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A Review of Challenges, Innovations, and Future Directions in 3D Printing for Building Projects

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Abstract

In recent years, robotic construction using 3D printing has shown significant potential for transforming the construction industry. 3D printing has become a promising approach in construction, enabling engineers and managers to create models with precisely controlled, complex architecture, shapes, and surface coatings. This review article aims to provide an overview of the challenges, innovations, and future paths in 3D printing within the construction industry. The research methodology is based on a literature review from 2020 to 2025, utilizing relevant keywords from various sources. In conclusion, while 3D printing in construction offers many opportunities, challenges such as material limitations, high initial costs, and regulatory concerns must be addressed. Future research should focus on developing new materials with enhanced properties and establishing regulatory frameworks to promote the widespread use of this technology in sustainable construction.

Keywords: 3D printing, Construction Management, Artificial intelligence in construction, Additive Manufacturing in Construction

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1. Introduction

1-1 General Background

Researchers and industry specialists have paid significant attention to using 3D printing in construction recently. This is primarily because it can potentially transform the way construction is done. This technology could help address critical issues in the construction sector, such as labor shortages, environmental concerns, and the need for cheaper building options[1]. The ability to create complex shapes using fewer materials, requiring fewer workers, and achieving better precision has made 3D printing an essential part of new construction methods[2]. In recent years, the application of 3D printing in construction has attracted the most attention, particularly from researchers and professionals involved in this industry. This is potentially due to its ability to revolutionize construction. Moreover, automation might solve construction problems in the final quarter of the 21st century—labor shortages, environmental concerns, and the need for more affordable buildings[3, 4]. Due to its ability to produce complex geometries while requiring fewer resources and better precision, 3D printing has become an essential part of new, non-traditional construction strategies[5]. Using 3D printing technology in construction can reduce construction costs by up to 40% and decrease project completion time by almost 70%, making it a favorable option for both large and small-scale implementations[6]. However, these challenges emerge underground as some of the most significant barriers to consumer adoption of such technologies, from developing suitable printing materials to ensuring quality in printed structures and the final inflation appearance[7, 8]. The technical complexity of 3D printing in construction requires specialized material design and production that must meet the specific printability needs and strength and durability requirements[9]. Such materials must exhibit specific rheological properties and ensure they can be extruded through printing nozzles, maintain their shape, and achieve sufficient strength after curing[10]. Additionally, the combination of various additive materials both increases the chances and presents the risks of optimizing mechanical properties and durability features[11]. However, these advantages come with challenges that may need to be addressed before the widespread realization of 3D printing in construction. These challenges include substantial capital costs associated with machinery and raw materials, specialized workforce training requirements, and final quality control implementation[12]. Furthermore, a critical barrier is a lack of a regulatory framework and building codes specifically for 3D printing[13, 14]. This research aims to provide a comprehensive overview of the emerging challenges and innovations in construction 3D printing technology, including material properties, quality assurance standards, and regulations. This paper seeks to bridge current research gaps through systematic literature analysis and case studies and recommends overcoming practical challenges, paving the way for enhanced adoption of 3D printing technology in the construction industry.

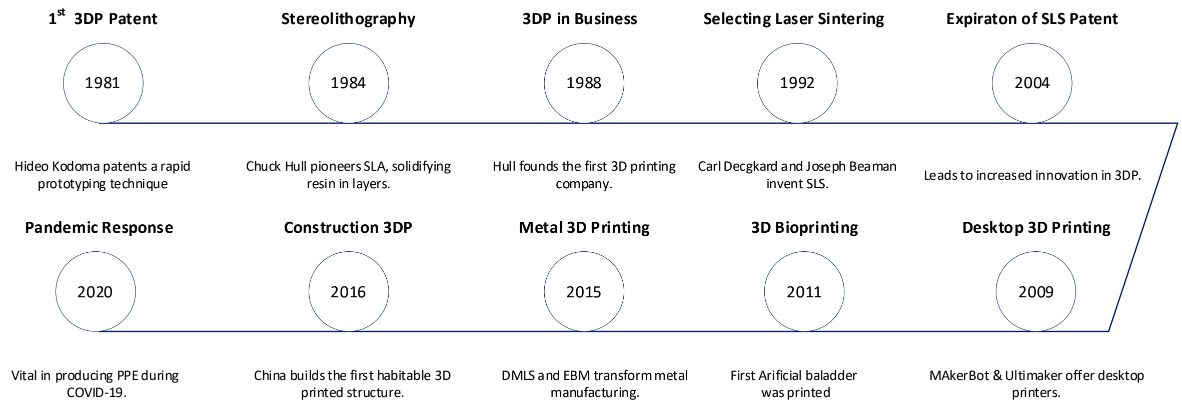

Fig 1: Milestones in 3D printing

1-2 Research Problems

This research problem is based on the technical and knowledge barriers that hinder the implementation of 3D printing technology in construction. While this technology has significant potential, it also presents specific challenges:

a: Material Development: New building materials must be developed specifically for 3D printing applications. Their appropriate mechanical and thermal properties are essential for ensuring the safety and durability of structures.

b: Quality Assurance: Structural safety and long-term durability are serious concerns since many projects lack reliable standards for the quality and reliability of printed structures. This is the greatest challenge, as no standard testing protocol or quality control exists.

c: Regulatory Challenges: The lack of a framework and laws for 3D printing in construction limits its widespread acceptance.

d: High Initial Capital Costs: The equipment and materials used in 3D printing require a high initial investment, which remains the primary barrier for most businesses adopting this technology for conventional construction projects.

1-3 Research Objectives

The goal of this research is to achieve the following:

- **Challenge Exploration**: To deeply examine the technical requirements and regulatory barriers in 3D printing technology used for building construction, focusing on material development and quality assurance.
- **Innovation Exploration**: To explore innovations in recent construction materials used for 3D printing and techniques to enhance these materials further to meet the necessary print properties and structural demands.
- **Practical Recommendations**: To provide valuable recommendations for addressing current challenges, including developing new quality standards and regulatory frameworks for 3D printing in construction.
- **Impact Assessment**: To assess the economic and environmental sustainability benefits of 3D printing technology compared to traditional construction methods.
- **Practical Applications**: To showcase effective applications of 3D printing technology in modern building projects, highlighting how this technology can be utilized in today's work.

This research is essential as it may help bridge the gap between theoretical knowledge and practical implementation of 3D printing technology in construction. By addressing these objectives, this study aims to contribute to the construction technology field and provide an optimal framework for building with 3D printing. This study is timely as there is a growing need for innovative and efficient construction solutions. The results and recommendations of this research will be valuable information for many stakeholders (construction professionals, researchers, and policymakers) involved in developing 3D printing applications in construction.

1.4 Literature Review

In 2015, Isaac Perkins and his colleagues conducted a study titled Three-Dimensional Printing in the Construction Industry: A Review. This study reviews the current state and future potential of 3D printing in the construction industry, examining its ability to automate production, accelerate building processes, and reduce material waste. The paper outlines three leading 3D printing techniques—contour crafting, concrete printing, and D-shape printing—that minimize waste using only the necessary materials. While 3D printing offers advantages such as faster construction times, reduced labor costs, and integration with building information modeling, challenges remain, including high costs, limitations in material selection, and unsuitability for large-scale projects. Additionally, most successful applications have been confined to laboratory settings, and real-world feasibility remains uncertain[15].

In 2016, Peng Wu and his colleagues conducted a study titled A Critical Review of 3D Printing in the Construction Industry. This study systematically reviews 3D printing technology in the construction industry, highlighting its potential benefits, including increased customization, reduced construction time, lower labor requirements, and cost savings. While 3D printing has been widely used in manufacturing for decades, its application in construction remains fragmented, with only a few tested projects. The review emphasizes the need for further research to address challenges such as large-scale implementation, the integration of building information modeling, mass customization demands, and the life cycle cost of printed structures. Future studies should focus on these areas to enhance the stability and broader adoption of 3D printing in construction[16].

In 2017, Yi Wei Daniel Tay and his colleagues conducted a study titled 3D Printing Trends in the Building and Construction Industry: A Review. This review paper explores the growing application of 3D printing, or additive manufacturing, in the building and construction industry, analyzing trends from 1997 to 2016. It highlights the significant advantages of 3D printing, such as reducing human intervention, minimizing material wastage, and eliminating the need for additional formworks, thus improving traditional construction methods. The paper also discusses recent advancements, particularly in 3D concrete printing at the Singapore Centre for 3D Printing, and outlines the future direction for enhancing the capabilities and quality of current systems. The review emphasizes the transformative potential of 3D printing in construction, with future research aimed at addressing existing limitations and enhancing system efficiency[17].

In 2018, Gozde Basak Ozturk conducted a study titled The Future of 3D Printing Technology in the Construction Industry: A Systematic Literature Review. This paper examines the impact of technological advancements on the construction industry, emphasizing the transformative potential of 3D printing. While initially developed for additive manufacturing, 3D printing has gained significant attention in construction due to its design optimization capabilities and advantages over traditional methods. The study reviews applications of 3D printing in various industries and explores its adaptation strategies in construction, analyzing primary literature sources and implementation trials. The findings classify emerging developments in 3D printing and provide insights into potential future applications in construction, highlighting its role as a strategic challenge in the industry's technological evolution[18].

In 2021, Tiago Freire and colleagues conducted a study titled 3D Printing Technology in the Construction Industry. This study explores the application and potential of 3D printing technology in the construction industry, particularly within the framework of Industry 4.0. The technology is recognized for its cost-effectiveness, speed, geometric flexibility, and environmental benefits, including the use of biodegradable or recycled materials. It operates through printheads mounted on rail-guided cranes or robotic arms, enabling the construction of structures such as bridges, emergency shelters, and disaster-recovery housing. The paper examines various printing techniques, equipment types, design possibilities, and advancements in energy efficiency and material innovation. Despite its promise, the widespread adoption of 3D printing in construction remains constrained by the absence of standardized regulations and certification frameworks[19].

In 2025, Md. Hazrat Ali and colleagues conducted a study titled *Development of a Novel 3D Construction Printer for Consistent Buildability of Novel Geopolymer Mortar and Its Challenges.* This research focuses on the development of a large-scale 3D construction printer and the challenges in its design. Key improvements include adding a second rail on the y-axis for stability, upgrading the electric motor, using a higher-ratio (1:50) gearbox, increasing the helical rod diameter from 10 mm to 20 mm, and replacing the aluminum cylinder with a transparent plastic one for real-time monitoring. Experimental evaluations optimized extrusion flow, layer adhesion, and temperature control. The findings highlight the printer’s potential to enhance automation and precision in construction, addressing key technical challenges and improving system reliability[20].

2. Research Methodology

This study is a review paper based on a systematic examination of the existing scientific literature on 3D printing in construction projects. In the first stage, relevant keywords such as 3D printing, Construction Management, Artificial Intelligence in Construction, Additive Manufacturing in Construction, and other related terms were selected to cover all critical aspects of the research topic. Systematic searches were conducted in reputable scientific databases, including Google Scholar, ScienceDirect, and PubMed. The searches focused on articles published between 2020 and 2025 to review the latest studies and research trends. The criteria for article selection included direct relevance to the research topic, research method quality, innovation in findings, and citation count. Based on these criteria, a set of articles was screened and reviewed. To enhance the comprehensiveness of the review, qualitative content analysis and citation analysis were employed to identify key sources and connections between studies. Finally, the findings from these articles were categorized and analyzed based on various parameters, including challenges, innovations, and future paths, to provide a comprehensive view of the current state and future opportunities for 3D printing in the construction industry. Information related to the publication trends in recent years is shown in Table 1.

Table 1: Number of articles published from 2020 to 2025 based on keywords.

No	Keywords	Google Scholar	Science Direct	PubMed
1	3D printing	26,600	77,005	21,421
2	Construction Management	625,000	265,855	39,565
3	Artificial intelligence in construction	111,000	64,438	15,824
4	Additive Manufacturing in Construction	36,000	46,198	875

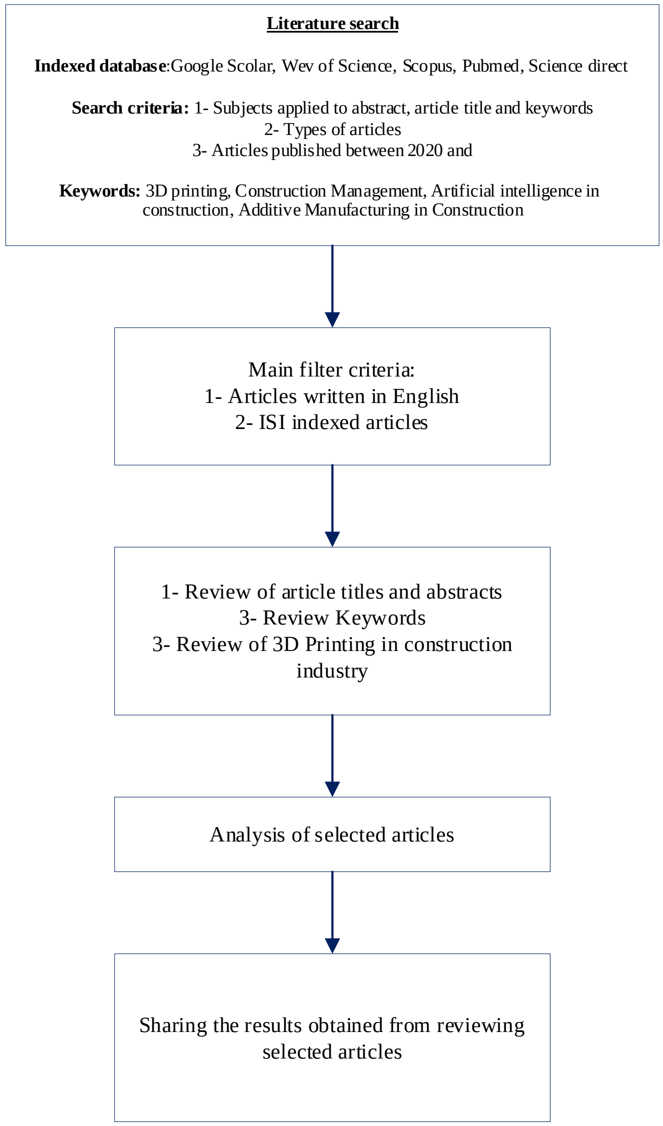

Fig 2: Steps of the systematic literature research method

3. Results and Discussion

In 2025, Mohammed Abdul-Kareem Malallah published a paper titled *Challenges, New Approaches, and Potential Future Paths for Three-Dimensional Printing (3DP) in Building Projects: A Review*. This study systematically reviews the literature and case studies to examine the challenges, innovations, and strategies of 3D printing in the construction industry. The results indicate that, despite advantages such as reduced costs and construction time, challenges such as material limitations, quality standards, and regulations hinder the widespread adoption of this technology. Recent advancements in material science, automation, and sustainability can improve the performance and efficiency of printed components. Finally, the paper proposes a framework for developing new adaptive systems to accelerate the adoption of this technology and create more sustainable methods in construction. Furthermore, tables are presented to analyze the application of 3D printing in the USA and China, evaluating the challenges, innovations, and proposed solutions for each country[21].

Table 2: USA 3D-painting projects[21].

Project	Challenges	Solutions	Innovations	Results
House Zero Texas, USA	Building a sustainable, comfortable home with 3D printing.	Print: ICON's 'Vulcan' 3D printer.	Iconic Assembly of 3D printed forms and conventional l materials.	Constructing an eco-friendly home that uses the least amount of energy.
	Maintaining the home sound and strong	Employing a unique mix called 'Lavacrete' for strength purposes.	Adopting internet-connected devices like bright lighting and air conditioning systems in the home.	Establish timelines and lower costs than traditional construction
Habitat for Humanity 3D Printed Home Virginia, USA.	Affordable housing through 3D printing.	Concrete walls are printed using an Alquist 3D printer.	The United States first sold 3D-printed homes.	15% cheaper than traditional construction.
	Challenging High Construction Costs	High cost: Where used local materials and improved printing.	Integrating bright solutions like home 3D printers for affordable spare parts and maintenance	Shorten build time to under a week.

Table 3: China 3D-painting projects[21].

Project	Challenges	Solutions	Innovations	Results
WinSun 3D Printed Houses Suzhou City, China	Developing 3D printing for fast residential building construction.	Using a large-scale 3D printer to print parts of the houses in the factory and then assemble them on site.	Building 10 residential homes in one day using 3D printing.	Reduce construction costs by up to 50% compared to traditional construction.
	Ensuring the durability and structural integrity of printed homes.	Using a special mix of recycled concrete to ensure durability and sustainability.	Reducing construction waste using recycled materials.	Provide an innovative model for sustainable and rapid construction.
3D Printed Office Building Beijing City, China	Build an office utilizing 3D printing while keeping architectural design and quality.	Using a sophisticate d 3D printer to print parts of the building on site.	The first 3D-printed office building in China.	Reduce construction time by up to 70% compared to traditional construction.

In 2025, Izabela Rojek and colleagues conducted an Emerging Applications of Machine Learning in 3D Printing study. This study examines recent advancements in 3D printing, focusing on its role in material engineering, mechanical engineering, and medical engineering. The combination of 3D printing with artificial intelligence (AI) and machine learning (ML) enables the optimization of the printing process, material selection, and lifecycle monitoring of products. However, the transition of this technology from academia to industry faces challenges such as slow development speed, limited productivity, moderate quality, and dependence on operator skills. Machine learning can mitigate these obstacles by automating data analysis and optimizing printing. Additionally, Table 4 is presented, which details the key aspects of this technology[22].

Table 4: Future trends emerging in ML in 3D printing[22].

Trend	Detailed Description
4D Printing and Smart Materials	Future advancements will integrate machine learning (ML) with 4D printing, where materials change shape or properties over time in response to environmental stimuli, benefiting applications in robotics, medicine, and aerospace.
ML-Driven Autonomous 3D Printing	Fully autonomous 3D printing systems will emerge, using reinforcement learning to self-correct errors in real-time, reducing the need for human intervention.
Scalability Challenges in Mass Production	Transitioning from small-scale prototyping to high-volume production presents challenges such as maintaining consistency, optimizing print speeds, and reducing cost per unit, all of which ML models can help address.
Decentralized Smart Manufacturing	ML-powered cloud-based 3D printing networks will enable distributed manufacturing, where production is optimized dynamically across multiple locations, reducing logistics costs and increasing efficiency.
Advanced Multi-Material Printing	Future ML models will improve multi-material printing by predicting material interactions and enabling seamless transitions between metals, polymers, and composites in a single print job.
Real-Time Performance Monitoring and Correction	ML-enhanced closed-loop feedback systems will allow 3D printers to continuously monitor prints and adjust parameters, ensuring higher reliability and less waste.
Sustainable and Circular Economy Initiatives	ML will play a critical role in recycling printed materials, optimizing material reusability, and reducing carbon footprints in industries such as construction, automotive, and consumer goods.
Aerospace Industry	Companies like Boeing and SpaceX are leveraging ML-driven 3D printing for lightweight, durable components, reducing aircraft weight and fuel consumption while maintaining structural integrity.
ML-Enhanced Bioprinting	Significant progress has been made in personalized medicine, where patient-specific tissues and organs are being developed using ML-optimized bio-inks.
Regulatory Compliance and Certification Hurdles	3D printing becomes more widespread; regulatory agencies will impose stricter guidelines to ensure quality control, safety, and standardization, which ML models can assist with by automating compliance checks.
Cybersecurity and Intellectual Property Protection	As 3D printing files become more valuable, ML-driven security systems will be crucial in detecting unauthorized access, protecting designs, and preventing counterfeit production.
Enhanced Digital Twin Integration	ML-powered digital twins will simulate entire production lines before real-world execution, reducing trial-and-error cycles and improving manufacturing efficiency.
High-Speed AI-Optimized Printing	ML will improve high-speed additive manufacturing techniques such as continuous liquid interface production (CLIP), allowing faster production with superior mechanical properties.
Automated Post-Processing and Finishing	ML will advance post-processing automation, optimizing support removal, polishing, and painting to create high-quality end-use products with minimal human intervention.
Collaborative ML and Robotics in 3D Printing	Future factories will integrate ML-driven robotic arms with 3D printers, allowing real-time adjustments, hybrid manufacturing, and enhanced production capabilities.

In 2024, Hanan Al-Raqeb conducted a study titled 3*D Concrete Printing in Kuwait: Stakeholder Insights for Sustainable Waste Management Solutions*. This study examines the potential integration of 3D concrete printing (3DCP) into Kuwait's construction waste management, analyzing insights from key stakeholders through a literature review, a survey of 87 experts, and 33 in-depth interviews. The findings reveal that increased productivity, cost reduction, design flexibility, and reduced material waste are the main benefits of 3DCP. However, regulatory, technical, and cultural challenges hinder its widespread adoption. Additionally, the differing perceptions of stakeholders emphasize the importance of education and awareness-building. The research offers two key contributions: first, a comprehensive analysis of Kuwait's technical and regulatory challenges, and second, a roadmap for integrating 3DCP through regulatory reforms, sustainable material research, and intersectoral collaboration. Table 5 provides stakeholders' perspectives on the future developments of Kuwait's construction industry and the role of 3D printing in these changes[23].

Table 5: Summary of participants' opinions on the advancements in the construction industry in Kuwait in the next 5 years and how 3D printing might contribute to these changes (open-ended)[23].

Participant	Comments
P1	Increased Adoption of 3DCP: The integration of 3DCP is expected to lead to faster construction and more customized structures, facilitating innovative architectural designs while aligning with sustainability goals by reducing construction waste.
P2	Government Support and Technological Integration: Strong government backing and integrating 3D printing with other technologies will further propel the industry's transformation. This shift will necessitate skills development and foster international collaboration.
P3	Economic Growth: Recognizing 3DCP as a disruptive technology is crucial for driving economic growth and competitiveness in Kuwait's construction sector. It has the potential to enhance productivity, reduce costs, and position Kuwait as a leader in technological advancement and sustainable development. Environmental Benefits: 3DCP significantly reduces construction waste and carbon emissions through its layer-by-layer printing process, which minimizes material wastage. The technology allows for creating energy-efficient structures while optimizing space and material use.
P4	Sustainable Materials: To ensure sustainability and contribute to a circular economy, it is essential to explore using geopolymer, recycled concrete aggregates, or waste materials in the mix design for 3DCP. Moreover, Modular and Prefabricated Construction: There is an

	increasing emphasis on modular and prefabricated construction methods to speed up project delivery and reduce on-site labor requirements. 3DCP is a game-changer, enabling rapid and cost-effective production of prefabricated building elements.

In 2024, Yuanyuan Li and colleagues conducted a study titled *Applications of Digital Technologies in Promoting Sustainable Construction Practices: A Literature Review*. This study utilized CiteSpace and HistCite to analyze 990 published articles from 2014 to 2023, identifying knowledge bases, key topics, and future trends. The results show that the application of digital technologies in sustainable construction, including 3D printing, has been explored in four main dimensions: environmental, social, economic, and green building assessment. Additionally, seven significant clusters were identified: barriers, energy efficiency, life cycle assessment, computer vision, renovation, building sustainability assessment, and management. The findings emphasize that despite the advantages of these technologies, multiple barriers, including social, financial, and technical factors, have hindered their rapid development in the construction industry. Table 6 presents the main obstacles to applying digital technologies in sustainable construction[24].

Table 6: Barriers to the application of digital technologies in sustainable construction[24].

Category	Barriers
Social and organizational barriers	– Resistance to digital technologies – Lack of standardized guidelines and limited training – Insufficient digital technological infrastructure support
Financial barriers	– Associated cost (high cost of software, hardware, etc.) – Ambiguous allocation of operational expenses among the involved parties
Technical barriers	– Interoperability and compatibility issues in different digital technologies – Shortage of qualified professionals to oversee the models
Data barriers	– Poor quality data and information-sharing culture – Unavailability of data – Data management complexity
Stakeholder barriers	– Lack of customer awareness about digital technologies – Deficiency in trust between consultants and contractors

Legal barriers	– The contractual practices in the construction industry still do not encourage the use of digital technologies – Integrating digital technologies into the current building codes and practices is still insufficient
Security barriers	– Privacy and security risks associated with data breaches – Difficulties in data analytics and information processing

In 2021, Yuying Song conducted a study titled *3D Printing in Construction: State of the Art and Applications.* This study evaluates the current status, challenges, and readiness of 3D printing technology in construction by examining academic and non-academic sources. The findings indicate that limitations in materials, methods, and printing systems continue to be obstacles to the widespread adoption of this technology in the construction industry. While the elimination of formwork could reduce construction costs by 35 to 63%, the lack of official standards and government support has slowed the progress of this technology. Figure 3 compares the distribution of the expenses between traditional construction and 3D printing[25].

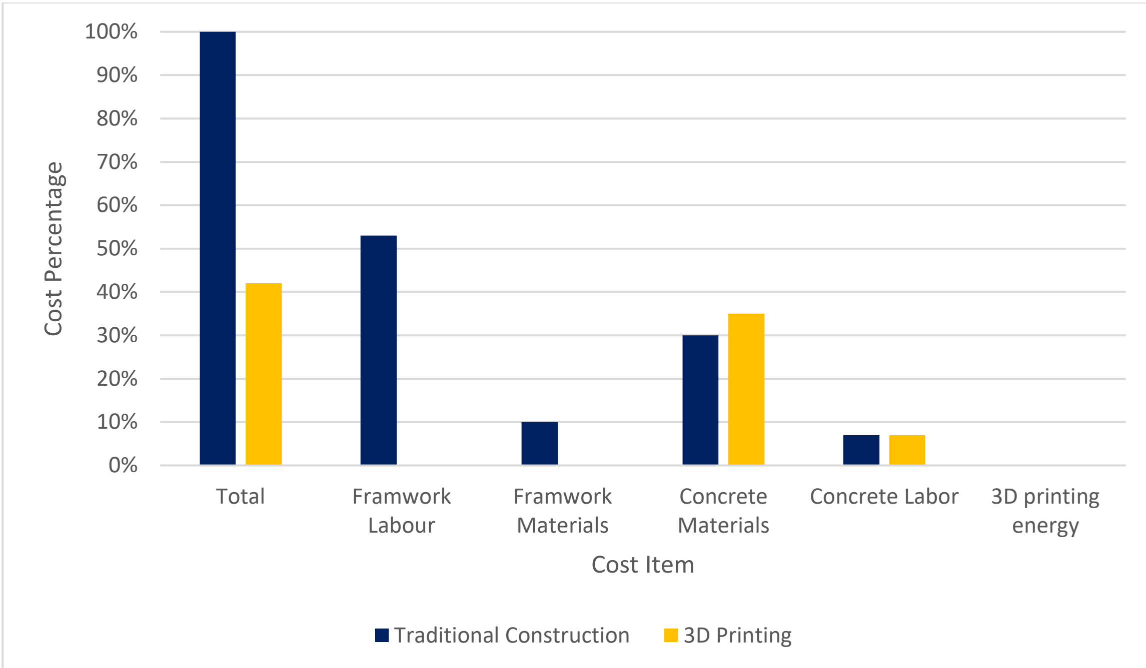

Fig 3: Typical cost distribution for a new concrete construction project by traditional construction and 3D printing methods (according to the project shown in Fig 4)[25]

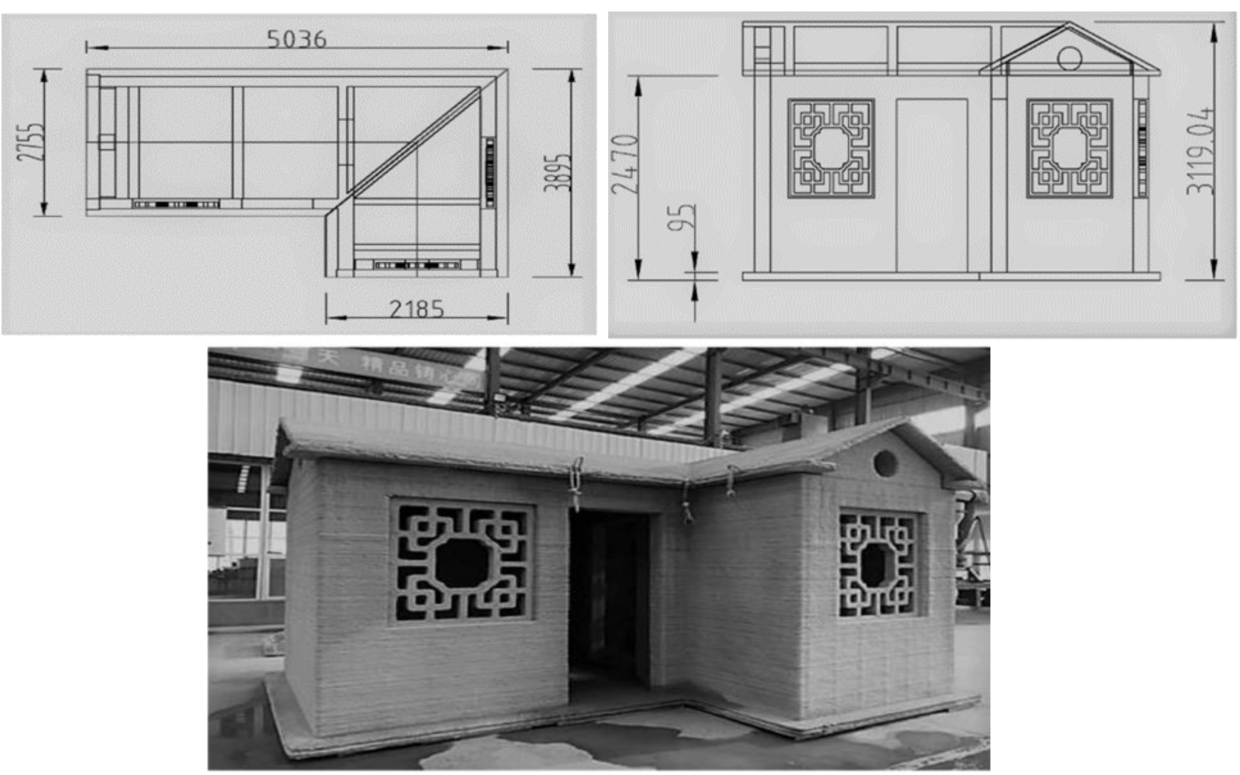

Fig 4: Real-world construction 3D printing and dimensions (mm) by Taikonghui, Zhengzhou Dingsheng Co., Ltd., P. R. China[25].

3. Conclusion

Despite existing challenges, 3D printing in the construction industry holds significant potential for transforming the sector. This technology reduces cost and time while allowing for more complex and precise designs. However, widespread adoption is hindered by limitations in developing suitable printing materials, the absence of quality standards, and regulatory constraints—additionally, high initial investment costs and the need for specialized workforce training present further obstacles. Recent advancements in material development, automation, artificial intelligence (AI), and machine learning (ML) offer promising solutions to these challenges. The development of novel materials, such as advanced polymers and composite materials with improved mechanical strength, flexibility, and thermal resistance, can significantly enhance the performance of 3D-printed structures. Furthermore, integrating sophisticated machine learning algorithms for real-time quality control enables continuous monitoring and optimization of production processes, minimizing defects and ensuring consistency. Establishing rigorous standards and certifications for these materials and methods remains essential to ensuring the quality and safety of printed structures, thereby strengthening industry confidence in this technology.

To fully realize the transformative potential of 3D printing in construction, transparent legal and regulatory frameworks must be established alongside economic and financial incentives for investors and contractors. Future research and innovation in materials and processes will facilitate the broader adoption of this technology in sustainable and cost-effective construction. This study's findings highlight that through collaboration among academia, industry, and policymakers, the effective development and implementation of 3D printing in construction can be achieved.

Future advancements should prioritize the development of high-performance, sustainable materials tailored explicitly for 3D construction printing. Research on advanced geopolymer composites, bio-based polymers, and recycled materials can enhance mechanical strength, durability, and environmental sustainability. Additionally, establishing standardized testing protocols and regulatory frameworks will be essential to ensure the reliability and safety of printed structures. Collaborative efforts between industry, academia, and policymakers can accelerate the integration of 3D printing into mainstream construction by addressing technical challenges and fostering widespread adoption.

Authors' Contributions

Pouya Partonia coordinated among the authors, collected data, wrote the original draft and revised manuscript versions, and finalized the selected articles. Sobhan Heidarian played a key role in refining the research idea and provided valuable insights throughout the study. Ghorbanali Dezvareh oversaw the manuscript's overall progress and ensured the quality of the research process.

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Declaration

Competing Interests

The authors declare no competing interests.

Ethical Approval

Ethical standards were used in this study. The research adhered to ethical guidelines, prioritizing the rights and welfare of all participants throughout the study.

Consent to Participate

Informed consent was obtained from all participants before their involvement in the study. Each participant was provided with comprehensive information regarding the study's purpose, procedures, risks, and benefits, and they voluntarily agreed to participate, ensuring their autonomy was respected.

Consent to Publish

All authors have consented to the publication of this paper. Participants involved in the study were informed that their data might be published in a scientific journal, and they provided their explicit consent for this purpose.

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