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# 3D Printing Technology In Construction Industry: A Systematic Literature Review

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**Abstract**

3 Dimensional (3D) printing has started creating the footprints in construction industries across the world. The key benefits identified are eco-friendly, faster construction, architectural freedom, construction free from formwork, and safety. In construction sector, 3D construction printing is a promising technology. Researchers are also exploring the new research avenues in 3D printing in construction industries. Purpose of this paper is to carry out a systematic review of Literature available in 3D printing in construction industry. This review paper will facilitate the researchers with a holistic information about the 3D printing technology and its applicability in building sector, advantages, opportunities, and challenges in its implementation. The review paper is developed based on examination of 124 articles for the period from 2004 to 2022.The literature is analysed, and the graphs are plotted based on country, researchers, name of journal, Publishers, key words etc. The advantages, limitations, challenges, and opportunities for application of 3D printing in construction are enlisted based on literature review. The paper offers research avenues in 20 major domains in context of application 3D printing in construction. The paper concludes that there are approximately 50 + research avenues available in this context and researchers have very good scope to investigate these.

*Keywords:3D Printing Technology; Construction Industry; 3D Concrete Printing; Additive Manufacturing; Robotic Construction Technology; Construction Process Automation*

## 1. Introduction

According to Pessoa et al. [1], construction industry is known as low-tech industry due to shortage of innovation in the building process and is dependent on manual labour for years. The construction industry remained stagnant as compared to the other sectors' productivity. Additionally, according to reports, buildings in the European Union are the biggest consumers of energy, using 40% of the total and emitting 36% carbon dioxide (CO2) [2]. Current construction industry is not sustainable as the methods and materials used in the process are not eco-friendly. The process of construction includes material transportation, off-site manufacturing, on-site material production and construction due to which it emits large amount of greenhouse gases thereby polluting the environment[3], [4]. The annual revenue of the construction industry is around 10 trillion USD which depicts about 6 percent of the global Gross Domestic Product (GDP). Thus, the construction companies are looking forward to increasing their productivity while reducing the overall cost[5]. The 3D printing technology works on the principle of deposition of material of one layer over other to create the given product from a Computer Aided Design (CAD). Since the improvement of 3D printing technology in 1980, it has become famous in a wide spectrum of usage till date. Its presence can be seen in aerospace industry, plastic and metal working, product designing, prototyping, dental applications, medical applications etc., whereas it is relatively a new technology in construction sector[6]. The 3D construction printing (3DCP) or cementitious large-scale additive manufacturing processes have been under research and more than 30 groups are involved in this research for last 10 years[7]. To diminish the limitations of conventional construction method including high quantity of wastage consisting of material waste, formwork waste, temporary support structures waste etc., time consuming process and geometrical restrictions for architects, 3DCP can prove to be better, cheaper, and faster process[8]. 3D printing technology was developed in Japan in around 1980 under the name as Rapid Prototyping. Currently, 3D printing has got a variety of applications in different engineering domains and relevant industries involved in design and development [3]. Thus, as compared to the conventional process of construction, 3DCP, a digital and automatic technology, brings number of benefits to the construction method such as great flexibility in architectural design [9]–[12], fabrication without formwork [13], quicker construction [14], better working conditions, material savings [15]–[17] etc..

*1.1. Basic Steps in 3D Printing in Construction Industry*

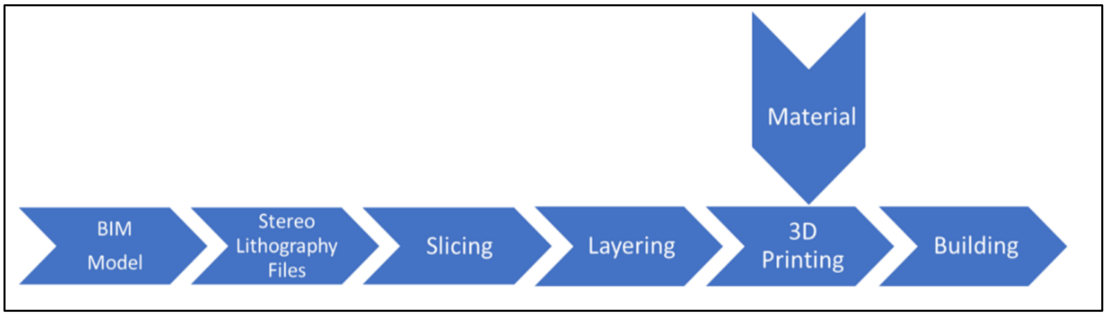


Fig. 1. 3D Construction printing process

A 3D Computer Aided Design model with a Building Information Model (BIM) is created in respective software as an input to the 3D printer replicating the product to be created. This model's format is then transformed into a STL (Standard Triangle Language) file format which is acceptable by printer. Using slicing software, required layer thickness, supporting material, precision, scan path, speed of movement, structure type etc. parameters are defined. This data in G-code and/or M-code format is fed to the 3D printer which then performs the operation so defined. The nozzle of the device ejects the printing material and layer-by-layer the product is created by depositing the layers one over another [3], [18]. This paper further discusses about the key contributions and future improvement suggestions given by existing research/review articles and are arranged systematically in tabulated format, followed by the systematic analysis of frequency of publication relative to the matter of discussion – 3D printing in construction segment, based on year of publication, publisher, journal, and country. The potential benefits are identified with regards to the implementation of 3D printing technology in the construction segment, followed by challenges faced/to be faced by the technology along with opportunities available in the industry. In addition, 50+ research avenues are identified for 3D Construction Printing Technology in different sectors of application having potentiality of application.

## 2. Key Contribution by Authors in Previously Published Articles

Previously published articles ranging from year 2004 to 2023 were reviewed and their key findings/contributions/novelties were identified, recorded, and systematically tabulated as shown in following Table 1. The tabulated data is limited to first 50 top searches by the search engine used – Google Scholar, IEEE, Science Direct.

Table 1. Key Contribution by Authors

| Sr. No. | Authors | Key Contribution | Future Scope |
|---|---|---|---|
| 1 | Nebrida, 2022[19] | The drift of construction technology in onsite construction was determined using the case study method | 3D Printing's structural capability study is necessary along with cost comparative studies with other construction technologies both onsite and offsite. |
| 2 | Besklubova et al., 2021[20] | The determination of the decision that use 3D printing for construction projects was done in this paper. It revealed 9 potential factors and their 32 measurements. | Investigations on the technological capabilities of 3D printing based on larger sample size for model validation. |
| 3 | Gomaa et al., 2021[21] | The improvement stage of a cob-specific 3D printing system which meets current digital construction requirements was described in this paper. | Scaling of the model into an industrial demonstration. Exploration of application of machine learning, response of material, computer vision techniques for manufacturing to be more intelligent, responsive, and automated. |
| 4 | Bedarf et al., 2021[22] | This paper provided a definition of the construction industry's foam 3DP (F3DP) field, as well as an overview of recent developments, obstacles, and routes for future investigation. This review provides a systematic overview of promising developments in F3DP for construction and opens up new avenues for sustainable construction process research and development. | Study of effects of tool path layout on end results and durability of the 3d printed structures for meeting higher expectations of the construction industry. |
| 5 | Xiao et al., 2021[23] | Extrusion based 3D construction printing technologies at larger scales were broken down into three categories in this analysis based on the various printed items and construction methods: On-site 3D printing components, formworks, and monolithic 3D printing concrete. | Further investigation and development of building codes for regulating large scale 3D printing applications in building industry. |
| 6 | Bai et al., 2021[24] | In this study, the usage of sand from the desert (small), river-sediment ceramsite sand (medium), and recycled concrete (large) as constituents in the additive manufacturing (3D printing) of concrete was the subject of an experimental inquiry. This article provided workable ideas based on experimental statistics for raising the eco-use of waste and underutilised solids in 3D printing that fulfil the minimal standards for strength and durability. | Investigation and analysis of curing time and factors influencing it like relative humidity, internal curing, aggregate content etc. |
| 7 | Y. Zhang et al., 2018[25] | This paper presented a novel concrete ink for 3D printing that is intended to be injection moulded through a nozzle to print elements layer-over-layer for an innovative method of additive manufacturing. According to the findings, this concrete's buildability rose by 150 percent and 117 percent, respectively, when a little amount of NC or SF was added, and its thixotropic and green strength were also greatly enhanced. | NA |

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| 8 | Kazemian & Khoshnevis, 2021[26] | For "inline actual extrusion value assessment throughout construction 3D printing," this study suggested four different approaches. Some of these techniques include computer vision, extrusion pressure measurements, electrical resistance measurements, and agitator motor power usage measurements. | Use of non-destructive testing (NDT) can be made to monitor and analyse early age properties of the structures like mechanical strength. |
| 9 | Duarte et al., 2021[27] | This paper surveyed and concentrated examples from memorable structures. To print the identified forms, a set of strategies, which include crucial toolpaths and intermediate stages, were defined taking into account material requirements and the printing process. | Feasibility analysis of structures from a structural performance point of view by modelling the structures and 3d print the samples for testing its fresh-state stability and printability. |
| 10 | Ting et al., 2021[28] | The usage of reconditioned glass cullets as fine collections in printing technology was the subject of this study. | Future study to reduce – to certain extent – the need for finer cullets of glass by investigating the grinding process of reconditioned glass cullets in Construction 3D Printing. |
| 11 | Zhu et al., 2021[29] | An artificial IVD composite scaffold was built using 3D printing and electrospinning in this paper. The results of an animal experiment showed that the biomimetic artificial IVD scaffold was able to keep the disc space and make the new extracellular matrix. | Research on artificial Intervertebral disc composite scaffolds using various structural models for obtaining different mechanical properties. |
| 12 | Pessoa et al., 2021b [30] | 3D-Printed buildings' thermal efficiency was the primary focus of the authors' investigation into additive manufacturing's (AM) potential application to the construction industry. This study outlined novel approaches to enhance the thermal properties of printed structures. | Shifting from manual to automatic methodology to be grounded on integrated isolation mixture which will be continuously printed along with cement-based mortar layer. |
| 13 | Ning et al., 2021[31] | This study proposed research interests, obstacles, and potential topics as well as a comprehensive plan to advance 3D printing in building sector. | Comprehensive research and discussion on sustainability of 3D construction printing is required. |
| 14 | C. Wu et al., 2021[32] | The paper discussed the broad possibilities for incorporating 3D printing in the building sector and serves as a datum for future researchers interested in 3D architectural printing technology. | Wide acceptance of the technology to be based on constant updates technology with respect to 3D construction printing to create a benchmark in the construction sector. |
| 15 | Babbar et al., 2021[33] | The usage of construction 3D printing is examined in the paper, along with its advantages and disadvantages, and its potential for sustainable development was evaluated. | The technology of 3D printing to be explored with its potential in other fields such as aerospace, biomedical, mechanical and automotive sector. |
| 16 | Tho and Thinh 2021 [34] | In this paper, a Cable-Driven Parallel Robot (CDPR) for concrete 3D printing for building houses was explained. An extruder of concrete for the 3D printing process was also the focus of the paper's analysis and design. The results showed that this design, with its high accuracy and steady production path, is appropriate for 3D printing in the construction industry. | Mechanical properties' enhancement for with materials used and printing velocity of the printer along with solidification speed to have different printing speeds. |

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| 17 | Munir & Kärki, 2021[35] | Each stage’s comprehensive economic evaluation was presented in this study to better distribute resources. The findings proved that 3D printing a geo polymer on a construction site was more cost-effective than printing in a factory. | Cost reduction and efficiency enhancing with developments in the technologies for pre-treatments of waste materials, conditions of curing, workflow digital design for the construction sector. |
| 18 | Volpe et al., 2021[36] | A novel concept, design, and prototype for a precast building envelope that can be prefabricated using extrusion based. Based on this study, the innovative materials, construction automation, and prefabricated systems could significantly boost the construction industry's future sustainability. | Social acceptance and use of the 3D printing technology to be promoted by developing a prototype in a pilot case study. |
| 19 | Singh et al., 2021[37] | This article provided important recommendations for future enhancements, such as predictive analytics in 3D Printing, automation with robotics, eco-friendly 3D Printing, and IoT-based5G technology-based CM. It also carried out the analysis of the constraints of existing study. | Integration of Industry 4.0 technologies with 3D printing like robotics, predictive analysis, environment friendly, 5G tech., IoT based cloud manufacturing. |
| 20 | Teixeira et al. 2021 [38] | The goal of this study was to find a mortar composition with a lower impact on the environment and lower CO2 emissions by reducing the use of concrete as a material. | The scope of sustainability is to be travelled over for 3d printing mortars to be more sustainable. |
| 21 | Goh, Sing, and Yeong 2021 [39] | The authors believed that ML's object detection capability will significantly enhance in-situ monitoring of Additive Manufacturing processes. | Focusing on multiple tasks learning which will improve the reliability of the structures for enabling functional ability of the technology. |
| 22 | Pan et. Al. 2021 [40] | The authors set out to fill this void in this review by including both academic articles and all construction 3D printing projects and studies. | Development of building codes on 3d construction printing project for standardizing processes and other relative practices. |
| 23 | Muñoz et al. 2021 [41] | The analysis included the complete supply chain, operation, and end-of-life of the 3D printing equipment and was based on real data from the design and operation of a demonstration plant placed in Spain. For instance, greenhouse gases emissions have decreased by 38%. | Practicing more on depositing material where it is needed to be instead of just pouring the material to save the raw resources like concrete. |
| 24 | Lange, Jörg Feucht, Thilo Erven, Maren (2021)[42] | The most important thing is to figure out the right welding and process parameters. Additionally, good structures that require little material can be found using topology optimization. Because of 3D printings open design possibilities, this is possible. This opened for novel plan and creation procedures. | NA |
| 25 | Muthukrishnan, S (2020) [43] | RHA took the place of 20 percent cement by weight in this project. Fuse of Rice Husk Ash had proven critical development in mortar rheology at the rate expected for large-scale development 3D printing. | iRHA with completely removed crystalline silica to be obtained with further treatment to not limit the research with lab RHA. |

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| 26 | Marchment, Taylor Sanjayan, Jay (2020)[44] | In this paper, a novel in-process method for simultaneously inserting mesh reinforcement during the printing of layers of concrete was described. Calculations and tests showed that lapped mesh reinforcement worked well as a continuous reinforcement. | Automatic stitching of mesh through rebar ties shall be investigated for further automation of the process. |
| 27 | Abou Yassin et al., 2020 [45] | A method for combining 3D concrete printing with non-standard steel rebar shapes was presented in this paper. Outcomes displayed the streamlining proportions of printing heads (steel) to substantial printing heads utilizing the current innovation and commitment critical decreases in time and cost while giving a clean, more secure, more computerized, and a boundless development process. | In-depth discussion on addressing bond for concrete and printed steel along with distribution of stress in the components and mixing techniques for fresh concrete continuous support. |
| 28 | Yu et al., 2020 [46] | Cementitious filament was extruded on aggregate bed in this paper to form layer-over-layer models in a concrete printing process. A successful printer had been developed for prototypes, and the aggregate content of the printed concrete may reach around 40%. In addition, the printed structures met the general engineering requirement of gaining compressive strength of 48.9 MPa and flexural strength of 7.5 MPa after 28 days. | Further efforts needed to improve the composition of materials, printing paste properties optimization, varying grades of aggregates, changing parameters of printing process etc. |
| 29 | Kloft et al., 2020 [47] | The findings of a relative study on the impact of the two cementitious material printing methods SC3DP and extrusion on the interlayer connection strength were presented alongside the fundamentals of the Shotcrete 3D Printing technology. | Application of shotcrete 3d printing technology to be made for reducing cold joint generation risks and gain benefits of complex geometry freedom to high degree with reinforcement integration and surface finish. |
| 30 | Shahzad et al., 2020 [48] | In this review, the organized change and advancement of setting time, flowability, and Mechanical strength for a sulfo-aluminate high-action material (Farce) were accomplished, and the materialas ended up being appropriate for C3DP. | Reduction in construction waste and promoting reduction in global warming by coordinated adjustment and optimizing setting time, mechanical strength, flowability for construction 3d printing. |
| 31 | Alhumayani et al., 2020 [49] | The environmental influences of major 3D printing (3DP) construction were assessed in comparison to those of traditional construction techniques employing 2 distinct types of building materials in this study. According to the findings of the study, innovative material science and the utilization of renewable energy sources have the potential to significantly enhance the construction potentials of 3DP cob and 3DP concrete, respectively. | Modification of material mixes to be carried out for reduction in 3D printing concrete’s environmental impact. |
| 32 | Sandeep et al., 2020 [50] | The primary objective of this paper was to examine the competitive environment of the various 3D printing industries with an emphasis on adoption strategies. | Efforts to be made towards human bio-fabricating with printing of bio-organs and artificial bones. |

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| 33 | Khan, 2020 [51] | By studying the mix's fresh and hardened characteristics and highlighting on the required printing parameters, this paper aimed to examine the concrete-mixtures, including fiber-reinforced Geo polymer mixes, that are acceptable for the 3D printing process. | Standardization with codes of manufacturing using 3D printing for performing extrudability, buildability and pumpability tests, layer size, rate of discharge, speed of nozzle and time gap. |
| 34 | Allouzi et al., 2020 [52] | The most recent developments in construction-related 3D printing processes are reviewed in this paper. The compositional, conservative, natural, and primary elements of 3D printing were presented. | Applying 3D printing as an alternate method to conventional construction and working on it for further potential impact assessment and extending work done by 3D printing towards whole construction process. |
| 35 | Classen et al., 2020 [53] | The presented article suggested an innovative 3D printing technique for Structural systems called Additive Manufacturing of Concrete Reinforcement, which is feasible for practical case. This method was based on an extensive review of research and development for digital fabrication of RC structures as well as an examination of practical requirements. | Investigating reinforcements of steel into 3D printing process to enable 'reinforced concrete' production through additive manufacturing process. |
| 36 | Ortega et al., 2020 [54] | Since standardization ensures a technology's viability, this article proposed quality-control tests and an assessment methodology to demonstrate that regulation was not a barrier to the use of innovative products like 3D printing. | Promoting use of 3D printing technology for its adoption in construction sector by further analyzing its applicability using stress tests, testing buildability etc. |
| 37 | Hossain et al., 2020 [55] | An extensive body of research had been carried out to comprehend the most recent advancements, potential outcomes, and difficulties associated with the widespread implementation of 3D printing in construction projects. This study also looked into how the growing use of 3D printing in construction might affect the labour market. | In-depth discussion and detailed investigation required to promote the technology's adoption by reducing cost of machine, hardware, software which is currently outweighing the cost saving with respect to labour, machine time, material etc. |
| 38 | El-Sayegh et al., 2020a [4] | The related literature on the use of 3D printing in construction was critically examined in this paper. The various construction-related 3D printing methods were discussed and evaluated in this paper. | Collabourative construction to be adopted by architects and structural designers by extending the scope of building to allow 3D printing process to be possible. |
| 39 | Manju et al., 2019 [56] | The methods and future trends of using a 3D printer in the construction sector were the subject of this study. | Suggestions made for reducing nozzle size, using fine materials, using limestone and other construction materials for improving the accuracy and structural aesthetics. |
| 40 | (Furet et al., 2019 [57] | Introduction of Batiprint3dTM, a brand-new advanced additive manufacturing method for building concrete buildings. The advanced technique that was proposed involves deploying a mobile, poly articulated robot to construct a complicated wall out of 3D-printed materials. | Focusing on sustainability in constructing homes by investigating earth or clay 3D printing. |
| 41 | Xia et al., 2019b [58] | By using just slag compositions, it was possible to produce geopolymer materials that successfully meet the requirements of powder-based printers that are commercially accessible. | Implementing geopolymer materials with powder based 3d printing process in building sector. |

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| 42 | Mechtcherine et al., 2019 [59] | The views of engineering (mechanical), concrete technology, construction management and data management were all highlighted in relation to the new technology. Also, some illustrative outcomes of completed work in various disciplines were shown. | Safety concerns and critical weather situations and interruptions in work are to be resolved with respect to the on-site use of 3d construction printing. |
| 43 | B. Lu et al., 2019 B. Lu et al., 2019 [60] | Aiming to carefully bridge the gap between the need and the state of the art of 3D printable cementitious materials. In various stages of material development, the demand for 3D printable cementitious material was examined. | Efforts to be made toward proper control over the performance of printing procedure for having desired structural performance. |
| 44 | Marchment et al., 2019 [61] | Application of cement-based paste at interface for minimizing the voids and enhance bonds are thus strengthening the interior bonds was explored. | Investigation on manipulation of lubrication layer properties to ensure expected output from the process. |
| 45 | Shakor et al., 2019 [62] | Identification of different mix designs with new experiments for analysis of printability of new mixes was carried out. | Focusing on the work of developing physical-based models at different sizes to ensure improvement in parameters related to printing process in extrusion process optimization. |
| 46 | AbdulrahmanAlber et al., 2019 [63] | Presented an 'active extrusion system for 3D printing' of cement-based for building sector, designed from first principle to allow extension to other materials. | Achieving greater geometrical accuracy in structures with improvements in control of extrusion process in printing. |
| 47 | Bong et al., 2019 [64] | Investigated the impact of mixture factors, such as the type of hydroxine mix and the type of silicate solution, on extrudability, regain of shape, and mechanical performance to optimize the ambient temperature cured geopolymer for 3D printing in the construction industry. | Enhancing scope of 3D printable cement-based materials, techniques of reinforcing in components of building, establishment of standards and overall cost reduction to be focused. |
| 48 | Lee et al., 2019 [65] | In order to extend the discussion, this study used text-mining-based association analysis referring to articles published over the past 20 years that identify 3D printing research trends which allowed to pinpoint the areas of study required for 3D printing in the building sector of the future. | Necessity of performing performance evaluation and cost analysis of 3D construction printing for promoting adoption of 3D printing in building sector. |
| 49 | Xia et al., 2019a [66] | The authors of this paper had recently created a novel process for geopolymer creations to intersect the requirements and demands of widely available powder-based 3D printers. | Investigating adjustment of power formulation and selection of most effective post processing method for enhanced characteristics of printed models with the use of improved cementitious materials. |
| 50 | Ghaffar et al., 2018a [67] | The crucial roles of transdisciplinary research and the significance of material formulations were highlighted. | Attempts shall be mad to incorporate ReSOLVE principle (Regenerate, Share, Optimize, Loop, Virtualize& Exchange) in a systematic manner for promoting circular resource efficiency adoption. |

## 3. Research Methodology

To gain knowledge, a systematic investigation of existing research work is carried out by referring the articles and published papers. In this review paper, data collection and selection are done by content analysis and qualitative method. Articles depicting the feasibility, scalability, opportunities, and challenges of 3D printing technology in the construction industry were evaluated to have a clear perspective. We identified a plethora of research articles counting more than 150 out of which, after filtering with keywords '3D Printing Technology' and 'Construction Industry', 124 articles were reviewed from google scholar search engine published by publishers namely – Tylor & Francis, Springer, Elsevier, MDPI, IEEE, ASME, ASCE, Wiley, Trans Tech, IOP Science, Hindawi etc.

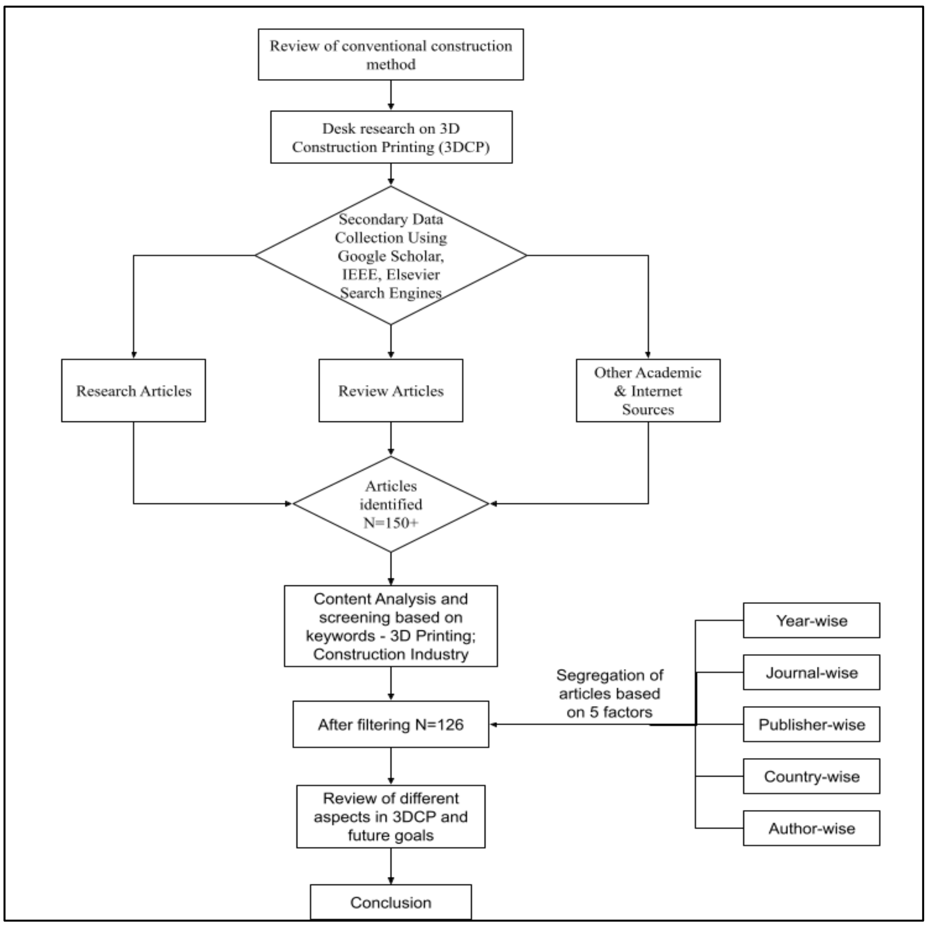


Fig. 2. Research Methodology

### *3.1. Research Objective*

Conventional construction process has some serious issues with sustainability. The waste generation and carbon generation in this process are of higher amount. The time period of building a house or any structure is quite long. Some buildings even may take months to build. Moreover, it becomes difficult to build a house in remote areas and where remote conditions are not suitable. Also, the noise pollution and dust spread makes the vicinity inconvenient. Introduction of 3D construction printing or 3DCP can prove to be a great change in construction industry and can resolve the mentioned issues of conventional construction. But as this process is new in the sector, there's scepticism about its potential in clients and contractors. Thus, more convincing thoughts and facts are to be presented with durable projects which already are being encouraged by many companies. The investigation is conducted with respect to the research questions we collected and recorded systematically and gathered the required information accordingly referring to the existing studies on relevant topics of discussions.

*3.2. Graphical Representation of Research Articles DataBase*

The research and review articles collected were investigated and are graphically presented on the basis of year-wise publications, journal-wise publications, publisher-wise publications, and country-wise publications. This study helps to understand the trend of technology and its application and hype among industry and people. The collected articles were stratified based on keywords relating to the subject of discussion – 3D Printing in Construction Industry.

*3.2.1. Research Articles DataBase Year-Wise*

The trend represents increased research on 3D printing in construction industry in the year 2021. The 21st century is often referred to as the digital age. The technology behind 3D printers has made some significant strides in recent years. Printing is now easier, more economical, and more accessible as a result of these improvements. Hence, 3D printing is proving to be an emerging and beneficial technology in this industry. Other possible reasons for more research publications in the year 2021 are –

- *Increasing use of 3D construction printing:* Many construction organisations are implementing 3D printing to increase productivity, shorten construction times, and reduce waste. It's possible that the greater use of 3D printing in the building sector may result in more studies and publications on the topic in 2021.
- The construction sector is becoming increasingly concerned with sustainability, and 3D printing technology offers the potential to cut waste and minimize the carbon impact of construction projects. As a result, there might be a rise in demand for studies and publications on this subject in 2021.
- *COVID-19 Pandemic*: The COVID-19 pandemic has caused disruption in the building sector, demanding the development of fresh, creative ideas. Several of the difficulties brought on by the pandemic, like supply chain interruptions, labour shortages, and social segregation measures, might have been resolved using 3D printing technology. This might have prompted further study and writing on 3D printing in the construction sector in 2021.
- *Advancements in 3D Printing Technology*: In 2021, there may be a greater interest in studying and publishing on 3D printing in the construction business because of advancements in 3D printing technology, including the development of new materials and printing techniques.

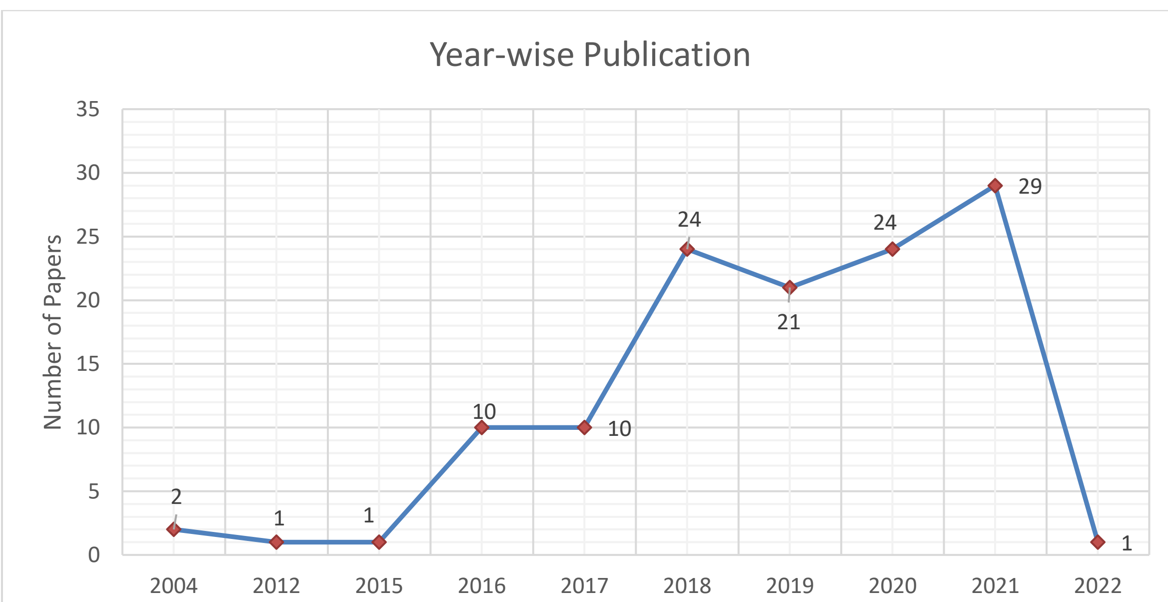


Fig. 3. Year-wise Publications[4], [19]–[108]

*3.2.2. Research Articles DataBase based on Publishing Journals*

Analyzed trend showed inclination of authors towards ‘Automation in Construction’ and ‘Construction and Building Materials’ journals than other available journals as these journals directly relate to the ‘3D Printing Technology’ and ‘Construction Industry’ keywords and tend to be perfect for these research articles. Other possible reasons for more publications published in journal of ‘Automation in Construction’ and ‘Construction and Building Materials’ are –

- Relevance: Both 'Automation in Construction' and 'Construction and Building Materials' are very important journals for the construction sector. They concentrate on subjects including building technology, building materials, and construction automation, all of which are pertinent to 3D printing in construction. As such, authors may opt to publish their research in these journals since they are more likely to find an audience interested in their work.
- Peer review: The rigorous peer-review procedures used by "Automation in Construction" and "Construction and Building Materials" ensure that the published research satisfies high levels of quality. Since they appreciate the peer-review process and want to make sure that their research is thoroughly examined before publication, authors may decide to publish in these journals.
- Impact factor: Construction and Building Materials and Automation in Construction both have significant impact factors (7.693 and 10.517 respectively), demonstrating their importance in the construction sector. Authors are inclined to publish in these journals to increase the visibility and impact of their work.
- Editorial focus: The editorial policies and primary areas of journals vary. The topics of "Automation in Construction" and "Construction and Building Materials" are particularly suited to the issue of 3D printing in construction because they both have a specific focus on construction technology and materials. As such, authors may opt to publish in these journals because they find that their study aligns well with the editorial focus of the publication.

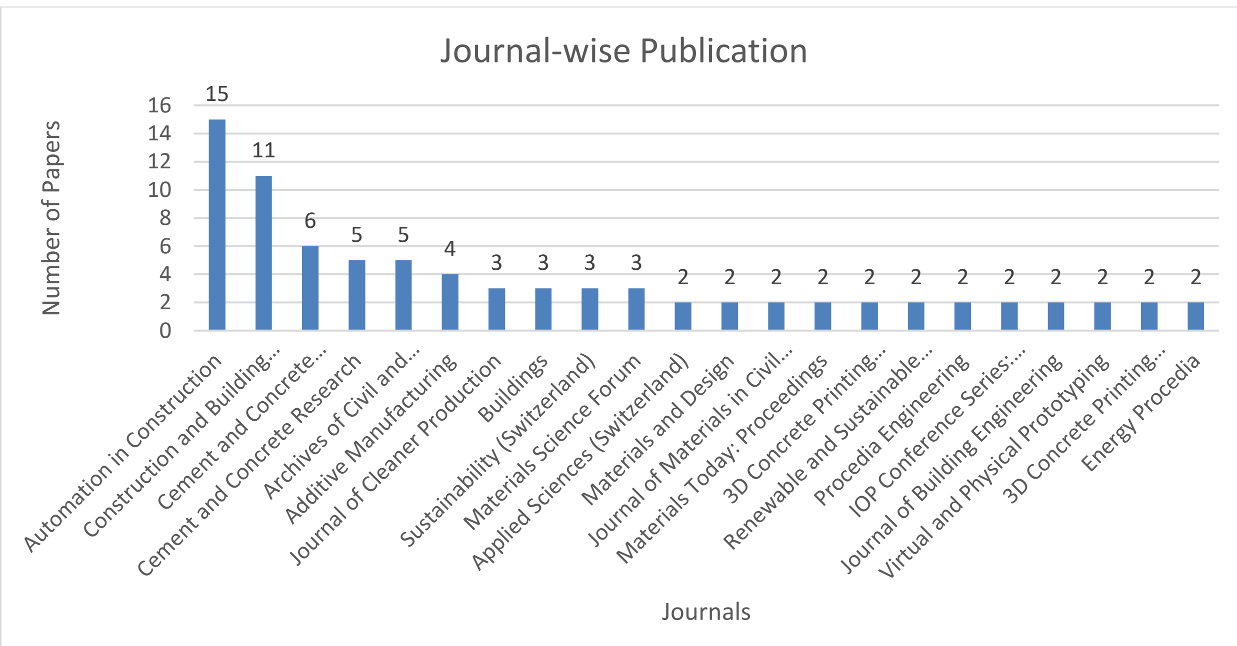


Fig. 4. Journal-wise Publications

*3.2.3. Research Articles DataBase Based on Publisher*

Elsevier is leading in total number of articles published followed by MDPI. Most of the authors prefer Elsevier as Elsevier journals have high impact factor because of its reputation for publishing high-quality peer-reviewed research. Also, it takes around 2.4 weeks on an average for an article to get published which appears to be the least among all with an acceptance rate of around 32%. Peer reviewers are valued for determining the significance, validity, and originality of published articles, whose expert suggestions help to improve the research and manuscript. Other possible reasons for authors to choose publisher 'Elsevier' over other publishers are –

- Reputation: Elsevier is one of the largest and most well-known academic publishers in the world. They are known for providing top-notch research in a variety of disciplines, including engineering and construction. As such, authors are inclined to publish with Elsevier because of their reputation and trustworthiness in the academic world.
- Impact factor: Elsevier journals have high impact factors, showing that they are significant in their respective domains. Because they want their study to have a bigger impact and reach more people, authors prefer to publish with Elsevier.
- Variety of journals: Elsevier publishes a wide range of journals in the domains of engineering and construction, including journals expressly focused on 3D printing in construction. Writers may opt to publish with Elsevier since they can discover a journal that is precisely suited to their study area.
- Editorial focus: The topic of 3D printing in building is a good fit for Elsevier journals in this domain's particular editorial focus. When authors feel that their research aligns well with the editorial objective of a journal, they are inclined to publish with Elsevier.

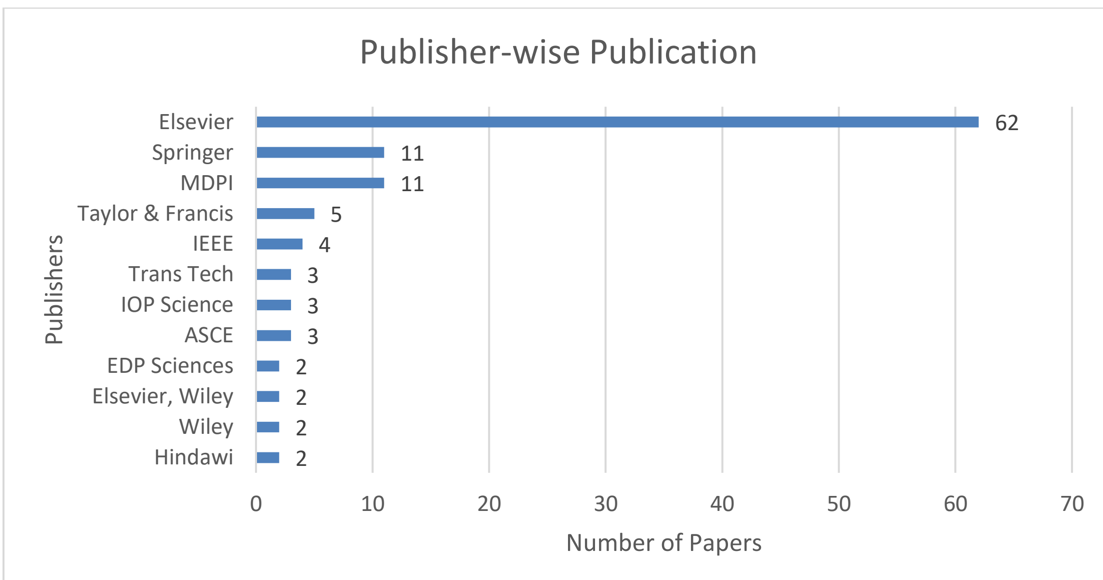


Fig. 5. Publisher-wise Publications

*3.2.4. Research Articles DataBase Based on Countries*

Focusing on development in terms of technology, Australia is seeming to be more inclined towards research on 3D Printing Technology and its application in construction sector. Australia contributed 4.1% of the world's published research in 2020 while having only 0.3% of the global population, placing it among the top 10 research contributors globally. Authors from Australia published 23+ (Considering unlisted articles which couldn't be collected due to limitation by search engines used) articles followed by 16+ articles by authors in China. With reference to the generated trend, India is listed at rank 5. This depicts India's interest in 3D construction printing, possibly due to successful trials by Startups and Construction Companies in India. Other possible reasons for countries like Australia and China to have more research publications than other countries are –

- Research funding: In recent years, nations like Australia and China have made large investments in 3D printing research. The establishment of research facilities and projects that concentrate on 3D printing in building has been facilitated by this financing. Research outputs in these nations may have increased as a result of funding availability. The governments of Australia and China both promote and fund research and innovation. For example, Through the Australian Research Council's Discovery Early Career Researcher Award funding programme, the Australian Government provides funding for numerous research articles. [75].
- Industry demand: Both Australia and China have busy and rising construction businesses that are interested in embracing 3D printing technology. There may have been more research done in these nations to meet the demand due to the industry's need for this technology. Numerous 3D printing technologies have been created in recent years and used in the construction sector. For example, in Australia, in order to create site-specific architectural structure systems, in a research article by Keating et al. (2017), author(s) designed a digital construction platform that consists of hydraulic and electric robotic arms. Author Wu, Wang, and Wang (2016) provided an overview of the advancement of 3D printing technology and their applications in the building sector. Another author Li et al. (2017) created an integrated platform for building information modelling (BIM) to increase prefabrication's productivity [75]. Due to rising implementations, there has been a growth in the demand for research in this sector.
- Academic institutions: Australia and China have several prestigious academic institutions that focus on research output. Additionally, these organisations have set up initiatives and research facilities devoted to 3D printing in construction. The emphasis on research output may have led to a greater number of publications in these countries.
- International Collaboration: Researchers in Australia and China have partnered with other scholars from around the world on projects relating to 3D printing in construction. More research outputs and publications are the results from international Collaboration.

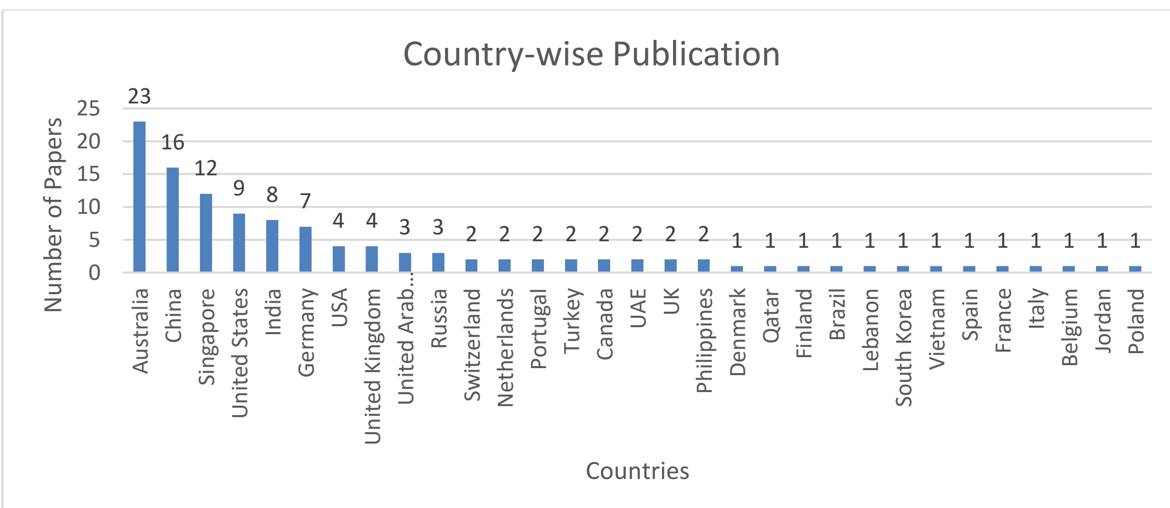


Fig. 6. Country-wise Publications

### *3.2.5. Research Articles Based on Keywords*

To depict the frequency of keywords used by various researchers in their respective research works, the frequency of publications was examined and created on a Pareto Chart. The primary and secondary focus of a research article, as well as its subject matter are based on its keywords. Primary and secondary keywords are shown in Table 1. The Pareto chart of the keywords utilized in various research articles is shown in Figure 7.

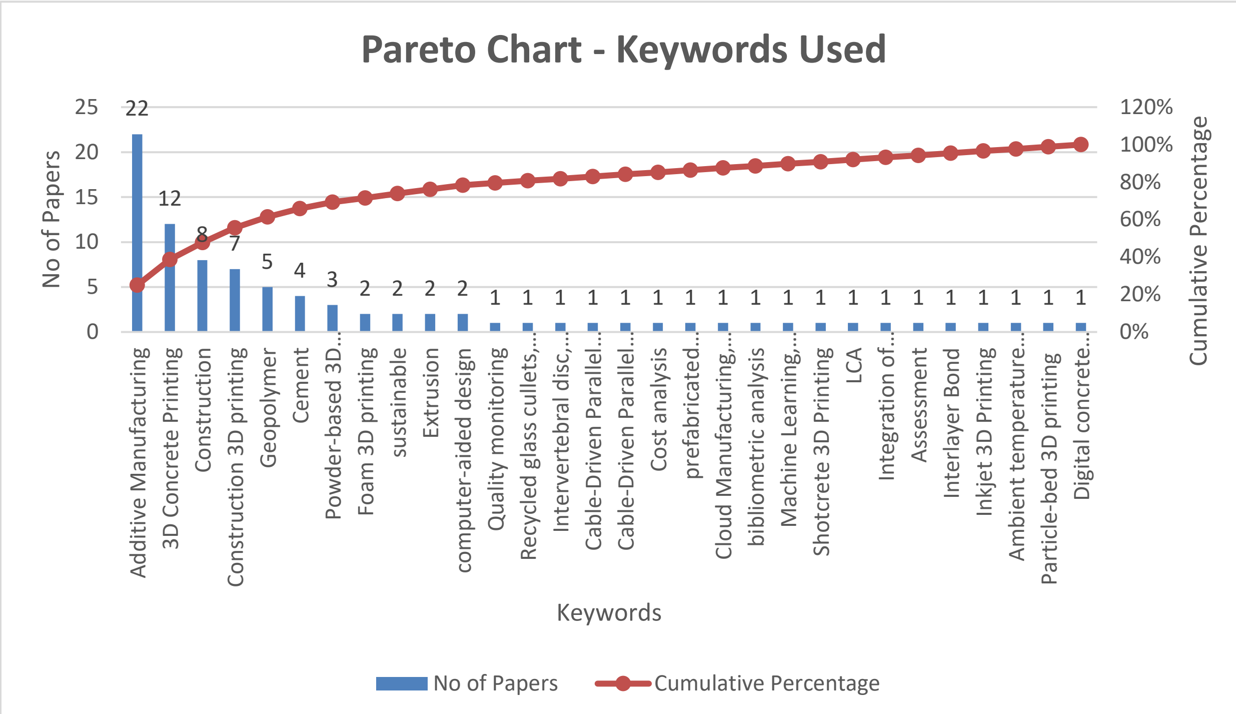


Fig. 7. Keyword-wise publications

## 4. Effect of 3D Construction Printing

### *4.1. Effect on Environment*

3D printing technology has been considered as the safer and sustainable alternative for manufacturing a product. There is a lot of material waste, formwork waste in case of conventional construction method, whereas in 3DCP, there is no material waste as such[37]. Moreover, it does not require any supporting structures or formwork. Also, being an electrically powered machine, less carbon footprints can be seen as compared to the conventional construction which uses multiple machines including concrete agitators[64]. 3D construction printing is also safer method, avoiding major fatalities which occur in conventional construction, reducing labour fatigue[94]. As this technology is proceeding, numerous advantages are coming on the surface which may reduce the scepticism from clients and contractors [18]. Buildings with 3DCP method will be more sustainable and the durability of the structure will be assessed based on material [2]. Due to increase of people’s standard of living and increase in population, construction industry is experiencing a rapid growth [3]. Rapid Growth of this technology for construction now depends on this new technology’s parameters, the level of sustainability and adverse effects on the environment it causes. The material used in this technology greatly contributes to the green environment as it can use materials like raw soil, geopolymers, peat, glass, recycled construction waste products, organic materials etc. while, conventional construction uses highly industrialized materials which have detrimental impact on environment [109] mainly because they are manufactured by non-sustainable methods [3]. Selection of material can directly impact the energy requirement for the printing process [8]. They require high energy consumption for the production as well as transportation [3], [8]. As compared to the conventional construction, results of environmental assessment have shown that for intricate geometries, 3DCP is more sustainable [110]. Moreover, being electrically operated, the 3D printers tend to reduce the environmental impact to a great extent [109]. The main advantage of this technology is that the materials can be recycled to reuse in the future projects thereby requiring less material [8], [110].

### *4.2. Effect on Cost*

Construction industry plays an important role in economic growth and development of the country [3]. The use of 3D printing technology imposes a new challenge in management function of the construction i.e., cost estimation [111]. Hence it is a hurdle to estimate the cost of construction with accuracy. Also, the initial cost of the printer is high and uncertain, which may cause uncertainty in buying the product[52]. On the other hand, construction cost is lesser than that in conventional construction because of precise use of materials and other significant benefits arriving with this technology [111]. For large scale applications, the printers are highly expensive and running maintenance requirements would pose cost increment of the project, but the price is expected to reduce with time due to increasing competition between the companies [111], [112]. The cost of construction for 3DCP is less as it reduces the required construction elements, reduces the transportation and inventory cost of materials [113], [114], and with only one operator needed for operation – labour cost is also reduced [111][35]. 3DCP can give great cost saving on waste reduction as compared to conventional method as the latter accounts for 30% of the cost only in formwork which in case of 3DCP is not required [6]. Also, as mentioned in [115], compared to buildings constructed with CMU (Concrete Masonry Units), 3D printing construction could save 10 to 25% of the total cost, and was 25 to 37% cheaper than the on-site casting construction [109].

## 5. Advantages and Challenges of 3D Printing Technology in Construction Industry

### *5.1. Advantages of 3D Printing Technology in Construction Industry*

With reference to the articles reviewed in this paper, the 3D printing technology in construction industry is identified[3] to be most useful and advantageous method which can replace conventional construction method in terms of time of construction[5], [111], [116], eco-friendliness, freedom of geometry of structures[3], [5], [8], [111], free from formwork[111], [117] and most crucial of all – the safety of workers[5], [8], [111] while working. The advantages are discussed in Table 5. Top and widely discussed advantages are listed in the table, which make this technology a beneficial technique that can be adopted for civil construction purposes.

Table 2. Advantages of 3D Printing Technology in Construction Industry

| Sr. No. | Advantages | Description | Reference |
|---|---|---|---|
| 1 | Eco-Friendly Technology | The 3DCP technology is introduced with the benefits of reducing waste generation in the process of construction. The material used can be raw soil and natural waste or it can be plastic which would result in less carbon footprints as compared to the conventional construction method. | [3] |
| 2 | Faster Construction than conventional method | Reducing the time of construction would benefit the contractor to get the project done and move on the next one, thereby making more revenue. The speed of construction in case of 3DCP is much faster than that of traditional method. A house can be printed using 3DCP in 24 hours. This would help grow the production rate and would aid in mass production of the buildings and/or structures. | [5], [111], [116] |
| 3 | Architectural Freedom | 3DCP will eliminate and the restriction on geometrical freedom in conventional construction and enable architects to create complex, aesthetic shapes in the building. | [3], [5], [8], [111] |

| | | | |
|---|---|---|---|
| 4 | Formwork free construction | Reduction in use of formwork is another advantage of this technology. The given part can be moulded on-site without any prior support structures or formworks. | [111], [117] |
| 5 | Increased Safety | Safety has always been a great concern in construction industry as any fatality or injury would cause the individual, the organization a major loss. It is a safer alternative to the conventional construction process due to digital and automation technologies. | [5], [8], [111] |

*5.2. Challenges of 3D Printing Technology in Construction Industry*

Every new technology has significant drawbacks in addition to its potential advantages. By looking through the database of published research articles, the limitations of 3D printing technology in the construction business are examined. Some important but major restrictions are addressed in following Table 6 which include Less employment opportunities[1], more time for production of structures and eventually leading to higher overall cost[118], substantial usage of electricity[3] than that in conventional methods of construction, impact on health of working individuals[119], material testing and development[109], risks with reference to cybersecurity and liability[111], transportation of the 3D printer to the site[8], lack of standardization[5] etc. which may affect the adoption rate of this technology by society. Hence challenges were identified to understand and address the shortcomings of this emerging technology – 3D printing in construction industry, so as to plan the resultant approaches to be taken towards the challenges and solve the same and hence promote the adoptability, applicability and reliability of this new technology.

Table 3. Challenges of 3D Printing Technology in Construction Industry

| Sr. No. | Challenges | Description | Reference |
|---|---|---|---|
| 1 | Fewer employment opportunities | With 3DCP overtaking conventional construction method, employment opportunities will reduce for unskilled labours. | [1] |
| 2 | Longer production time and higher overall cost | Even by having less labour and material usage, the overall cost of the project is will be higher. Also, production time can be longer, and size of the part is limited by size of the printer, unlike conventional construction method. | [118] |
| 3 | More electricity consumption than that in conventional method | Due to the use of a printer, the consumption of electric energy is more (about 100 times) than in conventional construction. | [3] |
| 4 | Change in indoor air quality of 3D printed house | If the use of additives (to speed up the layer solidification) is made, it would change/modify the quality of air inside the structure. | [119] |
| 5 | Impact on workers' health | During printing, due to material nature, ultrafine particles might emit and affect the health of the worker. | [119] |
| 6 | Difficulty in Rheological properties control | Controlling rheological properties like printability, buildability, open time, extrudability is a major challenge in 3D concrete printing. | [5] |
| 7 | Unfavourable construction site | Construction sites are often in open environment which are not suitable as printers need more controlled environment. Also, the uneven base/land may also hinder the accuracy of printer's movement. | [5] |

| | | | |
|---|---|---|---|
| 8 | Lack of standardization | Being a new technology, there is lack of standardized codes to be followed. | [5] |
| 9 | Complex cost estimation | With the required accuracy, it is difficult to estimate the project cost since the construction cost will vary due to competition while initial cost will be uncertain, depending on the printer. | [111] |
| 10 | Scepticism by society | There is scepticism of clients, contractors, designers on the potential of 3D printing technology, partially due to lack of knowledge about the technology. | [111] |
| 11 | Material Challenge | Due to limited range of available printable materials using 3D printing technology, a separate mixture for given situation might be needed to be prepared. | [109] |
| 12 | Increased material Cost | The 3D printing material is different, having printability, buildability, and open time, it may cost more than traditional cement, thereby increasing construction cost. | [111] |
| 13 | Cybersecurity issues | As 3D printing is led by a 3D CAD model, there is a risk of data theft, network breach, thereby causing financial loss to the stakeholders. Work interruption may occur due to viruses implanted by hackers. | [111] |
| 14 | Liability risk | Different people are responsible in 3D printing technology and parts; thus, it is difficult to decide as to who is responsible for a failure. | [111] |
| 15 | Necessity of cantilever parts | Printing cantilever parts is a major challenge for 3DCP method. | [8] |
| 16 | 3D Printer transportation challenge | It is difficult to transport the heavy and large size 3D printer to the construction site, which adds cost to the overall project. | [8] |

## 6. 3D Printing Technology in Construction Industry in Industry 4.0

The next industrial revolution is based on digitalization which can change the system of manufacturing and the method of governing, management of the system etc. The existing new emerging technologies consist of Internet of Things (IoT), big data, virtual reality (VR), Augmented Reality (AR), robotics, autonomously propelled vehicles, drones, photogrammetry, cloud computing and collaboration, robotics and 3D printing [120], [121]. A direct connection in people's standard of living and the material and method of construction process can be seen as Europe has 40% of its energy consumption in building sector and about 36% of the greenhouse gases are emitted in the EU from the construction sector [2]. Thus, the transition this sector seeks is innovation that can reduce waste and increase its productivity and efficiency [122], [123]. As the construction is project based, the stakeholders are more and clients, contractors, subcontractors, engineers, architects, and vendors, all need to cooperate in this project. Thus, the emerging technology – 3DCP can prove to be best suited for the job with its faster and economic way of working [120], [124] and can bring the necessary technological improvement in the AEC (Architectural Engineering and Construction) sector with industry 4.0.

## 7. Limitations of Review Research

The review study conducted had a few limitations, one of them is the study's sole data source, Google Scholar. Though it contains the most prominent journal articles in the subject, it does not include all of them, which could have had an impact on the study's findings. This study's search was restricted to the terms "3D Printing Technology" and "Construction Industry", which is another drawback. During the study, additional components of the technology like types of 3D printing process used in construction industry, material mix design and development were not considered. Therefore, the results might not be indicative of the full body of work on 3D Printing in Construction Industry as a result. Despite these shortcomings, the study's findings provide better insight into the structure and substance of academic papers on this subject.

## 8. Future Research Avenues

R1. Optimization of 3D printing parameters for construction materials:
*R1.1.* Machine learning and artificial intelligence (AI) algorithms for optimizing printing parameters based on material properties, geometry, and structural requirements.
*R1.2.* Integration of on-site monitoring and control systems to optimize printing parameters in real-time.

*R2. Study of material properties for construction 3D printing.*

*R2.1.* Investigation of the compatibility of existing construction materials with 3D printing technology.
*R2.2.* Exploration of the effect of material composition, microstructure, and processing parameters on the mechanical, thermal, and chemical properties of 3D printed materials.
*R2.3.* Development of advanced characterization techniques to evaluate the microstructure and properties of 3D printed materials at different length scales.
*R2.4.* Study of the long-term durability and stability of 3D printed materials and structures under various environmental conditions.
*R2.5.* Investigation of the performance of 3D printed materials in extreme environments such as high temperature, high pressure, and radiation.
*R2.6.* Exploration of bio-inspired and bio-mimetic materials for 3D printing in construction.
*R2.7.* Investigation of the use of recycled and sustainable materials for 3D printing in construction.
*R2.8.* Development of new materials with specific properties that are suitable for 3D printing in construction.
*R2.9.* Development of multi-material printing techniques to create structures with graded or heterogeneous material properties.
*R2.10.* Exploration of novel feed stocks, such as biomaterials, composites, and nanoparticles, for 3D printing in construction.
*R2.11*. Development of new binders and additives that can improve the strength, durability, and sustainability of 3D printed materials.

*R3. Investigation of the scalability of construction 3D printing.*

*R3.1.* Developing larger and faster printers: Research can be done to develop bigger, faster 3D printers that can print larger structures in less time. This increases the scalability of 3D printing in construction.
*R3.2.* Increasing the printing speed: Research can be conducted to increase the printing speed of 3D printers. This can help to reduce the time required to print structures, making the technology more scalable.
*R3.3.* Scaling up the supply chain: The supply chain for printing materials and equipment must be scaled up to increase the scalability of construction 3D printing. Research can be conducted to optimize the supply chain and reduce costs associated with printing materials and equipment.

*R4. Investigation of the use of 3D printing for retrofitting existing buildings.*

*R4.1.* Development of retrofitting techniques: new methods and procedures for using 3D printing to upgrade existing buildings can be developed through research. New materials, design approaches, and software tools for retrofitting with 3D printing could all be part of this.
*R4.2.* Evaluation of structural performance
*R4.3.* Cost-effectiveness: Buildings that are already in use can be costly and time-consuming to retrofit. The cost-effectiveness of using 3D printing for retrofitting can be evaluated, taking into account costs associated with materials, labour, and time.
*R4.4.* Environmental impact: The utilization of 3D printing for retrofitting existing structures might have ecological effects, like the utilization of energy and materials. The use of 3D printing for retrofitting has the potential to have an impact on the environment, and sustainable solutions can be developed through research.
*R4.5.* Real-world case studies: Real-world case studies of 3D printing to upgrade existing buildings can be the subject of research. A focus on various building types, climates, and locations could be part of this.

*R5. Study of the impact of 3D printing on the construction supply chain.*

*R5.1.* Supply chain optimization: In the context of 3D printing, new models for optimizing the supply chain can be developed as well as the key factors affecting the supply chain, such as material availability, transportation, and storage, can be identified through research.
*R5.2.* New business models: On-demand printing is one example of a new model that can be studied for its viability and impact on the construction supply chain.
*R5.3.* Quality control and assurance: new methods, like non-destructive testing and inspection, can be developed for ensuring the consistency and quality of 3D-printed components.

*R6. Development of new construction methodologies for 3D printing.*

*R6.1*. Multi-material printing: new printing methods for multi-material construction can be developed and the potential advantages of this method, such as increased strength, durability, and energy efficiency, can be investigated.
*R6.2*. Continuous printing: new methods for continuous printing in construction can be developed through research, and the feasibility of this method in terms of material handling, printing speed, and quality control can be evaluated.
*R6.3*. Hybrid construction methods: new methods for hybrid construction in 3D printing can be developed through research, and the potential advantages of this strategy in terms of cost, time, and performance can be evaluated.
*R6.4.* Smart construction: In 3D printing, new methods for smart construction can be developed and the potential benefits of this approach, such as improved energy efficiency, occupant comfort, and safety, can be investigated.
*R6.5.* Construction on demand: New on-demand 3D printing construction methods can be developed and their viability and efficacy in various contexts can be evaluated through research.

*R7. Integration of sensors and other monitoring devices into 3D printed structures.*

*R7.1.* Development of new sensing technologies that can be embedded into 3D printed structures, such as fibre optic sensors, piezoelectric sensors, and strain gauges.
*R7.2.* Monitoring of the building's structural health: Sensors can be incorporated into 3D-printed structures to track the health of the structure, as well as its structural integrity, temperature, humidity, and other elements that may have an impact on how long it lasts.
*R7.3.* Automation systems for smart 3D Printed buildings can be combined with sensors and other monitoring tools to provide more energy-efficient, secure, and occupant-responsive structures.
*R7.4.* Predictive maintenance: By continuously checking on the condition of 3D-printed structures, sensors can identify when maintenance or repairs are necessary, enabling proactive maintenance that lowers downtime and repair costs.
*R7.5.* Energy conservation: 3D printed structures can be created with built-in sensors that track energy use and improve energy conservation. This may involve sensors that modify the lighting, heating, and cooling systems depending on the number of occupants and other variables.
*R7.6.* Analysing real-time data on 3D printed building performance, occupancy rates, and other crucial parameters is possible with IoT (Internet of Things) gadgets and Big Data Analytics. The efficiency and sustainability of the building as a whole can be enhanced using this data.

*R8. Study of the structural integrity and durability of 3D printed buildings.*

*R8.1.* Scaling up: Most 3D printed buildings to date have been relatively small in size. Future research could focus on scaling up the technology to enable the construction of larger structures, such as commercial buildings or multi-story apartment complexes.
*R8.2*. Real-time monitoring and feedback: Real-time monitoring of 3D printed structures during construction could enable early detection of structural issues and allow for adjustments to be made. Future research could focus on developing new monitoring and feedback systems that can provide real-time data on the construction process.
*R8.3.* Smart materials: The use of smart materials in 3D printing can enhance the durability and structural integrity of

buildings. For example, self-healing materials could repair any cracks or damage in the building over time, while shape memory alloys could provide enhanced seismic resistance.

*R9. Investigation of the use of 3D printing in the production of infrastructure components such as bridges, dams, and tunnels.*

*R9.1.* Research in Component customization: There is a need of Component customization by 3D printing technology, which is particularly advantageous for infrastructure projects. In order to build components that are specifically suited to the requirements and limits of bridges, dams, and tunnels, 3D printing can be used.
*R9.2.* Research in improved durability: Investigation is needed to make the 3D Printed Components stronger and more durable than those made using conventional manufacturing processes. This is crucial for infrastructure projects since they frequently call for parts that can survive harsh weather and other environmental considerations.
*R9.3.* Research in Improved speed: Investigation is necessary to further increase the speed of 3D printing. This might be especially helpful when there is an urgent need for repairs.
*R9.4.* Research in reduction of Cost and waste is vital for extensive adoption of 3D printing construction-3D printing can assist in lowering the cost of producing infrastructure components by eliminating waste and increasing efficiency.

*R10. Exploration of the use of 3D printing for creating unique and intricate architectural designs.*

*R10.1.* Advanced design software: It is necessary to develop new software that will enable architects and designers to design new intricate structural geometries that can be printed quickly without sacrificing aesthetics or structural integrity.
*R10.2.* New printing materials: It is necessary to develop new materials that enable architects and designers to create distinctive designs that are impossible to achieve with conventional building materials.

## 9. Summary and Conclusion

To comprehend the significance of and impact of 3DCP technology in the construction sector, a literature review was conducted. The following five key advantages were found: safety, quicker construction, architectural freedom, formwork-free construction, and environmental friendliness. Despite the difficulties it currently faces, this technology holds promise and can revolutionize the way the construction industry operates today. The lack of understanding about this technology is the cause of the current scepticism, but with time and continued work by researchers and 3DCP companies, more and more buildings and structures will be constructed utilizing this technology. After reviewing more than 120 publications, 16 number of Challenges are derived. Graphs are plotted to analyze the existing body of knowledge. Inferences are derived based on the plots. This research paper gives a set of valuable ~50 number of Research avenues based on the review conducted. In relation to 3D construction printing, more creative, environmentally friendly, and economically viable processes have been introduced and are still being developed by researchers in the relevant fields, which will increase the likelihood that the public and business professionals will adopt this new technology. The current technological limitations of electric consumption, rigidity, material stability, material enhancement, material availability, favorable environmental conditions, and height constraint dependent on equipment/machine height will be resolved in the near future if the pace of advancement continues to increase as it has in the previous ten years.

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## CONFLICTS OF INTEREST

The authors of this paper declare that they have NO personal relationships or competing interests that could have appeared to influence the work reported in this paper.

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