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Three-dimensional concrete printing for sustainable construction and architecture: A comprehensive review

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Abstract

Three-dimensional concrete printing (3DCP) has emerged as a transformative technology in the construction and architecture industries, offering automation, design flexibility, cost savings, and reduced environmental impact. Over the past decade, research has advanced in material development, structural performance, process optimization, and large-scale applications, such as housing, infrastructure, and disaster relief. Despite this progress, challenges remain, including the absence of standardized mix designs, reinforcement strategies, quality control measures, durability data, and universal regulatory frameworks. This article aims to provide a systematic review of recent developments in three-dimensional printable materials, process parameters, architectural integration, structural performance, and sustainability outcomes. Global case studies and bibliometric insights are synthesized to identify regional leadership, emerging technologies, and existing gaps. Particular emphasis is placed on sustainability through waste-based supplementary cementitious materials, enhanced thermal and mechanical performance, and circular economy approaches. The review highlights key research gaps in material compatibility, large-scale structural validation, and life-cycle assessment, while proposing a roadmap for future adoption. By consolidating current knowledge, this study serves as a reference for researchers, architects, and industry professionals working toward sustainable and scalable applications of 3DCP.

Keywords: Three-dimensional concrete printing; Sustainable construction; Additive manufacturing in architecture; Construction materials; Digital fabrication; Smart technologies

1. Introduction

The advent of Industry 4.0 has reshaped traditional production systems by integrating robotics, digital technologies, and resource-efficient methods, driving greater automation and sustainability in manufacturing (Tahmasebinia *et al.*, 2023). Among its key innovations, additive manufacturing (AM), also known as three-dimensional (3D) printing, has become one of the most transformative innovations, enabling the direct fabrication of digital models into physical objects. Initially adopted in automotive, aerospace, and biomedical industries to improve efficiency and quality (Mallakpour *et al.*, 2021), AM has increasingly expanded into the construction sector as a method of producing complex, large-scale structures. Within Industry 4.0, 3D printing (3DP) is further enhanced by various technologies, such as autonomous robots, digital simulations, and advanced fabrication systems, creating a new digitally integrated building production process that typically combines architectural design, specialized printing equipment, and cementitious materials (Butt, 2020; Sepasgozar *et al.*, 2020)

Due to concrete's durability and versatility, cement-based materials have become central to additive construction research over the past decade. Efforts have focused on defining the rheological and mechanical properties required for printability, such as flowability, extrudability, buildability, and open time, while also ensuring strength and durability (G. Ahmed, 2023; Pasupathy *et al.*, 2023). Beyond structural efficiency, 3D concrete printing (3DCP) enables greater architectural freedom by eliminating the need for formwork, supporting innovative geometries, and accelerating construction timelines (Alabbasi *et al.*, 2023; Bazli *et al.*, 2023). Applications range from the fabrication of architectural elements, such as walls, columns, and roofs (Burger *et al.*, 2023; Gomaa *et al.*, 2021) (Figure 1) to full-scale structures.

For example, Huang *et al.* (2022) investigated the relationship between buildability and geometry in 42 prototype projects, while Sun *et al.* (2021) demonstrated the *in situ* casting of a 3D-printed building and assessed its thermal performance. Similarly, Weng *et al.* (2020) developed a prefabricated bathroom module using extrusion-based 3DCP, comparing its cost, environmental impact, and manufacturability with precast systems. Recent case studies highlight the potential of 3DCP in reducing labor and time. The Yhnova house project in France, built in just 50 h with a layered wall system, demonstrated both technical feasibility and efficiency gains (Furet *et al.*, 2019). Likewise, Salet *et al.* (2018) applied 3DCP to fabricate modular bridge components, which were assembled and successfully load-tested. These examples illustrate the transition of 3DCP from small-scale prototypes to large-scale applications, while underscoring the challenges of reinforcement, thermal regulation, and long-term durability.

Three-dimensional concrete printing (3DCP) is increasingly recognized as a sustainable construction method that reduces material waste and labor costs while supporting circular economy principles. However, widespread adoption still requires addressing key gaps, including standardized mix design, regulatory frameworks, and life-cycle assessments (LCAs). Therefore, this review consolidates the progress of 3DCP in construction and architecture, highlighting its technological, material, and design advancements, while critically examining challenges and future directions for sustainable implementation. The main contributions of the study are as follows:

- Consolidates technological, material, and design advancements in 3DCP.
- Synthesizes existing studies while highlighting sustainability pathways, cost and time benefits, and practical applications through global case studies.
- Identifies and analyzes the key challenges currently limiting large-scale adoption of the technology.

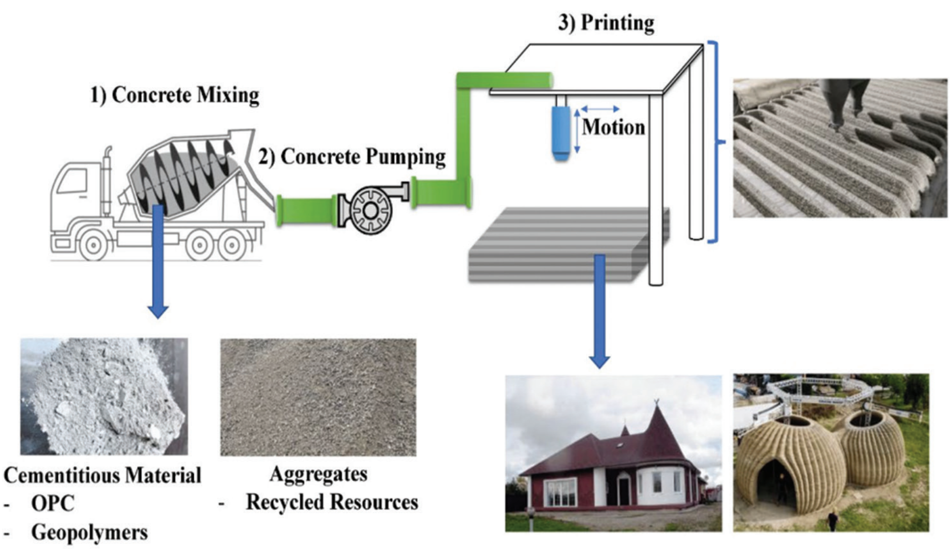

Figure 1. Three-dimensional concrete printing working process
Abbreviation: OPC: Ordinary Portland cement.
Source: Reprinted from Nawaz *et al.* (2024).

The rest of the article is structured as follows: Section 2 introduces 3DP technologies in construction, emphasizing binder jetting and material deposition approaches. Section 3 discusses materials used in 3DCP, including cementitious composites and supplementary binders. Section 4 reviews general applications across architecture and infrastructure. Section 5 presents case studies with a focus on cost-effectiveness and time savings. Section 6 outlines the major challenges hindering widespread adoption of 3DCP. Section 7 provides the overall conclusion, while Section 8 highlights the future research scope of 3DCP in sustainable construction and architecture.

2. Three-dimensional printing technologies in construction

The construction industry, known for its resource-intensive processes and significant environmental footprint, can benefit greatly from the integration of 3DP technologies (Vanegas *et al.*, 1996). The advent of low-cost 3D printers has made direct digital manufacturing increasingly feasible, empowering even users with basic computer skills to become local manufacturers using locally available resources (P. Wu *et al.*, 2016). The 3DP process in construction is often conceptualized as comprising three stages: input (design and materials), production (printing operations), and output (fabricated components) (D. Chen *et al.*, 2015). This model highlights how digital modeling and automation streamline the workflow from design to physical realization.

Scholars highlight that 3DP enables the fabrication of complex geometries more sustainably, requiring less material and eliminating the need for traditional formwork (Žujović *et al.*, 2022). AM also supports mass customization at no additional cost, offering design flexibility and efficiency. Recent advances extend beyond construction. 3DP plays a crucial role in energy conversion and environmental remediation, particularly through the fabrication of tailored catalysts with controlled properties (Pan *et al.*, 2021). For the built environment, several benefits of 3DP are recognized, including rapid prototyping, the ability to produce complex geometries, reduced material waste, cost-effectiveness for small production runs, and ease of iterative design modifications.

2.1. Applications and examples in construction

Practical applications of 3DP in architecture demonstrate its potential to redefine construction workflows. Four vertical 3DP applications have been described: (i) *In situ* walls with shell-and-fill structures, (ii) solid geometries, (iii) prefabricated panel components, and (iv) combined wall and column systems (Tabassum & Mir, 2023). These approaches allow accurate and efficient production of structural elements (Figure 2). Unlike conventional methods, 3DP provides nearly unlimited geometric flexibility while reducing environmental impacts. The technology supports mass customization, minimizes waste, lowers labor requirements, and improves both economic and constructability outcomes (Hager *et al.*, 2016).

Today, 3DP is increasingly applied to fabricate walls, floors, roofs, and structural components, as well as molds for concrete casting. Experimental projects have expanded the application of 3DP to infrastructure, including bridges and other large-scale works. These advances illustrate the potential of 3DP to complement or even replace traditional construction methods in selected contexts.

2.2. Binder jetting vs. material deposition methods

The rapid development of large-scale 3DCP is generally classified into two major techniques: binder jetting and material deposition methods (MDM) (Gebler *et al.*, 2014). In binder jetting, a liquid binder is deposited layer by layer onto a powder bed, selectively gluing cross-sections of the component. Unused powder remains in the build container to support subsequent layers until completion. In contrast, MDM involves the sequential extrusion of a viscous or semi-liquid material through a nozzle, following the defined path of a computer-aided design model (Tay *et al.*, 2017). MDM gradually builds up layers to create the final object, making it particularly suitable for printing cementitious composites (B. N. Panda *et al.*, 2017). Both methods present unique advantages: binder jetting offers high precision and intricate detailing, while MDM supports large-scale, continuous concrete printing. The current research is focused on optimizing these

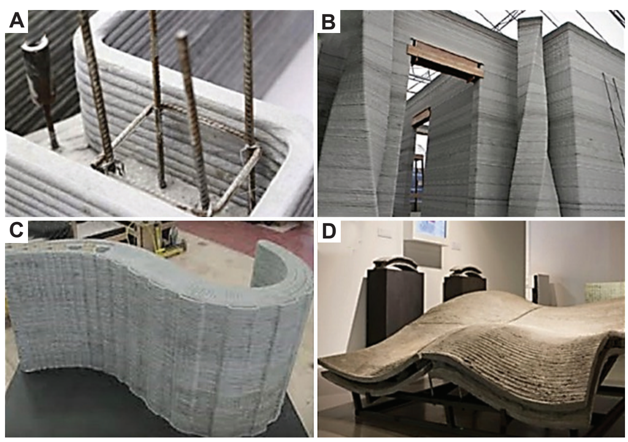

Figure 2. Examples of vertical three-dimensional printing in architecture. (A) An *in situ* wall with a shell and fill application. (N) A solid geometry. (C) A panel component. (D) *In situ* walls and columns.
Source: Reprinted with permission from Tabassum & Mir (2023).

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approaches for faster, more efficient, and customizable construction.

2.3. Life-cycle assessment and environmental impacts

Life-cycle assessment is a widely used tool for evaluating the environmental impacts of construction processes, including 3DCP (Kushwaha *et al.*, 2022). It provides a systematic framework to assess the full life-cycle of materials and structures, from raw material extraction and component manufacturing to the use phase, disposal, and potential recycling (Khasreen *et al.*, 2009). International standards, such as ISO 14040, emphasize the importance of accounting for material reuse and recycling pathways to ensure an accurate sustainability assessment (Shuaib *et al.*, 2021).

In the context of 3DCP, LCA highlights both opportunities and challenges. On the one hand, digital fabrication can minimize material waste, reduce labor, and shorten construction timelines, contributing to lower emissions. On the other hand, energy-intensive printing systems, lack of standardized material data, and uncertainties about long-term durability create gaps in sustainability evaluation (Motalebi *et al.*, 2024). A holistic life-cycle perspective is therefore essential to determine whether 3DCP can truly align with circular economy principles in the built environment.

3. Materials used for three-dimensional printing

The rapid advancement of AM has enabled the fabrication of objects from a wide range of materials, spanning from food products to advanced multifunctional composites. In construction and architecture, the spectrum of printable materials includes metals, polymers, composites, ceramics, cement-based materials, soil, salt, smart materials, and even experimental resources for space applications. Each material category demonstrates distinct advantages, challenges, and applications, shaping the evolution of 3DCP and sustainable building practices.

3.1. Metals and metal alloys

Metal AM is one of the fastest-growing fields, with nearly half of AM system manufacturers developing metal-based solutions (Sheydaeian & Toyserkani, 2018). Processes, such as directed energy deposition and powder bed fusion (PBF), are the most widely applied, while newer techniques include friction stir welding, direct metal writing, binder jetting, and cold spraying. Commonly used metals include stainless steel, aluminum, and titanium, alongside niche applications in gold (for jewelry) and nickel-based alloys (for aerospace and high-temperature environments up to 1,200°C) (Nie *et al.*, 2015). PBF-based selective laser melting (SLM) systems can achieve resolutions of ± 0.02 mm, offering superior mechanical and microstructural properties compared to conventional fabrication (Attar *et al.*, 2014).

3.2. Polymers and composites

Polymers are the most widely used materials in AM due to their adaptability to multiple printing systems and compatibility with all major AM platforms. Printable polymers exist in various forms, including thermoplastic filaments, resins, and powders. They are applied in industries ranging from aerospace and construction to fashion and medical devices (Ryan *et al.*, 2022). Composite materials, such as carbon fiber-reinforced polymers (CFRPs), carbon nanocomposites, and glass-fiber composites, provide lightweight, high-strength solutions for aerospace and construction. CFRPs, for instance, deliver tensile strength more than twice that of prestressing steel strands, while glass fibers offer thermal stability and fire resistance (Abueidda *et al.*, 2017; Bouzidi *et al.*, 2022; Ferreira *et al.*, 2017).

3.3. Ceramics

Ceramic-based 3DP has found major applications in biomedical fields, particularly in scaffolds for bone and dental tissue engineering. Ceramics are valued for their high compressive strength, thermal resistance, and long-term durability. However, limitations include lower resolution and the need for costly post-processing to achieve complex geometries. Optimized rheological control and particle homogeneity have enabled advances, such as honeycomb-structured ceramics with improved mechanical and crack-resistance properties (Derby, 2015; Maurath & Willenbacher, 2017; Minas *et al.*, 2016).

3.4. Cementitious materials and concrete

Concrete remains the most widely used construction material globally and has become the focus of AM research in construction (Schuldt *et al.*, 2021; Tay *et al.*, 2016). 3DP of cement-based mixes reduces labor and construction time, while enabling complex designs. Researchers are actively investigating sustainable formulations by incorporating industrial by-products, pozzolanic additives, and blended cement-clay systems to reduce cement consumption and carbon emissions (Iubin & Zakrevskaya, 2018; Ji *et al.*, 2019). Rheology-modifying admixtures are also introduced to improve extrudability, buildability, and mechanical performance (M. Chen *et al.*, 2018; Zareiyan & Khoshnevis, 2018). Architectural projects, such as Bloom, which featured complex curved walls produced with colored cementitious mixes, highlight the creative and structural potential of 3DCP (Figure 3) (Hager *et al.*, 2016; San Fratello & Rael, 2020).

3.5. Earth-based materials

Soil and earth-based materials are gaining traction due to their sustainability, local availability, and historical use in vernacular architecture. AM with clayey soils and sand blends has produced large-scale adobe structures compatible with eco-friendly construction practices (Dörfler *et al.*, 2019; Rocha *et al.*, 2023). A notable example is the Beacon, a 3D-printed soil structure demonstrating scalability and sustainability (Figure 4) (Xu *et al.*, 2017).

3.6. Salt materials

Salt, due to its translucency, offers unique applications in architectural design, allowing light transmission and semi-transparent structures. Compatible with inkjet-based printing, salt has been applied in experimental large-scale structures, such as Saltygloo (Figure 5A) in San Francisco, which demonstrated lightweight, esthetic, and eco-friendly construction possibilities.

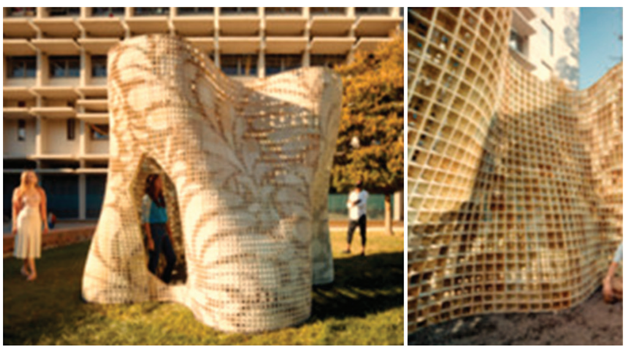

Figure 3. The faces of the Bloom, both inside and out
Source: Reprinted with permission from San Fratello & Rael (2020). Copyright © 2020 Published by Elsevier Ltd.

Figure 4. The complex system of undulating coils and the Beacon, composed of three-dimensional printing clay materials
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3.7. Smart and functionally graded materials

Smart materials, also called four-dimensional printing materials, are capable of altering their shape, size, or function over time in response to environmental stimuli, such as temperature or humidity (Kumar *et al.*, 2021; Shahrubudin *et al.*, 2019). This technology shows great promise in biomedical applications and adaptive architecture. Functionally graded materials have been developed by combining concrete with lime, metal powders, or cork to achieve variable porosity and density within a single print (Herrmann & Sobek, 2017). Other examples include experimental biomimetic objects, such as polyphytes, plant-inspired 3D structures produced using multi-material photopolymer resins (Figure 5B).

3.8. Special materials

Beyond construction, AM is being applied to print food products (e.g., chocolate, pizza, pasta), textiles, jewelry, and even extraterrestrial structures. Food printing enables customized, nutritious meals, while fashion applications shorten production cycles and reduce costs. In addition, lunar dust has been successfully tested for 3D-printed structures, offering prospects for space colonization on the Moon and Mars (Cesaretti *et al.*, 2014; Labeaga-Martínez *et al.*, 2017). The five primary materials include dirt, concrete, ceramics, metals, and polymers. Table 1 lists the materials along with their fundamental raw elements, printing techniques, and applications.

4. General applications of three-dimensional printing technology

In recent years, AM has advanced rapidly, with improved printing methods, higher precision, and more reliable material performance. These improvements have made 3DP a viable alternative to conventional manufacturing methods across multiple industries. Its adoption is driven by the ability to fabricate complex geometries, enable mass customization, and reduce material waste. The following subsections highlight key application areas of 3DP across various sectors (Table 2).

4.1. Aerospace industry

The aerospace sector represents nearly 18% of the global 3DP market, making it one of the most significant domains for AM applications. Aircraft and spacecraft demand lightweight yet strong materials, such as titanium alloys, nickel-based superalloys, and high-strength steels, all of which can be efficiently fabricated using 3DP with minimal waste compared to traditional methods (Grady *et al.*, 2015). AM allows on-demand production of spare parts, reducing long-term maintenance costs and storage

Table 1. Major materials used in three-dimensional printing for construction, their sources, methods, and applications

Material	Raw sources	Printing methods	Key applications in construction/ architecture	Advantages	Limitations	References
Metals and alloys	Stainless steel, aluminum, titanium, nickel alloys, gold	Powder bed fusion, directed energy deposition, binder jetting, cold spraying	Bridges, modular joints, and aerospace components for the built environment	High strength, precision (± 0.02 mm), durability	High cost, energy-intensive, limited large-scale use	Attar *et al.*, 2014; Nie *et al.*, 2015; Sheydaeian & Toyserkani, 2018
Polymers and composites	Thermoplastics, resins, CFRP, glass fiber composites	Fused deposition modeling, vat photopolymerization, and extrusion	Architectural models, façade panels, scaled prototypes, and lightweight structural parts	Lightweight, versatile, customizable	Limited fire/ ultraviolet resistance, weaker than metals/concrete	Abueidda *et al.*, 2017; Bouzidi *et al.*, 2022; Ferreira *et al.*, 2017; Ryan *et al.*, 2022
Ceramics	Alumina, zirconia, bioceramics	Extrusion-based printing, binder jetting	Tiles, ornaments, biomedical scaffolds (bone/teeth)	Heat-resistant, durable, bio-compatible	Low resolution, expensive post-processing	Derby, 2015; Maurath & Willenbacher, 2017; Minas *et al.*, 2016
Cementitious materials and concrete	Cement, sand, industrial by-products, pozzolans, clay blends	Extrusion/MDM, contour crafting	Walls, floors, columns, bridges, full-scale houses	High availability, structural durability, and complex geometries	Mix design challenges, reinforcement difficulties, and curing control	Hager *et al.*, 2016; Iubin & Zakrevskaya, 2018; Ji *et al.*, 2019; M. Chen *et al.*, 2018; San Fratello & Rael, 2020; Schuldt *et al.*, 2021; Tay *et al.*, 2016; Zareiyan & Khoshnevis, 2018
Earth/ soil-based	Clay, sand, natural soil blends	Extrusion/MDM	Eco-friendly adobe walls, experimental housing, and low-cost shelters	Sustainable, low-cost, locally sourced	Low structural strength, weathering issues	Dörfler *et al.*, 2019; Rocha *et al.* 2023; Xu *et al.*, 2017

Abbreviations: CFRP: Carbon fiber-reinforced polymer; MDM: Material deposition method.

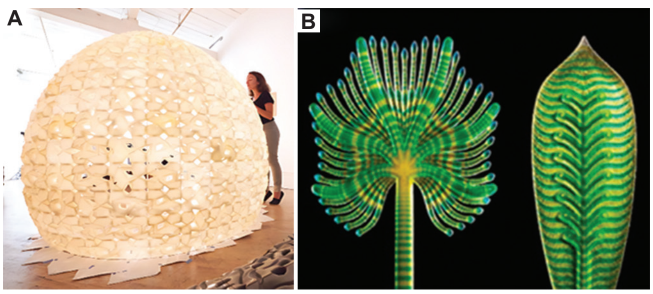

Figure 5. The Saltygloo, exterior and interior face (A) External and internal sides of the Saltygloo. (B) interactions between vascular three-dimensional printing and polyphytes.
Source: Figure by the author.

requirements. Furthermore, planetary construction (Figure 6) using *in situ* resource utilization is being explored for extraterrestrial habitats, where local materials, such as Martian soil, could replace costly imports from Earth (Kading & Straub, 2015; Yazici, 2018).

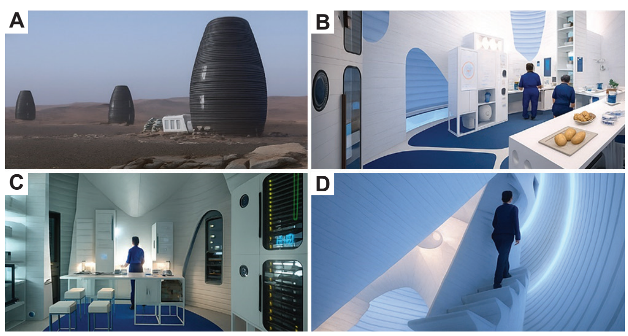

Figure 6. Marsha, three-dimensional printing on Mars. (A) Exterior shape. (B) and (C) Interior design. (D) Staircase.
Source: Reprinted with permission from G. Ahmed (2023). Copyright © 2023 Elsevier Ltd.

4.2. Healthcare and biomedical industry

The biomedical field accounts for approximately 11% of the AM market and continues to expand rapidly (Y. Liu *et al.*, 2016). Applications include 3D-printed skin, bone scaffolds, cartilage replacements, organ models, and patient-specific implants (Varpe *et al.*, 2025; Q. Yan *et al.*, 2018). AM has enabled customized prosthetics, orthotics, and hearing aids, reducing lead times compared to

Table 2. General applications of three-dimensional printing across industries

Industry	Applications	Key Benefits of 3DP	References
Aerospace	Aircraft parts, satellite components, and planetary construction using ISRU materials	Lightweight and strong parts, reduced waste, on-demand spares, and cost savings in space travel	Grady *et al.*, 2015; Kading & Straub, 2015; Yazici, 2018
Healthcare	Implants, prosthetics, tissue engineering, and drug delivery systems	Patient-specific designs, reduced lead times, biocompatibility, and precision in treatments	Burn *et al.*, 2016; Cubo *et al.*, 2016; Davoodi *et al.*, 2022; Duan, 2017; Murphy & Atala, 2014; Q. Yan *et al.*, 2018; Varpe *et al.*, 2025; Y. Liu *et al.*, 2016
Construction	Houses, bridges, walls, and BIM-integrated design	Faster construction, lower material use, design freedom, and sustainable building methods	Ngo *et al.*, 2018; Stoof & Pickering, 2018
Protective	Armor plates, blast-resistant panels, PPE, and helmets	Enhanced safety, rapid production, reduced cost, and customizable performance	C. Yan *et al.*, 2015; Harris *et al.*, 2017; Imbalzano *et al.*, 2016
Automotive	Prototyping, lightweight parts, electric vehicles, and racing car components	Rapid design iteration, weight reduction, improved aerodynamics, and cost-effective tooling	Choudhuri *et al.* 2025; Lim *et al.* 2016; Tuli *et al.* 2024
Food	Customized meals, chocolates, pizzas, and layered foods	Personalized nutrition, improved hygiene, waste reduction, and esthetic appeal	Dankar *et al.*, 2018; L. Liu *et al.*, 2019; Y. Chen *et al.*, 2020; Z. Liu *et al.*, 2017
Fashion	Shoes, dresses, handbags, jewelry, and textiles	Design flexibility, customization, sustainability, and enhanced material properties	Armstrong *et al.* 2023; Attaran, 2017; S. Wu *et al.*, 2022; Vanderploeg *et al.*, 2017
Electronics	PCBs, sensors, antennas, batteries, and IoT devices	Precision, faster prototyping, integration with smart systems, and cost-effective production	Foo *et al.*, 2018; Lee *et al.*, 2017; Saengchairat *et al.*, 2017

Abbreviations: 3DP: Three-dimensional printing; BIM: Building information modeling; ISRU: *In situ* resource utilization; IoT: Internet of Things; PPE: Personal protective equipment; PCB: Printed circuit boards.

traditional manufacturing (Davoodi *et al.*, 2022). Moreover, bio-fabrication, which integrates living cells into bio-inks, supports tissue engineering and regenerative medicine, offering innovative solutions for organ transplantation and drug delivery systems (Duan, 2017; Murphy & Atala, 2014). Recent advances highlight the role of 3DP in precision medicine, where implants and treatments can be designed to meet individual patient requirements (Burn *et al.*, 2016; Cubo *et al.*, 2016).

Mars Habitat, a sustainable initiative that employs elements found on Mars, allows for exploration and residence in an alien environment. The habitat includes four levels and a distinct internal atmosphere, allowing for mobility while avoiding boredom. The habitat is created from a recyclable polymer composite comprised of basalt fiber and renewable bioplastic, which outperforms concrete in strength, durability, and crush tests (Sun *et al.*, 2024).

4.3. Construction industry

Although construction currently represents only 3% of the total AM market, its potential for transformation is immense. 3DCP has demonstrated advantages, such as shorter construction times, reduced waste, sustainable material use, and greater architectural freedom (Ngo *et al.*, 2018). The integration of building information modeling with 3DCP allows real-time collaboration among stakeholders and enhances design, scheduling, and sustainability assessments. Case studies and pilot projects across the globe have proven 3DCP's feasibility for producing walls, bridges, and even entire houses (Stoof & Pickering, 2018).

4.4. Protective structures

AM has facilitated the production of high-performance protective structures. Applications include sandwich panels with lattice cores, blast-resistant components, and monolithic metal armor plates for military vehicles (C. Yan *et al.*, 2015). Lightweight materials, such as Kevlar-reinforced composites and ultra-high-performance concrete, are also being 3D printed for personal protective equipment, helmets, and bulletproof vests (Harris *et al.*, 2017). These applications reduce costs, improve safety, and accelerate production compared to conventional methods (Imbalzano *et al.*, 2016).

4.5. Automotive industry

The automotive industry has embraced 3DP for prototyping, tooling, and production of lightweight structural parts. Notable examples include the Local Motors 3D-printed electric car (2014), OLLI autonomous bus, and XEV Yoyo compact electric vehicle (Choudhuri *et al.*, 2025). High-performance cars, such as Formula-1 Renault RS19 and Lamborghini Aventador, also incorporate 3DP for weight reduction and enhanced aerodynamics (Lim *et al.*, 2016;

Tuli *et al.*, 2024). Various technologies, such as fused deposition modeling, stereolithography, selective laser sintering, and SLM, are commonly employed, using several materials, including acrylonitrile butadiene styrene, CFRPs, and aluminum. These innovations demonstrate how AM supports rapid iteration, cost savings, and improved performance.

4.6. Food industry

Food 3DP is emerging as a fast-growing market, valued at US$201 million in 2022 and projected to reach US$1.9 billion by 2027 (Dankar *et al.*, 2018). The technology enables the preparation of customized, nutritionally optimized meals for patients, athletes, and consumers with dietary needs. Carbohydrate-based foods, chocolates, pizzas, and multi-layer colorful designs are among the most common 3D-printed items (L. Liu *et al.*, 2019). In addition to personalization, 3DP in the food industry enhances hygiene, reduces waste, and shortens preparation times (Y. Chen *et al.*, 2020; Z. Liu *et al.*, 2017).

4.7. Fashion industry

In fashion, 3DP has gained traction for producing customized, sustainable, and experimental designs. Applications include shoes, dresses, handbags, masks, and jewelry, often using polymers, organic materials, or metallic powders (Armstrong *et al.*, 2023; S. Wu *et al.*, 2022). Advantages include shorter production cycles, design flexibility, and reduced environmental impact. In addition, 3D-printed textiles can be lightweight, water-repellent, impact-absorbing, and highly customizable, combining esthetics with functionality (Attaran, 2017; Vanderploeg *et al.*, 2017).

4.8. Electronics industry

AM in electronics enables the fabrication of printed circuit boards, sensors, antennas, batteries, and radio-frequency components (Lee *et al.*, 2017). Various techniques, such as inkjet printing, aerosol jet printing, and fused deposition modeling, enable the integration of conductive materials, including silver nanoparticles, graphene, and copper (Foo *et al.*, 2018). These applications support the Internet of Things, biomedical sensors, and rapid device prototyping. Future trends include 3D-printed motherboards, smart robots, and fully functional electronic systems (Saengchairat *et al.*, 2017).

5. Case study: Cost benefits and time saving of 3DCP

3DCP offers automation that can significantly reduce the costs of conventional construction methods in three major directions: (i) Time cost reduction: The construction period for a 3D-printed structure can be as little as one-quarter of the time required for an equivalent building using traditional techniques (Ma *et al.*, 2018). (ii) Material-cost reduction: By precisely controlling the feedstock and extrusion process, 3DCP ensures exact placement of material, minimizing waste and reducing raw material consumption to near zero. (iii) Labor-cost reduction: Digital fabrication reduces dependence on manpower, which typically accounts for almost 50% of the total cost of a project. This also minimizes errors and unnecessary rework due to human mistakes (Nayaka *et al.*, 2024).

Other than cost, 3DCP improves safety by reducing the number of workers exposed to hazardous construction tasks. On average, traditional construction projects report 40 injuries per 1,000 workers in the USA, and 52 per 1,000 in Australia (Hager *et al.*, 2016). In addition, formwork, which can represent 35–60% of the overall cost, is eliminated in 3DCP. However, costs related to large-scale 3D printers remain uncertain, with estimates suggesting that operations and maintenance at approximately US$75/h. Despite this, studies indicate that while conventional costs increase with complexity, 3DCP costs remain relatively stable, giving it a strong advantage for complex and small-to-medium scale projects.

Research demonstrates that 3DCP can significantly reduce overall expenditure. For example, studies found that 3DCP is 10–25% cheaper than masonry blocks and 25–37% cheaper compared to cast-in-place concrete walls. Han *et al.* (2021) showed that although materials for 3DCP can be costlier due to the additives, recycling aggregates reduces costs and improves sustainability. Similarly, Anjum *et al.* (2017) reported that 3DCP can reduce material waste by 79.3%, construction costs by 68.1%, construction time by 81.4%, labor dependency by 77.5%, and improve safety by 75.6%. Several real-world case studies further demonstrate the potential of 3DCP:

(i) Estonian low-cost housing: A collaboration between the University of Tartu and the Estonian University of Life Sciences successfully built homes using peat-based concrete, reducing housing costs by up to 10 times.
(ii) India: Adoption studies showed significant benefits in waste reduction, cost, and time savings.
(iii) ICON (USA/Mexico): ICON developed a portable gantry-style printer and built its first 32.5 sqm house in Austin (2018) within 47 h at a cost of US$10,000. Later, 50 low-income seismic-resistant homes were built in Tabasco, Mexico, each completed in 24 h of printing time.
(iv) Oman Project (2021): The German University of Technology collaborated with COBOD and CEMEX to build the largest 3D-printed concrete house (195 sqm) in only five days, at a cost of only €1600 per home using 99.5% of locally sourced materials.

(v) Dubai "Office of the Future": Constructed in 17 printing days, with 2 days of installation, this project used 50% less manpower, generated 60% less waste, and reduced construction costs by 50–70%.

These examples highlight how 3DCP is not only cost-efficient and time-saving but also a step toward safer, more sustainable, and highly scalable construction. With printer costs projected to fall below US$103,000 by 2025 and performance improving by 5% annually, widespread adoption of 3DCP is expected to accelerate in the coming years. Figure 7 shows two 3DCP houses in that project, and Table 3 shows the cost and time benefits of 3DCP compared to conventional construction.

5.1. Innovative three-dimensional-printed structures and global case studies

A growing number of innovative projects worldwide have demonstrated the cost-effectiveness, speed, and versatility of 3DCP. These case studies not only showcase the feasibility of large-scale construction but also highlight diverse approaches, materials, and business models for scaling the technology.

Residential homes and communities: In 2021, SQ4D announced the first 3D-printed home in New York to receive occupancy certification (Figure 8A). The 130 sqm, two-story house, constructed using the Autonomous Robotic Construction System, was listed at US$299,999, approximately 50% cheaper than comparable traditional houses. Similarly, Apis Cor built a US$10,000 home in Russia within 24 h in snowy conditions, estimating a lifespan of 175 years (Figure 8B). ICON, in collaboration with New Story, has pioneered community-scale projects in Texas and Mexico, with homes priced at US$10,000–US$450,000 depending on scale and customization (Figure 8C and D). In Europe, the "Yhnova" project in France delivered a 95 sqm four-bedroom home in 54 h,

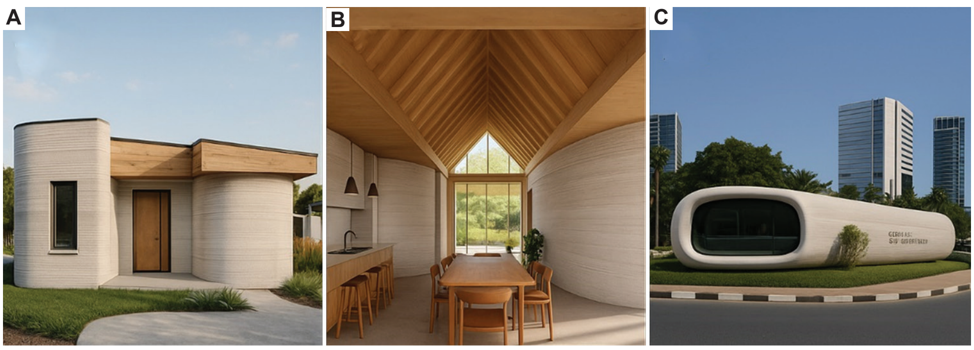

Figure 7. Three-dimensional printed houses. (A) Exterior view of one of the ICON's three-dimensional printed residences in Tabasco, Mexico (US$10,000). (B) Interior view of the residence in (A). (C) The astounding three-dimensional printed "Office of the Future" in Dubai (built in 17 days, cost US$140,000). Sources: (A-B) Reprinted with permission from G. Ahmed (2023). Copyright © 2023 Elsevier Ltd. (C) Figure by the author.

Table 3. Cost and time benefits of three-dimensional concrete printing compared to conventional construction

Factor	Conventional construction	Three-dimensional concrete printing	Benefit	References
Construction time	Months to weeks	Days (e.g., five days for a 195 sqm home in Oman)	75–80% faster	Ma *et al.*, 2018
Material usage	High, with 5–10% waste from formwork	Precise material placement, near-zero wastes	Waste reduction up to 79%	Nayaka *et al.*, 2024
Labor requirement	40–60% of the total project cost	50–80% less labor	Reduced manpower and improved safety	Nayaka *et al.*, 2024
Formwork costs	35–60% of the concrete project cost	No formwork required	Full elimination of shuttering	Hager *et al.*, 2016
Unit cost with complexity	Cost increases with complex designs	Costs remain constant regardless of design complexity	Advantage for complex and customized structures	Hager *et al.*, 2016
Overall cost savings	Not applicable	10–37% cheaper than masonry/cast concrete	Significant reduction in total cost	Han *et al.*, 2021
Printer costs	Not applicable	US$75/h operational; falling under US$103,000 by 2025	Rapidly decreasing barrier to adoption	Anjum *et al.*, 2017

Figure 8. (A-L) Innovative three-dimensional printed structures
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costing £176,000, about 20% cheaper than conventional housing (Figure 8E).

Community and multi-family projects: The Coachella Valley development in California (2022) by Mighty Buildings and Palari Group created a neighborhood of 15 sustainable homes, each 135 sqm with pools and terraces (Figure 8F). In Belgium, Kamp C used Europe's largest COBOD Building On Demand 2 printer to construct a two-story 93 sqm circular home in 21 days, with the expectation of reducing future builds to only 2 days (Figure 8G). Germany's first multi-family 3D-printed apartment, a 380 sqm three-story structure with five units, was completed by PERI Group in 2021 (Figure 8H). Milan's "3D Housing 05" (2018) showcased the potential of stylish design by combining recycled concrete with architectural innovation (Figure 8I).

Similarly, the Czech "Prvok" floating house (43 sqm) was built from nano-polymer concrete, reported to be seven times faster to complete than conventional brick housing (Figure 8J). Experimental and low-cost housing: WASP's "Gaia" project in Italy (Figure 8K) used a soil-concrete mix to construct a 20 sqm hut for just US$1,000, demonstrating ultra-low-cost housing potential. The Netherlands' "Project Milestone" is another example of milestones, delivering a series of habitable printed homes aimed at addressing labor shortages (Figure 8L).

Commercial and public infrastructure: Apis Cor has since opened waitlists for United States customers, offering standardized or custom-designed homes, such as the "Spirit" (214 sqm, two stories) and "Liberty" (167 sqm, one story), with rollout expected from 2024 (Figure 9). Beyond housing, AICT demonstrated large-scale infrastructure by building the world's first 3D-printed public park in 2021, covering 5,523 sqm. Using recycled aggregates and a six-axis robotic system, AICT fabricated over 2,000 concrete elements, including benches, retaining walls, and sculptures, within just 2.5 months (Figure 10). This project highlights not only the esthetic potential of 3DCP but also its contribution to sustainability and circular economy principles (Table 4) (Sakin & Kiroglu, 2017).

Table 4. Selected global case studies of three-dimensional-printed structures (G. Ahmed, 2023; Sakin & Kiroglu, 2017).

Project/location	Year	Size/type	Cost	Time	Key features
SQ4D House, New York (USA)	2021	130 sqm, two-story, three bedrooms	US$299,999	48 h	First certified home, ARCS tech, 50% cheaper
Apis Cor House, Russia	2017	Single-story, ~40 sqm	US$10,000	24 h	Printed in snow, estimated lifespan 175 years
ICON+New Story, Mexico/Texas	2018–2021	Single-family homes, 46–150 sqm	US$10,000–US$450,000	24–168 h	Seismic-resistant, community-scale housing
Yhnova Project, Nantes (France)	2018	95 sqm, four bedrooms	£176,000 (20% cheaper)	54 h	First family to live in a 3DCP home
Mighty Buildings+Palari, California	2022	15 homes, 135 sqm each	US$595,000	-	Full 3DP neighborhood with pools and terraces
Kamp C, Belgium	2020	93 sqm, two-story	-	21 days	Multi-floor circular design
PERI, Germany	2021	380 sqm, three-story, five apartments	-	~1 year	Germany's first multi-family 3DP apartment
3D Housing 05, Milan (Italy)	2018	100 sqm house	€1,000/sqm (estimated)	7 days	Recycled concrete, showcased at Design Week
Prvok Floating House, Czechia	2020	43 sqm	-	- (7×faster[a])	Nano-polymer concrete, floating structure
Gaia Project, Italy (WASP)	2019	20 sqm hut	US$1,000	10 days	Soil–concrete mix, ultra-low-cost housing
Project Milestone, Netherlands	2021–2022	Series of five homes	-	-	Addressing labor shortages
AICT 3D-Printed Park, China	2021	5,523 sqm park, more than 2,000 elements	Comparable to traditional	2.5 months	Recycled aggregates, 88% green area ratio

Note: [a]The exact construction time is unavailable; however, the 3DCP method is approximately seven times faster than conventional construction methods.
Abbreviations: 3D: Three-dimensional; 3DCP: Three-dimensional concrete printing; 3DP: Three-dimensional printing; ARCS: Autonomous Robotic Construction System.

Figure 9. Apis Cor three-dimensionally printed homes in the United States
Source: Figure by the author.

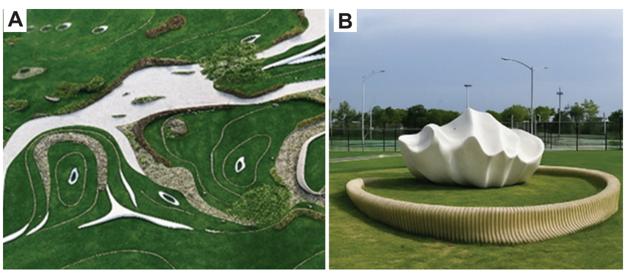

Figure 10. AICT built the world's first 3D printed park in China. (A) 3D-printed landscape of the AICT Park. (B) 3D-printed pavilion within the AICT Park.
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5.2. 3DCP footbridges: Global demonstrations

In addition to housing, several pioneering projects have demonstrated the potential of 3DCP for infrastructure, particularly pedestrian and bicycle bridges. To date, both contour crafting, concrete printing, and D-Shape techniques have been applied to fabricate short- to medium-span bridges across Europe and Asia. These pilot projects confirm the technical feasibility of additively manufactured bridges and have attracted strong scientific and industrial interest (Figure 11) (Asensio *et al.*, 2023).

Early demonstrations (2016–2017): The first 3DCP footbridge was built in Parque de Castilla, Alcobendas (Figure 11A) (Spain, 2016), using D-Shape technology. The 12 m span U-shaped arch consisted of eight prefabricated segments reinforced with steel microfibers (de la Fuente *et al.*, 2022). In Gemert (Figure 11B) (Netherlands, 2017), the first post-tensioned 3DCP bridge was realized. The 8 m span, 3.5 m wide beam bridge incorporated high-performance steel cables embedded within printed mortar filaments to prevent brittle failure and ensure durability.

Figure 11. Three-dimensional concrete printing footbridge projects. (A) Parque de Castilla (credit: Institute for Advanced Architecture of Catalonia, IAAC). (B) Gemert (credit: Marc Zoutendijk). (C) Wisdom Bay Park (credit: Tsinghua University). (D) ZhaoZhou (credit: Xinhua). (E) Striatus (credit: naaro). (F) The Bridge Project (credit: Municipality of Nijmegen). (G) N243 route (credit: Witteveen+Bos).
Source: Reprinted from Asensio *et al.* (2023).

Advances in China (2019): In Shanghai's Wisdom Bay Park (Figure 11C), a 14.4 m span arch bridge was fabricated using 3DCP and reinforced with polyethylene fibers, consisting of 44 deck segments and additional parapet/pavement elements. The Tianjin (2019) project (Figure 11D) produced the world's longest-span 3DCP pedestrian bridge at the time, reaching 17.9 m. Designed as a replica of the ancient ZhaoZhou stone bridge, it combined fiber-reinforced cement mortar with post-tensioned bars to achieve structural stability.

Architectural and structural innovation (2020–2021): The Striatus bridge in Venice (Italy, 2021) (Figure 11E) marked a design milestone. Built with incremental 3DCP, the 15.1 m span, 16 m long arch consisted of 53 alveolar segments arranged in a compression-only structure, stabilized with tie bars. Around the same time, the Nijmegen bridge (Netherlands, 2021) (Figure 11F) became the longest 3DCP bridge to date, with a total length of 29.5 m. Built for cyclists, the structure used 46 post-tensioned alveolar segments supported by 3DP piers (Bos *et al.*, 2017; Salet *et al.*, 2018).

Recent multi-bridge applications (2022): The most recent implementation is a set of four bicycle bridges along the N243 route in the Netherlands (2022) (Figure 11G). Each bridge spans 11 m, composed of six post-tensioned hollow-core box segments. These projects demonstrate the scalability and replicability of 3DCP bridge technology (Table 5).

These pioneering bridges validate the structural feasibility of 3DCP for small- to medium-span pedestrian and cycling applications. They highlight innovations, such as post-tensioning, fiber reinforcement, and compression-only geometries, while also proving replicability (e.g., N243 series). Nevertheless, challenges remain in establishing standardized design codes, ensuring long-term durability, and performing integrated sustainability assessments that compare economic, environmental, and social indicators against traditional bridge construction.

6. The challenges of 3DCP

Despite its rapid progress and promising applications, 3DCP still faces several technical, structural, and socio-economic challenges that limit its global adoption. The following remain critical areas requiring coordinated research and industry collaboration (G. Ahmed, 2023).

6.1. Development of technical standards and specifications

Unlike conventional concrete, 3DCP materials differ in composition, mixing, deposition, and mechanical behavior. Current testing protocols (American Society for Testing and Materials, European Norm standards) are insufficient for 3D-printed structures. New performance-based specifications must account for rheology, buildability, anisotropy, long-term durability, and load resistance (gravity, seismic, wind, creep, etc.). Chung *et al.* (2021) analyzed 139 academic articles, 98 printer models, and expert surveys, proposing a technical specification framework comprising 19 core and 67 supplementary items. However, international consensus and codification are still lacking.

6.2. Mix design optimization and anisotropy

Reliable, durable, and printer-compatible mixes are critical for 3DCP adoption (B. Panda *et al.*, 2018). Mixes must balance pumpability, extrudability, and buildability, while maintaining low shrinkage and adequate interlayer bonding. Achieving compatibility across different printers remains difficult. The anisotropic behavior caused by layer-by-layer deposition, setting delays, and extrusion pressure leads to directional variations in strength and durability (Wang *et al.*, 2017). Collaborative efforts, such as COBOD and CEMEX's "D.fab" mix with local aggregates, illustrate cost-effective solutions.

6.3. Construction scale limitations and automation

At present, 3DCP projects are constrained by printer dimensions (≈ 10 m in x/y axes, ≤ 8 m in z axis), restricting applications to low-rise structures and precast elements

Table 5. Selected three-dimensional concrete printing footbridge projects worldwide

Location	Year	Type	Span/size	Technique	Construction company	Reference
Alcobendas, Spain	2016	Arch (U-shape)	12 m span, 1.75 m wide	D-Shape	Acciona (Spain). D-Shape (Italy)	de la Fuente *et al.*, 2022
Gemert, Netherlands	2017	Beam	8 m span, 3.5 m wide	CP	BAM Infra (Netherlands). Weber Beamix (Netherlands)	de la Fuente *et al.*, 2022
Shanghai, China	2019	Arch	14.4 m span, 3.6 m wide	CP	Unknown	Bos *et al.*, 2017
Tianjin, China	2019	Arch	17.9 m span, 4.2 m wide	CP	Hebei University of Technology (China)	Bos *et al.*, 2017; de la Fuente *et al.*, 2022; Salet *et al.*, 2018
Venice (Striatus), Italy	2021	Arch	15.1 m span, 12 m wide	CP	Incremental3D (Austria). Holcim	Bos *et al.*, 2017; de la Fuente *et al.*, 2022; Salet *et al.*, 2018
Nijmegen, Netherlands	2021	Beam	29.5 m length, 3.6 m wide	CP	BAM Infra (Netherlands). Weber Beamix (Netherlands)	Bos *et al.*, 2017; de la Fuente *et al.*, 2022; Salet *et al.*, 2018
N243 Route, Netherlands	2022	Beam	11 m span, 4.5 m wide	CP	BAM Infra (Netherlands). Weber Beamix (Netherlands)	Bos *et al.*, 2017; de la Fuente *et al.*, 2022; Salet *et al.*, 2018

Abbreviations: CP: Concrete printing.

(Jo *et al.*, 2020). Notable projects include the Dubai Office Building, the Canal House in the Netherlands, and a concrete castle in the USA. However, true scalability for mid- and high-rise structures remains a challenge. Full automation is also not achieved, as reinforcement, utilities, and finishing often require manual intervention. Advances in multi-robot systems and hybrid automation are needed for large-scale adoption.

6.4. Reinforcement strategies

Integrating reinforcement remains one of the biggest technical barriers. Extruded 3DCP is brittle and weak in tension (Mechtcherine *et al.*, 2018). Fiber reinforcement improves ductility but is insufficient for structural safety (Z. Ahmed *et al.*, 2020). Alternatives include embedding rebar before printing, post-tensioning, or simultaneous cable applications. Novel methods, such as polymeric lattice meshes (Bai *et al.*, 2020). and interlayer lapping reinforcement show promise, with some increasing flexural strength up to 290%. Hybrid reinforcement strategies (integrating fibers, rebar, and post-tensioning) are currently the most viable.

6.5. Cost and environmental considerations

While 3DCP reduces formwork, labor, and material waste, costs remain high due to specialized printers and proprietary mixes. Material costs dominate (≈ 83% of printed structure cost), especially when supplementary cementitious materials and admixtures are used. Although recycled aggregates can offset costs, global affordability remains a concern. From a sustainability perspective, 3DCP reduces waste and transportation emissions, but its reliance on cement raises concerns about its carbon footprint (Freund *et al.*, 2020; Marchment & Sanjayan, 2020). Competing solutions, such as Boxabl foldable homes, Tesla tiny homes, and solar-roof housing, offer equal or superior eco-efficiency in some cases.

7. Conclusion

This review has shown that 3DCP is no longer a conceptual technology but an emerging reality that is reshaping the global construction industry. The integration of digital fabrication, robotics, and advanced material science has enabled 3DCP to address persistent challenges in conventional construction, including high labor dependency, excessive material waste, and limitations in design flexibility. Case studies of printed houses, bridges, and public infrastructure confirm that the technology offers tangible benefits, including reduced cost, shortened construction times, improved material efficiency, and sustainability gains. Furthermore, the ability to directly translate digital models into physical structures opens opportunities for architectural innovation, mass customization, and affordable housing solutions.

Despite these advantages, the widespread adoption of 3DCP remains constrained by several technical, economic, and regulatory challenges. At present, there is no unified international framework of design codes and standards for additive construction. Most printed projects remain at pilot scale, and issues, such as reinforcement integration, structural anisotropy, large-scale automation, and printer scalability, remain unresolved. Moreover, the cost-effectiveness of 3DCP is highly sensitive to the availability of suitable materials, the price of large-scale printers, and the efficiency of supporting technologies, such as reinforcement placement and curing systems. The long-term durability, safety, and life-cycle environmental impacts of printed structures must also be rigorously validated before 3DCP can transition into a mainstream practice.

8. Future research scope

Future research on 3DCP should primarily focus on developing innovative and sustainable materials. While current advances in cementitious and geopolymer binders show promise, further optimization of rheology, setting times, and interlayer bonding is needed to ensure long-term durability, structural reliability, and compatibility with large-scale printing systems. Equally important is investigating the reinforcement strategies to address the inherent brittleness of 3DCP structures. Conventional reinforcement methods, such as rebar placement or post-tensioning, remain labor-intensive, and future studies must explore integrated reinforcement systems, fiber-reinforced composites, and hybrid approaches that preserve geometric freedom without compromising mechanical performance. In addition, the challenge of scalability and full automation must be addressed to extend 3DCP from low-rise housing and small infrastructure components to high-rise buildings and complex megastructures. This requires advances in robotics, multi-axis printing systems, and adaptive digital workflows that minimize on-site human intervention.

Another critical direction lies in environmental sustainability and LCA. Although 3DCP reduces waste and formwork usage, the high cement content remains a concern for carbon emissions. Research should therefore emphasize low-carbon binders, integration of recycled aggregates, and closed-loop circular-economy models that valorize construction and demolition waste. Moreover, economic feasibility studies are essential to assess cost competitiveness against traditional construction methods, taking into account printer costs, maintenance, labor savings, and long-term operational efficiencies. Alongside technical and economic progress, the establishment of standardized codes, specifications, and regulatory frameworks will be vital for mainstream adoption. Current testing methods developed for cast-in-place concrete are inadequate for 3DP structures; hence, internationally recognized guidelines must be developed for rheology, durability, structural design, and safety requirements.

Finally, future research should adopt a multidisciplinary perspective, integrating material science, structural engineering, digital design, and sustainability science. Collaboration between academia, industry, and regulatory bodies will be crucial to accelerate innovation and overcome existing barriers. With coordinated efforts, 3DCP has the potential not only to revolutionize construction productivity but also to contribute significantly toward sustainable, affordable, and resilient built environments worldwide.

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Conflict of interest

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Author contributions

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Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data

No new data were created or analyzed in this study. This article is a comprehensive review of existing literature, and all data supporting the findings are sourced from previously published studies, which are cited accordingly.

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