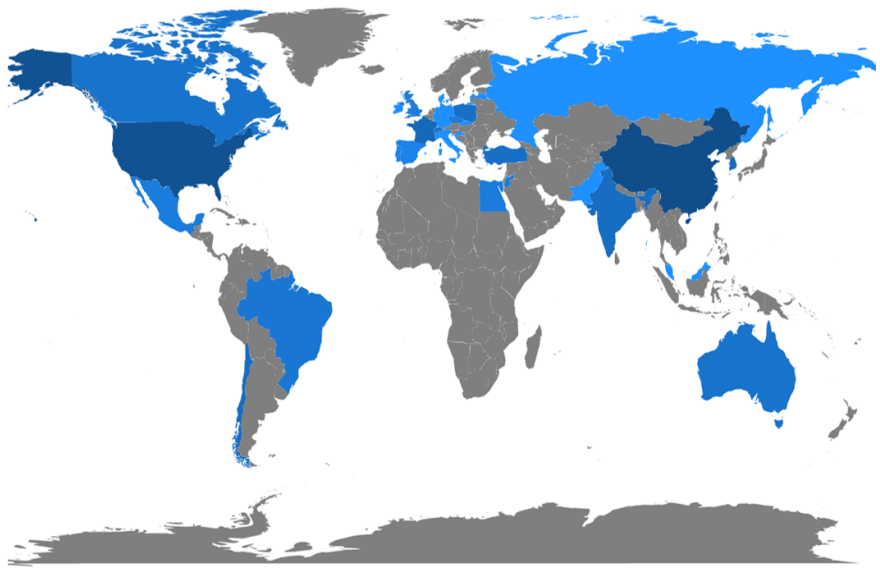


Figure 4. *The number of publications published per year (Source: WOS)*

Country and Citations

It is essential to review the publications by country in order to determine the importance of the topic in various countries. Figure 5 shows the number of publications by country. Universities and research centers in China have published 43 papers in this research field. A total of 74 articles were produced in this literature review from 30 countries.



Country	Publication
China	43
US	34
Singapore	10
France	9
South Korea	8
Chile	7
India	7
Poland	6
Turkey	6
Australia	5
Canada	5
Sweden	5
Brazil	4
Czech Republic	3
Egypt	3
Jordan	3
Mexica	3
England	3
Portugal	2
Spain	2

Figure 5. *The number of publication's countries and top 20 most cited countries (Source: Biblioshiny)*

Scientific research continues by building upon previous research and becoming a part of the literature. Therefore, it is important to give and receive citations to establish a foundation for further studies. Figure 6 illustrates the top 20 most cited countries in the field. The top three most cited countries are the US with 657 citations, Singapore with 473 citations, and France with 344 citations.

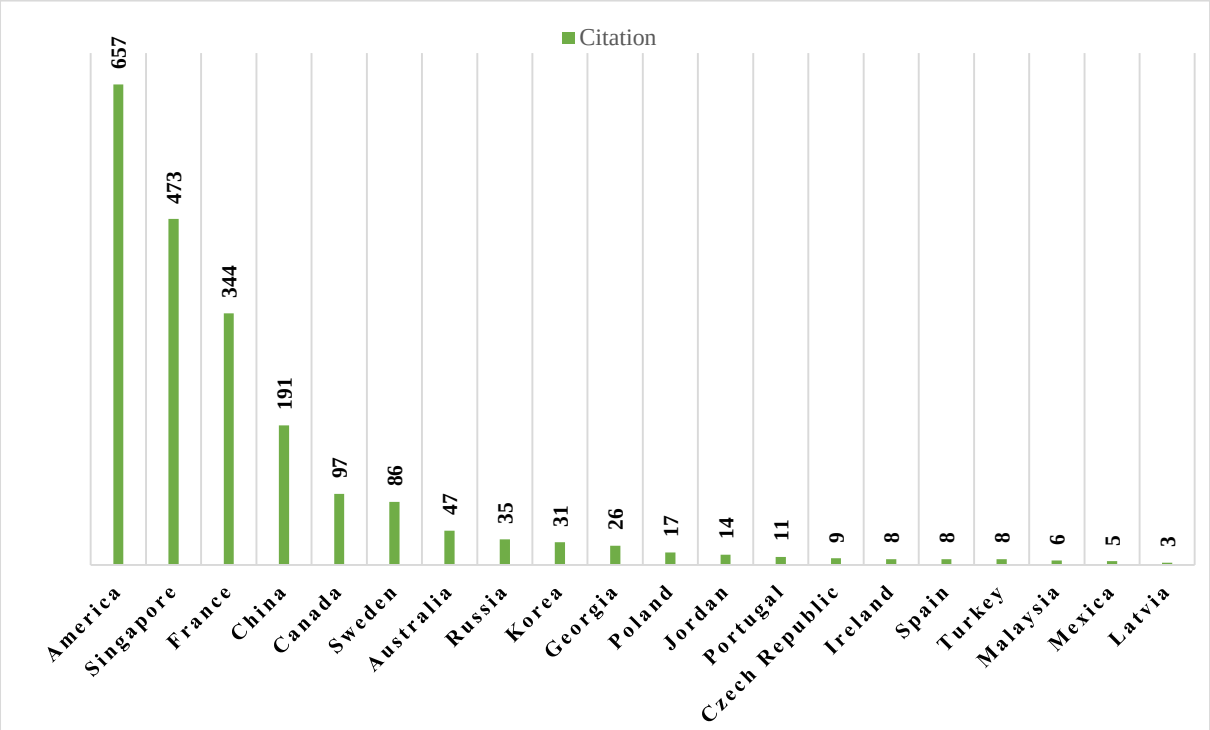


Figure 6. *Top 20 most cited countries*

Research Area

A total of 74 publications consists of 68 research articles and 6 review articles. As shown in Figure 7 this research consists of 11 main research areas, including *"Materials Science"* (63% of articles), *"Engineering"* (41%), *"Construction Building Technology"* (21%), *"Physics"* (14%), *"Chemistry"* (12%), *"Polymer Science"* (10%), *"Metallurgy Metallurgical Engineering"* (8%), *"Science Technology Other Topics"* (8%), *"Mechanics"* (5%), *"Environmental Sciences Ecology"* (4%) and *"Architecture"* (1%). Additionally, some articles may include one or more research areas. As a diverse area, architecture can benefit from research conducted in other disciplines. When the title of architecture is reviewed, it becomes clear that further research in the field is required since it should be a significant and innovative discipline in 3DP technology.

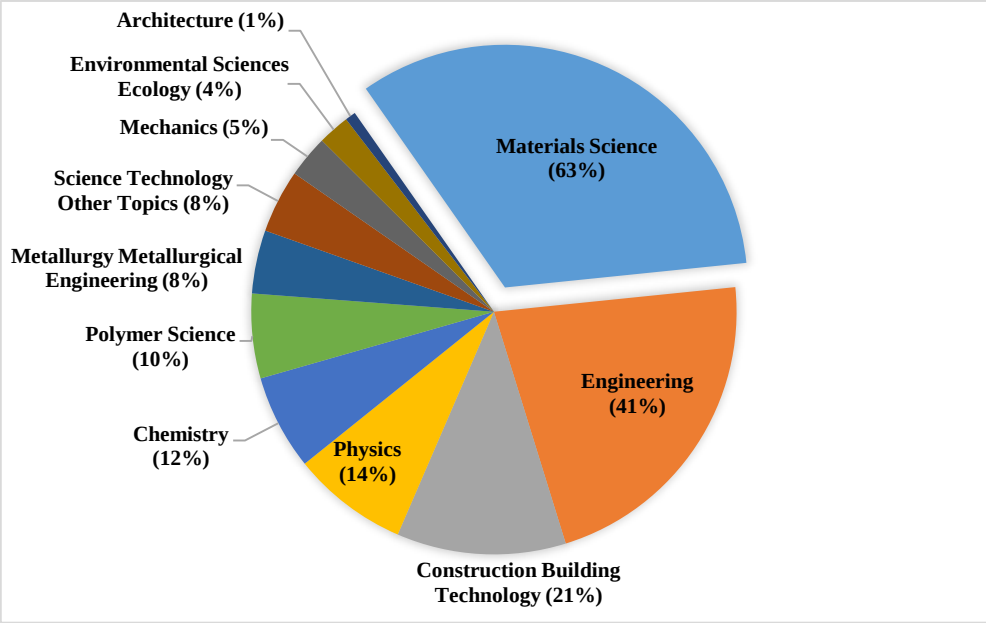


Figure 7. *The research area of the articles*

Content Analysis of Selected Articles

When determining the prominent subjects, a content analysis of the research related to the construction sector is carried out. Table 1 shows the content analysis of the articles detailed below. The articles in the literature mainly focus on cement-based materials, polymers, concrete, recycled materials, new material mixtures, and waste materials. After examination in the laboratory, the materials are tested for printability in a laboratory to assess the print quality and shape stability. Then, the printed sample strengths are tested experimentally. The 3D printing materials must be designed with a mix of materials that flow easily and can be extruded and constructed.

Table 1. *Examined the materials in the selected articles*

Rank	Title	Author and Reference	Material
1	Structural built-up of cement-based materials used for 3D-printing extrusion techniques	Perrot, Rangeard [41]	Cement
2	A Study on the Flame-Retardant Performance of Recycled Paper Building Materials Manufactured by 3D Printer	Hwang, Park [42]	Recycled cellulose from waste paper WC (wet cellulose) / exterior wall covering material
3	Anisotropic mechanical performance of 3D printed fiber reinforced sustainable construction material	Panda, Paul [43]	Concrete glass fiber reinforcement
4	State-of-the-art of 3D printing technology of cementitious material-An emerging technique for construction	Ma, Wang [44]	Cement
5	Fresh Properties of Cementitious Materials Containing Rice Husk Ash for Construction 3D Printing	Muthukrishnan, Kua [45]	Use of rice husks in cement
6	Synthesis and characterization of 3D-printable geopolymeric foams for thermally efficient building envelope materials	Alghamdi and Neithalath [46]	Fly ash-based geopolymer
7	Preparation and microstructural characterization of a novel 3D printable building material composed of copper tailings and iron tailings	Li, Zhang [47]	Copper and iron waste
8	Energy efficient 3D printed buildings: Material and techniques selection worldwide study	Alkhalidi and Hatuqay [48]	Different concrete mixes
9	Conventional Construction and 3D Printing: A Comparison Study on Material Cost in Jordan	Allouzi, Al-Azhari [49]	Concrete
10	Foam 3D printing for construction: A review of applications, materials, and processes	Bedarf, Dutto [32]	Foam in 3D printing construction (F3DP)

11	SaltBlock as a 3D printed sustainable construction material in hot arid climates	El-Mahdy, Gabr [50]	SaltBlock (sand and salt)
12	Fast Setting Binders for Application in 3D Printing of Bio-Based Building Materials	Sinka, Zorica [51]	Biocomposite (Agricultural waste products-use of hemp parts)
13	The Thermal Conductivity of 3D Printed Plastic Insulation Materials—The Effect of Optimizing the Regular Structure of Closures	Grabowska and Kasperski [52]	Prototype insulation materials made of plastic
14	Utilization of waste materials in a novel mortar–polymer laminar composite to be applied in construction 3D-printing	Lin, Dyro [53]	Use of biochar or fly ash from waste materials in cement with polymer reinforcement
15	Coordinated adjustment and optimization of setting time, flowability, and mechanical strength for construction of 3D printing material derived from solid waste	Shahzad, Wang [54]	Sulfoaluminate high-activity material

2.3. Applications in the Construction Industry Produced with 3DP Technology

Table 2 shows the existing structural applications produced by organizations/teams with 3D printing technology. The implementing companies include Winsun, XtreE, Cobod, Cybe, Icon, Wasp, and Apis Cor, which are the leading companies in the industry. 20% of the twenty-five applications produced with 3D printing technology were printed in America.

Table 2. *The structural applications produced with 3D printing technology*

Rank	Image	Project	Location, Year	Constructed	Function	Material	Reference
1		3DP apartment building	China, 2014	Winsun	House	Concrete	[55]
2		3DP Castle	USA, 2014	Total Kustom	Castle	Concrete	[56]
3		Apis Cor House	Russia, 2016	Apis Cor	House	Concrete	[57]
4		Krypton Post	France, 2016	XtreeE	Column/Structural element	Concrete	[58]
5		Urban Cabin	Netherlands, 2016	Kamermaker	House	Bioplastic	[59]
6		The BOD	Denmark, 2017	Cobod	Office	Concrete	[60]

7		3DP Pedestrian Bridge	Spain, 2017	Acciona	Bridge	Concrete	[61]
8		Bicycle Bridge	Netherlands, 2017	Eindhoven University	Bridge	Concrete	[62]
9		3B Studio 2030	Saudi Arabia, 2017	Cybe	House	Concrete	[63]
10		3DP House in Milan	Italy, 2018	Cybe	House	Concrete	[64, 65]
11		Chicon House	USA, 2018	Icon	House	Concrete	[66]
12		Gaia House	Italy, 2018	Wasp	House	Clay	[67]
13		3D-printed community	Meksico, 2020	Icon, Échale	House	Concrete	[68, 69]
14		KampC House Project	Belgium, 2020	Cobod	House	Concrete	[70]
15		Prvok	Czech Republic, 2020	Scoolpt	House	Concrete	[71]
16		3DP House	USA, 2021	Icon	House	Concrete	[72, 73]
17		Tecla	Italy, 2021	Wasp	House	Clay	[74]
18		Milestone Project	Netherlands, 2021	Weber	House	Concrete	[75]
19		3DP House	USA, 2021	Icon	House	Concrete	[76]
20		Beckum House	Germany, 2021	Cobod	House	Concrete	[77]
21		House Zero	USA, 2022	Icon	House	Concrete	[78]

22		Indian Army House	India, 2022	South Western Air Command	House	Concrete	[79]
23		3D Printed Office	Austria, 2022	Cobod	Office	Concrete	[80]
24		3DP House	Borneo, 2022	Cobod	House	Concrete	[81]
25		Viliaprint	France, 2022	XtreeE, Demathieu Bard	House	Concrete	[82]

3. RESULTS

This research focused on 74 articles from the Web of Science, including 48 journals and 295 authors at 110 institutions from 30 countries. Most publications are published by Chinese and American universities and research centers. "3d printing" was the most commonly used keyword and dominated the studies. It was determined that publications in this study area began appearing after 2013 and have shown rapid development since 2020. Chinese universities and research centers have produced more scientific publications (43 papers in the past 9 years) than those in other countries. The publications of American universities and research centers have received the most citations, with 909. Over half of the research is in the field of *"Materials Science"* (63%). The papers in the literature were analyzed and it was found that cement-based materials, polymers, concrete, recycled or waste materials, and innovative material mixtures are being explored. However, concrete is the most popular, common, and essential material for 3D printed construction in the examined papers.

The 25 structural applications produced with 3D printing technology can be divided into three groups. The first group consists of 3D-printed buildings (houses, offices, castles, etc.). The second group is 3D-printed bridges for pedestrians. The third group consists of structural elements such as columns. 92% of the samples examined are building applications. 8% of the samples investigated are structural elements and bridge applications. The functions of the 25 3D-printed constructions are shown in Figure 7. These constructions consist of houses (76%), bridges (8%), and other functions (16%). The country where 25 applications produced with 3D printing technology are printed the most is America. Compared to other countries, America stands out in applications and literature in this field.

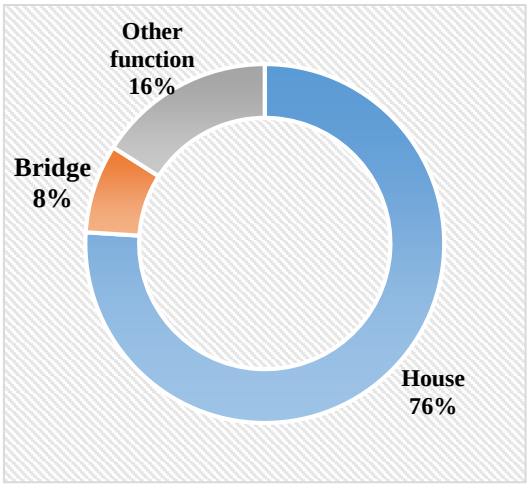


Figure 7. *The function of the twenty-five 3D-printed constructions*

Figure 8 shows the materials of the structures produced with 3DP technology. The production material of the twenty-five 3D-printed constructions consists of 88% concrete, 8% clay, and 4% bioplastic material.

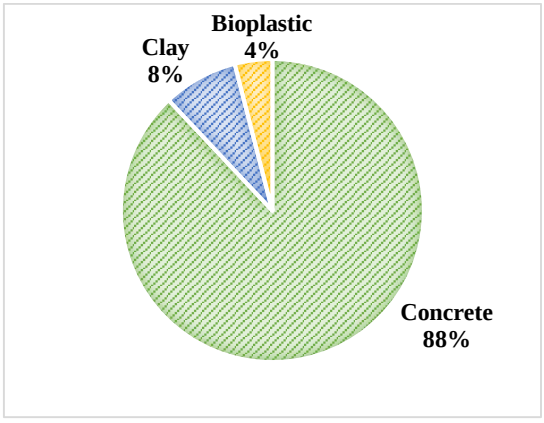


Figure 8. *The production material of the twenty-five 3D-printed constructions*

4. CONCLUSION

Recently, the prevalence of 3D printing technologies in the construction industry and architectural applications has significantly increased. A literature review was conducted to analyze the data, including the material research used in 3D printing technologies in the construction industry. The review examined the most frequently used keywords related to the materials used in 3D printing technology in the construction industry, the total number of publications by country, research articles, content analysis, and the most cited articles. According to the information obtained from the systematic literature review, 25 construction applications of 3D printing materials focus on cement-based materials. America is a major country in both the application and literature in this area. 3D printing concrete is more advanced and widely used in construction than metal or polymer printing. Currently, residential and office buildings and several pedestrian bridges have been built using 3D printing concrete. Through its low cost, high efficiency, automatic construction, design flexibility, and reduced personnel requirements, 3D printing technology for cementitious materials is a viable alternative that has the potential to transform the traditional building and construction process.

The 3D printing technology in the construction sector is a faster, safer, less labor-intensive, and generally more effective method than conventional construction methods. One advantage of this technology is waste reduction through the creation of recycled and waste-based concrete, as well as near-zero waste in 3D printing construction processes. However, there are still challenges to be addressed in the implementation of this technology. For example, experts, particularly designers and engineers, must be educated on how to

introduce and implement 3D printing technologies in the building industry. Additionally, the construction sector needs to update and develop the norms, standards, and codes used in construction designs to accommodate this technology. The government should support the research, development, and manufacture of 3D printing technology.

The study of material research on 3D printing technology is still in the early stages of development. 3D printing material design mixtures require specific material properties such as printability, extrudability, and buildability. The characteristics of materials used for 3D printing construction, such as fire resistance, durability, acoustics, and thermal capabilities, are rarely described. Therefore, more research should be conducted to characterize and potentially improve the material qualities of 3D-printed buildings.

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