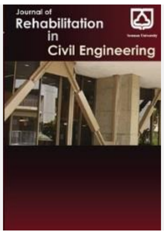

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Environmental Assessment of 3D Printed Concrete: Potentials and Challenges, Perspectives, and Opportunities (2013-2023)

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ABSTRACT

3D Printed Concrete (3DPC), or additive manufacturing in construction (AMC), is rapidly transforming the construction industry. By offering enhanced automation, faster construction processes, and reduced labor costs, 3DPC minimizes material waste and enables intricate architectural designs that are not feasible with traditional methods. A comprehensive review spanning 2013–2023 confirms its viability, particularly in remote or challenging environments where conventional construction faces limitations. This technology eliminates traditional formwork, granting unprecedented design flexibility and enabling the creation of complex geometric shapes. The review highlights recent advancements in 3DPC while acknowledging challenges hindering widespread adoption, including high initial costs, the need for rigorous pre-fabrication structural modeling, and complex regulatory approvals. Conducting cost-benefit analyses is critical for broader industry acceptance. The study emphasizes 3DPC's sustainability potential, particularly in reducing environmental impacts. Recognizing the ecological drawbacks of Portland cement, 3DPC offers a pathway to reduce cement consumption and mitigate the construction industry's carbon footprint. Strategies to optimize energy and environmental performance include exploring alternative cementitious materials (e.g., geopolymers, recycled aggregates) and refining printing processes to minimize waste. Furthermore, the research examines 3DPC's socio-economic implications, such as job creation in advanced manufacturing and localized production benefits. Despite challenges like regulatory complexity and upfront investment, 3DPC represents a promising avenue for a more sustainable, efficient, and innovative future in construction.

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1. Introduction

Because of its superior strength, durability, availability, adaptability in design, fire resistance, and affordability, concrete is frequently utilized in the construction industry [1,2]. However, the construction industry needs to develop and adopt more innovative, efficient, and sustainable strategies and technologies to meet the demands of the built environment and adapt to changing social and economic circumstances. The construction industry faces numerous challenges, including labor shortages, environmental concerns, and the need for faster and more efficient building methods. In this context, 3D printed concrete (3DPC) emerges as a transformative technology that addresses these issues through automation, reduced waste, and enhanced design flexibility [3]. By eliminating the need for traditional formwork and enabling precise material placement, 3DPC not only lowers labor costs but also minimizes environmental impacts [4,5].

Furthermore, technological advancements in 3D printing have facilitated the creation of complex architectural designs and the use of innovative, sustainable materials. These benefits position 3DPC as a pivotal solution for the modern construction landscape, particularly in achieving sustainability and reducing the carbon footprint of building projects [6]. Companies such as CyBe, Apis Cor, and Winsun are actively involved in 3D printing (3DP) projects for construction in Asia and Europe, showcasing the increasing global acceptance of 3DP technology in the building industry [1,7]. Several research studies have explored the current state and potential applications of 3DP in the construction industry [3,8–11]. One of the main advantages of 3DPC technology is its potential to save costs due to its high level of automation, quick building speed, and low labor requirements. Additionally, 3DP eliminates the need for formwork, significantly enhancing design flexibility and reducing resource consumption [12–14]. This represents a significant advantage for the building industry. These advantages have the potential to address several issues associated with traditional building methods, such as limited industrialization, environmental pollution, labor shortages, and excessive use of raw materials [14–16].

As 3DP technology has advanced, various structures have been constructed worldwide. The two most common extrusion-based 3DP techniques used in the construction industry are contour crafting and concrete printing [17]. These techniques typically utilize materials based on cement or geopolymer. Notably, on-site construction has garnered significant research interest, making concrete printing particularly relevant [16,18]. Regarded as an innovative solution that enhances automation in civil engineering, 3DP improves design efficiency and environmental sustainability. With increased automation and reduced labor requirements, this technology offers opportunities for customized designs, waste reduction, a lower carbon footprint, and cost-effectiveness. However, regulatory challenges and costs remain significant barriers to the widespread adoption of 3DP technology in the construction industry [7]. Despite its potential environmental benefits, the impact of 3DP technology in construction has not been thoroughly studied [19,20].

Most research has focused on small-scale environmental effects. For example, Faludi et al. [21] compared the environmental impacts of additive manufacturing machines with traditional CNC milling machines, demonstrating reduced energy consumption and waste in additive manufacturing. Kreiger and Pearce [22] investigated the advantages of distributing conventional versus 3D printed polymer products. 3DPC, or additively manufactured concrete, has the potential to create complex structures with less waste and potentially lower labor costs. This method involves constructing a structure directly from a digital model by depositing concrete material layer by layer [23,24]. 3D concrete printing can be accomplished through various methods, including extrusion-based techniques, where cement-based materials are extruded through a nozzle, and powder-based techniques, where a binder is selectively applied to a powder bed. To achieve the desired properties, the mix design often incorporates additives such as superplasticizers, accelerators, and fibers [25]. However, the use of 3DP in the construction industry is still in its infancy and faces challenges related to developing new materials, understanding structural behavior, and establishing construction codes. Research on the mechanical properties, sustainability, and thermal performance of 3DPC structures is ongoing [23,24].

Additive manufacturing, or 3DP, has the potential to revolutionize construction methods in the infrastructure sector. This layer-by-layer manufacturing process for producing 3D objects from digital files is gaining increasing attention from the building industry [26]. The application of 3DP technology in construction offers several advantages, including reduced waste, lower carbon emissions, and enhanced customization opportunities [27]. It also facilitates the development of high-performing, environmentally friendly materials and structures for civil infrastructure.

The precise control and shaping of a material's internal structure enabled by 3DP allow for the creation of innovative cement-based materials that effectively blend form and function [28]. While previous reviews have examined the technological aspects, potential, and material development of 3DP in construction, it is equally important to assess the technology's sustainability, energy efficiency, and environmental impact [1,11,29,30]. By understanding the ecological and environmental implications of 3DP technology for concrete construction, researchers can better direct future studies and address challenges in this field by establishing essential performance metrics.

The versatility and potential of 3DP technology in the construction industry are evident in the growing number of 3D-printed structures, including residential homes, bridges, and even historical fortifications. Concrete printing is particularly advantageous for on-site construction due to its ability to incorporate coarse aggregates. Typically, cementitious or geopolymer materials are used in 3DP applications for construction. This research highlights the importance of optimizing the printing process to achieve better environmental outcomes in real-world applications. By providing insights and recommendations for future studies, this analysis aims to advance the development and implementation of 3DCP technology in the construction industry.

3DPC offers several significant advantages over traditional construction methods. These include enhanced sustainability through reduced waste and lower cement usage, increased efficiency and speed due to automation, greater design flexibility for complex structures, and improved site safety with reduced labor requirements. These benefits position 3DPC as a potential game-changer in the construction industry. A summary of key studies and their contributions to the field of 3DPC is presented in Table 1.

Notes:

- **Methodologies:** include theoretical analyses, experimental testing, case studies, and comparative reviews.
- **Key themes:** Automation, sustainability (waste reduction, low-carbon), material innovation, and design flexibility dominate 3DPC research.
- **Gaps:** Limited large-scale environmental impact studies ([19,20]), regulatory hurdles, and code development needs ([23,24]).

Table 1. A summary of key studies and their contributions to the field of 3DPC.

Reference(s)	Focus	Methodology	Key Findings
[1,2]	Advantages of traditional concrete	Comparative analysis	Superior strength, durability, fire resistance, and affordability of concrete.
[3]	3DPC as transformative technology	Conceptual review	3DPC addresses labor shortages, waste reduction, and design flexibility.
[4,5]	Environmental and labor benefits of 3DPC	Case studies	Eliminates formwork, reduces labor costs, and lowers environmental impacts.
[6]	Sustainability of 3DPC	Theoretical analysis	3DPC reduces carbon footprint and supports sustainable construction.
[7]	Global adoption of 3DP technology	Industry case studies (CyBe, etc.)	Growing acceptance in Asia/Europe; regulatory and cost barriers remain.
[8–11]	Applications of 3DP in construction	Literature review	Explores automation, speed, and material efficiency in 3DP.
[12–14]	Cost and design advantages of 3DPC	Technical analysis	High automation, fast construction, and elimination of formwork.
[14–16]	Challenges in traditional construction	Comparative review	Solves issues like pollution, labor shortages, and raw material overuse.
[17]	Extrusion-based 3DP techniques	Technical review	Contour crafting and concrete printing are dominant methods.
[16,18]	On-site 3D concrete printing	Case studies	Aligns with on-site needs; enhances automation and design precision.
[19,20]	Environmental benefits of 3DPC	Gap analysis	Limited research on large-scale environmental impacts.
[21]	Environmental impact of additive manufacturing	Comparative LCA (vs. CNC milling)	Additive manufacturing reduces energy use and waste.
[22]	3D printed polymer products	Material comparison	3DP polymers offer distribution advantages over conventional methods.
[23,24]	Structural behavior of 3DPC	Experimental testing	Challenges include material behavior understanding and code development.
[25]	Material design for 3DPC	Material science experiments	Mix designs require additives (superplasticizers, fibers) for optimal properties.
[26]	Additive manufacturing in construction	Industry trend analysis	Growing interest in layer-by-layer digital fabrication.
[27]	Sustainability of 3DPC	Conceptual review	Reduces waste, carbon emissions, and enables customization.
[28]	Innovative cement-based materials	Material development	Enables precise control of internal structure for functional designs.
[29,30]	Sustainability assessment of 3DPC	Literature review	Calls for focus on energy efficiency and environmental footprint.

2. Novelty of the current study and research gap

This study not only analyzes current trends and research gaps in 3DPC but also actively proposes strategies to minimize its environmental and energy impact. A key strategy involves investigating alternative, eco-friendly cementitious materials that can replace traditional, carbon-intensive options. The research further explores the optimization of the 3DP process itself, focusing on techniques to reduce waste during material mixing, printing, and post-processing. This includes examining precision control of material deposition to minimize excess concrete usage and investigating reusable formwork systems. Beyond environmental considerations, the study also addresses the broader socio-economic implications of widespread 3DPC adoption. This includes the potential for new job creation in specialized fields such as design, operation, and maintenance of 3DP equipment, as well as the advantages of localized manufacturing. Localized production can reduce transportation costs and lead times while potentially stimulating local economies. While acknowledging the current limitations and challenges facing 3DPC technology—such as material performance in harsh environments and the need for further development of scalable printing systems—this research ultimately positions 3DPC as a promising pathway toward a more sustainable, efficient, and transformative future for the construction industry.

3. Methodology

In this paper, a comprehensive literature analysis was conducted using various databases and search techniques. The review focused on peer-reviewed journal articles, conference papers, and theses published between 2013 and 2023 to ensure relevance and robustness. Additionally, conference proceedings, book chapters, and scholarly theses were included, provided they were written in English and subjected to peer review. Sources were selected based on their direct relevance to environmental assessment, sustainability, and technical advancements in 3DPC. Priority was given to studies that significantly contributed to understanding the environmental impacts of 3DPC, its methodologies, and future applications. To achieve comprehensive coverage, major scientific databases such as Scopus, Web of Science, and Google Scholar were utilized. The focus on the environmental evaluation of 3DPC was maintained by excluding studies that solely addressed technological advancements or sustainability assessments of green concrete without considering 3DP. Furthermore, limiting the assessment of 3DP for construction based on predetermined selection criteria ensured that the review remained centered on the environmental implications of this technology. Through meticulous selection and removal of duplicate results, only studies that added substantial value to the subject matter were included. This methodology contributes to providing a thorough and insightful analysis of the environmental assessment of 3DPC.

4. 3DP Technology for concrete construction

Similar to other 3DP techniques, the fundamentals of 3DP technology for concrete construction follow a consistent procedure. This process typically consists of three primary steps: (1) the actual 3DP of the concrete, (2) slicing and tool path creation to convert the digital model into printable layers, and (3) computer-aided design (CAD) of the intended structure. Within the concrete construction industry, three main 3DP technologies are frequently employed:

1. Extrusion Printing: Also known as the extrusion-based layer method (EPM), this technique follows CAD tool instructions to deposit the chosen concrete material incrementally, layer by layer. Extrusion printing is often utilized for on-site construction because it can manufacture buildings directly in place [31].

2. Powder Jetting: Commonly referred to as binder jetting, this method forms solid layers by selectively adding a binder material to a powder bed. The binder binds the powder particles together to create the desired structure. According to Lowke et al. [32], powder jetting is often used off-site to prefabricate intricate geometries that can be assembled later.

3. 3D Printed Formwork: This hybrid approach combines 3DP with traditional formwork techniques. In this method, 3DP technology is used to create the basic formwork or mold for the concrete structure. The finished concrete structure is then formed by adding concrete material to the printed formwork. This technique leverages the advantages of both traditional casting methods and 3DP, enabling the production of complex geometries [1].

Each of these 3DP techniques has its own benefits and applications. The selection of a specific technique depends on various factors, including project specifications, site characteristics, and desired outcomes (see Figure 1).

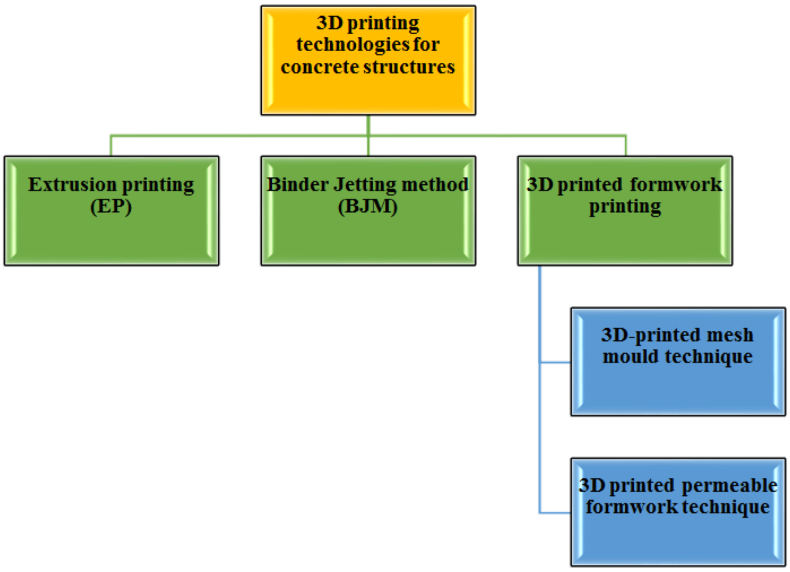

Fig. 1. 3DP technologies for concrete structures [1].

In the realm of 3DPC, the relationship between printing properties and material characteristics is crucial. According to Guamán-Rivera et al. [12] and Lu et al. [33] , several properties are essential for fresh 3D-printable concrete, including low slump for workability and rapid hardening to ensure structural integrity. However, these specifications present challenges, as the material must also exhibit strong interlayer bonding, be extrudable, and retain its shape during the printing process [12]. Ji et al. [34] emphasize that the fresh properties of concrete are primarily influenced by its composition, particularly the types and amounts of mineral additives and cement substitutes used. To enhance printability, it is vital to adjust the flow characteristics and setting times through the incorporation of various cement substitutes and mineral additions, such as fly ash or silica fume [35]. Achieving the desired structural integrity, surface finish, and overall quality of the printed structure depends on multiple factors, including material selection, rheological behavior, printability assessment, curing procedures, and post-processing techniques [36]. These key concepts are visually summarized in Figure 2, which illustrates the various considerations and factors to keep in mind when printing concrete in three dimensions.

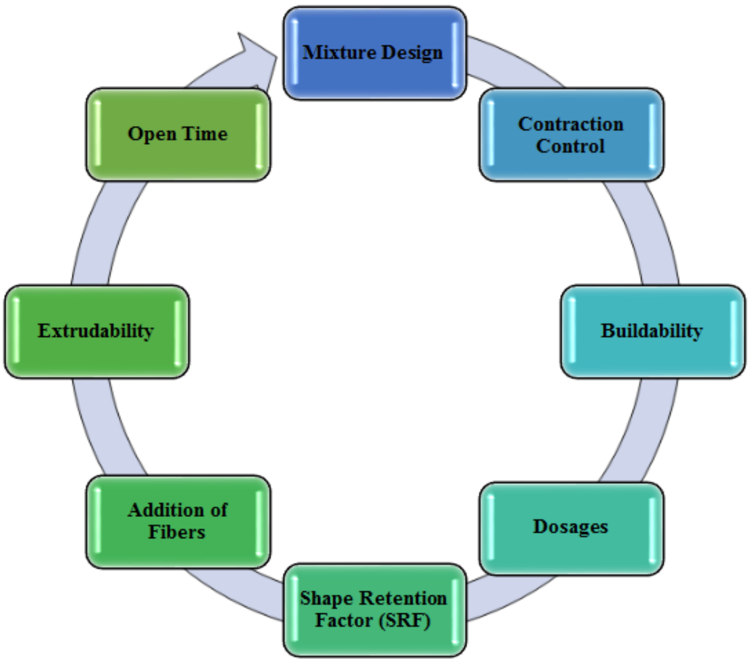

Fig. 2. Various factors to the 3DP of concrete [12].

As illustrated in Figure 2, several key terms are defined regarding the concrete printing process. One of the most critical properties is extrudability, which dictates how effectively and reliably the material can be extruded through the printing equipment. The extrudability of concrete is influenced by various factors, including the quantity and distribution of dry components, the rheological properties of fine aggregates, particle size distribution, and the dosage of additives such as superplasticizers and air-entrainers. The inclusion of fibers also plays a significant role in this aspect [37,38].

Another essential factor to consider is open time, which refers to the duration that fluid concrete can be printed without losing its shape. This property is affected by hydration mechanisms, water loss, and environmental conditions. Proper management of these parameters ensures that the concrete remains printable for the desired time frame [12,37]. Buildability is another critical characteristic of freshly mixed concrete, allowing it to maintain its shape without distortion during the layer-by-layer 3DP process. Enhancements in buildability can be achieved through the use of modifiers and appropriate aggregate gradation, which improve the concrete's flow and stability [31,38]. Lastly, the Shape Retention Factor (SRF) is a dimensionless measure indicating the ability of printed concrete to retain its shape after extrusion. A higher SRF signifies better stability under its own weight, a lower slump, and a higher yield point [12,39].

To achieve buildability and dimensional precision in concrete printing, effective contraction control is crucial. This involves managing the dimensional changes or shrinkage that occur as concrete cures. Various factors influence the contraction of printed concrete, including the amount of cement used, the water-to-cement ratio, and the incorporation of additives such as fibers and superplasticizers [40,41]. In developing 3D printable concrete compositions, different dosages of binder materials—such as cement, fly ash, slag, and silica fume—are utilized alongside fine aggregates and additives like superplasticizers and accelerators.

The choice of materials and their respective proportions are determined based on the desired characteristics of the printed elements. When designing a mixture, several performance criteria are considered, including mechanical properties, rheology, and the extrusion process itself. Additionally, factors such as storage methods, preparation techniques, and advancements in pumping and extrusion technology play a significant role. A notable recent development in 3D printable concrete is the incorporation of fibers, such as carbon, glass, or basalt fibers. These fibers enhance the flexural properties of the printed elements by improving their bending strength and ductility [40–44].

4.1. Performance requirements of 3DPC

Printability, which encompasses both extrudability and buildability, is a critical performance requirement for 3D printable concrete (3DPC) and is closely linked to the material's rheological characteristics. Extrudability refers to the ability of fresh concrete to be continuously pushed through the nozzle of an extruder, allowing for the smooth deposition of material. On the other hand, buildability pertains to the printed concrete's capacity to support the weight of subsequent layers without experiencing significant deformation or collapse.

The mechanical properties of 3DPC, which evolve as the concrete undergoes hydration, are also essential for ensuring the stability and integrity of printed structures. As the hydration process progresses, the material gains strength, influencing both extrudability and buildability. To assess the performance of 3DPC systems, several common metrics are utilized, as illustrated in Figure 3. These metrics typically include parameters such as viscosity, yield stress, and setting time, all of which play a crucial role in determining how effectively the concrete can be printed and how well it will perform under load.

Fig. 3. Some common performance metrics of 3DPC [16,36,45].

According to Yang et al. [25] , inadequate interlayer bonding strength in 3DPC can lead to anisotropic mechanical characteristics, potentially compromising the material's endurance. The service performance of a 3D printed structure is significantly influenced by its toughness, which encompasses both mechanical properties and durability features. Incorporating fibers into cementitious materials has been shown to enhance ductility and reduce the reliance on traditional steel reinforcement [25]. This approach not only improves the structural performance of 3DPC but also contributes to more sustainable construction practices. To inform future research on developing novel testing techniques with effective evaluation indices, as well as optimizing mix proportions for enhanced fresh and hardened properties, a comprehensive review of 3DPC mix design is essential. This review should consider various materials and mix design methodologies [16]. Performance indicators for the 3DP process in construction are specifically designed to encourage the use of additives and admixtures that enhance particular properties, whether in a cured state or while the concrete remains fresh. The overarching goal is to promote sustainable concrete formulations that minimize environmental impacts [45]. As illustrated in Figure 4, there are numerous practical applications of 3DP technology within the concrete construction industry, showcasing its potential to revolutionize traditional building practices.

Fig. 4. Few real-world examples of 3DP technology for concrete construction exist: [1,46–48] (i) 3D Housing 05, Milan , (ii) Double-Story Administrative Building in Dubai, (iii) Printed the house in one piece with a fixed 3D concrete printer in Westerlo, Belgium , (iv) World's largest 3DPC bridge in shanghai.

4.2. Mix design of 3DPC using materials

The current state of concrete construction using 3DP technology is primarily focused on developing cementitious materials that meet the essential criteria of "printability" and "buildability." These terms refer to the material's ability to be extruded and support itself as structures are constructed layer by layer. Successful printing relies on fresh concrete possessing the appropriate rheological characteristics [49]. The concrete manufacturing process has a significant environmental impact, prompting efforts to develop more sustainable alternatives. This includes substituting recycled materials for natural aggregates, such as fly ash, blast furnace slag, and marble sludge. Additionally, research is underway to reduce the reliance on conventional Portland cement—known for its substantial CO_2 emissions—by exploring alkali-activated binders and unconventional materials. To mitigate environmental effects and partially replace Portland cement in 3DPC, there is an increasing use of supplementary cementitious materials like fly ash, silica fume, and lime filler [50]. The precise control over material placement afforded by 3DP technologies is expected to contribute significantly to reducing construction waste. The introduction of synthetic admixtures has led to notable improvements in material performance characteristics, enabling the optimization of mix designs to produce high-performance concrete with reduced porosity, thereby enhancing durability indirectly [23]. A significant advancement in this field is the incorporation of fibers into concrete mixes for 3DP, which can greatly enhance bending strength and ductility while reducing the need for steel reinforcement. This is particularly crucial given the challenges associated with achieving high mechanical properties in 3DPC without traditional steel reinforcement [51]. Sustainability remains a critical consideration for 3DPC. Despite its advantages—such as lower environmental impact and cost-effectiveness—there is ongoing debate regarding the true sustainability of the technology. Some studies suggest that digital fabrication has minimal effects compared to traditional material production, while others argue that it has considerable impacts that warrant further investigation [29,52]. In summary, the objective of creating sustainable concrete for 3DP involves balancing environmental benefits with the durability and mechanical performance requirements of printed structures through optimized mix design. Key strategies in this endeavor include the incorporation of recycled materials and the use of supplementary cementitious materials [23]. Notably, geopolymer concrete emerges as a more environmentally friendly alternative to conventional Portland cement concrete [29,53,54].

According to Al-Majidi et al. [55], geopolymer concrete is produced by reacting alkali-based compounds with amorphous aluminosilicate materials such as fly ash, natural zeolite, and blast furnace slag. These environmentally friendly materials play a significant role in reducing carbon emissions and minimizing waste [53,54]. While sodium hydroxide is a commonly used activator in the production of geopolymer concrete, Al-Majidi et al. [55] highlight its considerable negative environmental impact. Conversely, since geopolymer concrete requires less Portland cement, it effectively reduces both waste and carbon emissions [54]. Achieving structural stability and ductility is essential in 3DPC applications. The incorporation of fibers has garnered significant interest as a means to enhance the tensile strength and ductility of printed concrete [56]. Numerous studies have explored the effects of various materials, including steel fibers, basalt, polypropylene (PP), polyvinyl alcohol (PVA), and glass fibers, on interface strength, post-peak behavior, and compressive strength. The ultimate properties of the concrete are largely influenced by fiber alignment, with parallel alignment notably improving tensile strength [57,58]. For successful 3DP, it is also crucial to ensure that the fibers used are compatible with the printing technology. The increasing focus on utilizing waste and byproduct materials in concrete not only offers socioeconomic advantages but also contributes to environmental sustainability. Various industrial wastes and byproducts—such as fly ash, blast furnace slag, marble sludge, incinerator ashes, glass powder, metal slag, and rubber—are being employed to reduce carbon emissions and enhance sustainability [59]. Meyer [60] notes that incorporating blast furnace slag into concrete can lower the heat of hydration while simultaneously increasing strength. Additionally, the substantial waste generated during marble processing presents an opportunity for utilization. Since the carbonate in blast furnace slag has already undergone oxidation, this approach aids in reducing CO_2 emissions and energy consumption. Xing et al. [54] suggest that these materials hold promise for various applications, including road construction. Figure 5 illustrates the concrete materials utilized in 3DP technology.

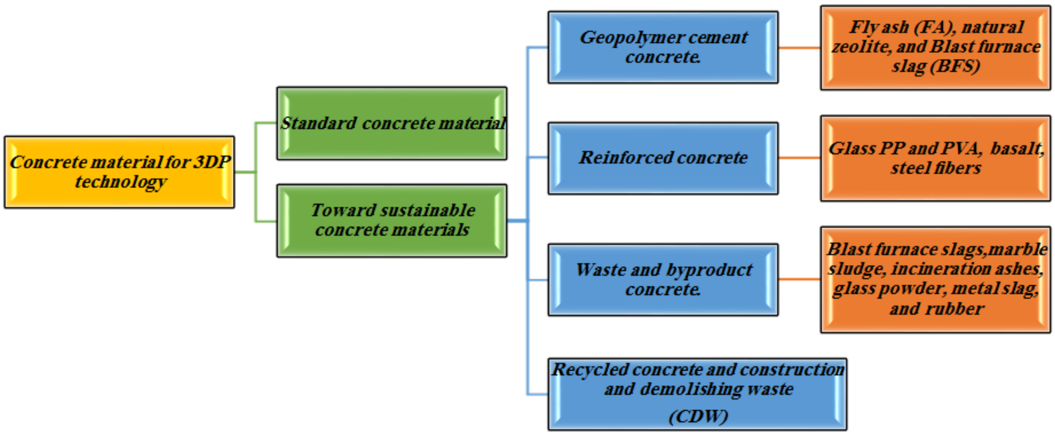

Fig. 5. Concrete material for 3DP technology [1].

When employing additive manufacturing in 3DPC to meet specific performance specifications, precise material selection is critical (see Figure 6). The desired properties of fresh 3DPC are achieved through the strategic use of various admixtures, aggregates, fibers, and supplementary cementitious materials (SCMs). A key step in the development process is the mix design for 3DPC, which involves the careful combination of these materials. The performance of 3DPC has been evaluated in relation to different components, including SCMs, admixtures, fibers, and aggregates, to aid in the selection of suitable raw materials. For example, Hou et al. [16] found that incorporating recycled sand into 3DPC can significantly enhance its buildability and green strength. Additionally, to ensure a long service life for 3DPC structures, factors such as printability and durability must also be addressed during the mix design process [16]. To effectively evaluate fresh concrete during the printing process, it is essential to develop in-line procedures that incorporate feedback and conditioning systems. As current mix design techniques for 3DPC are still evolving, further research is needed to improve their effectiveness in future applications [16]. The rheological properties of the concrete—specifically yield stress, viscosity, and thixotropy—are closely linked to the performance requirements of 3DPC, which include extrudability, buildability, open time, and setting time [16,34,45].

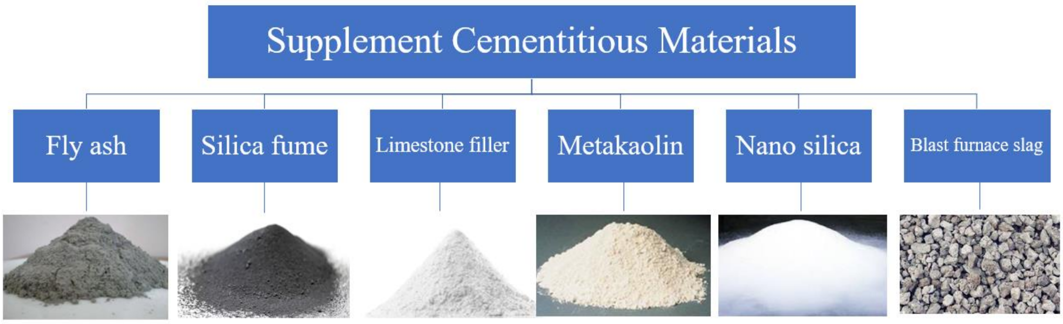

Fig. 6. The SCMs used in concrete and their influence on concrete performance.

Panda and Tan [61] developed a form of 3DPC that incorporated a substantial volume of fly ash, ranging from 45% to 80% of the binder mass. Chen et al. [62] demonstrated that a mixture of silica fume and fly ash could effectively replace 45% of the cement content. Additionally, Chen et al. [63,64] utilized metakaolin to enhance thixotropy, thereby improving the buildability of 3DPC. Kruger et al. [65] and Reales et al. [66] found that adding 1% nano-silica positively influenced several properties of 3DPC, including re-flocculation rate, thixotropy, and initial static yield stress. Hou et al. [16] showcased the potential of using a ternary binder system to improve both the fresh and hardened properties of concrete while simultaneously reducing CO_2 emissions. Salah et al. [51] investigated the effects of nano-$CaCO_3$ (NC) on the microstructure, workability, and strength of 3D printed cementitious materials. Their findings indicated that increasing the amount of NC decreased the fluidity of fresh 3DPC due to its high specific surface area, which enhanced mix consistency and stiffness but also reduced the vertical displacement of the filament. They observed that as the filament width decreased over time, the fresh mixes became more printable, although extruded filaments tended to lose their shape after certain durations. The adoption of 3DP technology in construction allows for faster project completion and greater creative flexibility by eliminating the need for traditional formwork [16]. However, preparing 3DPC presents significant challenges that can impact both the mechanical performance and the printing process of structures [16]. Unlike conventional concrete, 3DPC exhibits unique printability and anisotropic mechanical properties, which impose specific constraints on its rheology, green strength, and interlayer bonding [16]. Understanding the mechanical characteristics of 3D printed cementitious materials is essential for ensuring reliable performance and successful construction processes [16]. Recent advancements in the 3DP of cementitious materials have facilitated the fabrication of engineered structures [17]. Research into the mechanical properties of cementitious powder-based 3D printed structures has revealed a layered orthotropic microstructure, characterized by parallel strips within each layer [17]. Compression and flexural testing have been employed to assess the mechanical features and failure patterns, confirming that these 3D printed structures exhibit laminated characteristics [17]. Additionally, researchers have proposed failure criteria based on the maximum stress criterion and established a stress-strain relationship for orthotropic 3D printed material structures [17]. Finite element analysis has demonstrated that printing orientation significantly influences the load-bearing capacity of these structures [17]. These findings highlight the necessity of understanding the mechanical properties of 3D printed cementitious materials to ensure their effective application in engineering and construction [16]. Aggregates, which comprise 60% to 75% of the total volume of concrete mixes, play a pivotal role in influencing the strength of the mixture [67]. The type and quantity of aggregates used can significantly affect the mechanical properties of concrete, while the size of coarse aggregate particles can impact the final texture and processability of the concrete [52,57]. Therefore, it is crucial to consider the influence of coarse aggregate structure on the suitability of concrete for 3DP, despite the potential benefits of adding more aggregate to reduce manufacturing costs and achieve specialized finishes [52,57]. Table 2 presents the mechanical characteristics of materials utilized in 3DPC.

Table 1. Mechanical Properties of Materials in 3DPC.

Material	Age [Days]	Target Fresh Density (Kg/m^3)	Dry Density (Kg/m^3)	Compressive Strength [MPa]	Flexural Strength [MPa]	Ref
Foam Concrete	7-28	1200	980	1.94-2.12	8.20-10.40	
3DP Cementitious Materials Containing Nano-$CaCO_3$	7-90	-	-	2,400 N/s	50 N/s	[24,25]
silica fume (SF)	28	-	-	70.7 MPa	20.66 MPa	[51]
graphene nanoplatelets (GNPs)	28	-	-	133.3 MPa	20.66 MPa	[51]
Recycled Sand Aggregate (RSA)	28	2410.7	1014/1070	19.3	in Z direction was 4.5 MPa, in X direction increased to 3.5 MPa	[68]
	14	2410.7	1014/1070	16.6	3.1	
	7	2410.7	1014/1070	11	1.2	
Recycled Brick Aggregate (RBA)	28	1787	-	39.9	-	[69,70]

Ding et al. [68] found that specimens made with recycled sand in 3DPC exhibited slightly lower compressive strength compared to those using natural sand. However, the incorporation of recycled sand did not lead to a consistent trend in the development of splitting tensile strength and flexural strength. Notably, the anisotropic nature of the 3DPC was maintained, as the addition of recycled sand did not affect the anisotropy of the compressive and flexural strengths. Utilizing recycled sand in 3DP represents a cost-effective approach for producing 3DPC, particularly given the rising prices of river sand [68].

4.3. Environmental assessment of 3DPC

The environmental impact of producing and using concrete components made with 3DP (3DP) technology is an important area of study within the broader context of sustainable construction practices. This evaluation involves examining various factors, including emissions, waste generation, resource utilization, and energy consumption, to gain a comprehensive understanding of the environmental performance of 3DPC. Research in this field has highlighted several methods for assessing the environmental performance of construction projects. Alhumayani et al. [7] identified techniques such as CML (Centrum voor Milieuwetenschappen Leiden), EDIP (Environmental Design of Industrial Products), ReCiPe, and TRACI (Tool for the Reduction and Assessment of Chemical and other Environmental Impacts) as valuable tools for environmental evaluation. Yao et al. [71] conducted a comparative study on the environmental performance of geopolymer technology versus conventional concrete using Life Cycle Assessment (LCA) methodology across four different scenarios.

Their findings revealed that 3DP technology facilitates the creation of complex building components that not only reduce waste but also demonstrate improved environmental performance. The significance of 3DPC in the construction industry can be summarized in several key areas:

1. Energy Consumption: 3DP technology has the potential to enhance energy efficiency in buildings by allowing for the production of multilayered, well-designed components that effectively reduce heat transfer and improve thermal insulation. This innovation may lead to a decreased reliance on traditional HVAC (heating, ventilation, and air conditioning) systems in structures that utilize 3D printed materials [72].

2. Air Quality: The precision and customization capabilities of 3D printers can significantly benefit indoor air quality. By enabling the fabrication of tailored ventilation and air purification components, such as 3D-printed air filters, these technologies can effectively remove airborne pollutants and enhance overall indoor air quality [73,74].

3. Water and Wastewater Treatment: In the realm of water management, 3DP plays a crucial role by allowing for the production of high-precision components used in pollution reduction, filtration, and treatment systems. For instance, 3D printed water filters can efficiently eliminate various contaminants, contributing to cleaner drinking water [73,75].

4. Sustainable Development: The use of 3DP in construction promotes sustainable practices by enabling the creation of eco-friendly building materials with complex geometries while minimizing material waste. This aligns with broader goals of sustainable development within the construction industry. Innovations like EcoPrinting, which utilizes waste polymers as raw materials and boasts a near-zero carbon footprint, exemplify how 3DP can contribute positively to both humanitarian efforts and infrastructure repair [76].

In summary, the adoption of 3DP technology in concrete construction presents numerous opportunities for enhancing environmental performance, promoting sustainability, and addressing contemporary challenges in the construction industry.

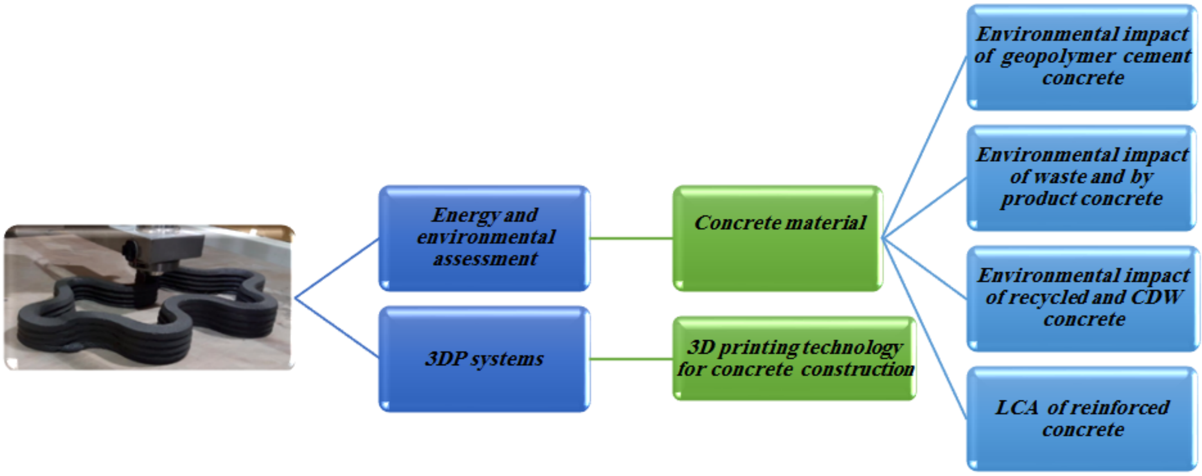

Fig. 7. Sustainability assessment for 3DCP technology for concrete construction [1,47].

A Life Cycle Assessment (LCA) study cited in [77] found that 3DPC reduces GHG emissions by 40–78% compared to conventional concrete mixtures when supplementary cementitious materials (SCMs) such as slag, fly ash, or calcined clay are used. This reduction is attributed to material optimization and reduced cement content. Another study demonstrated that adding 2 wt% biochar to 3D-printed concrete decreases its carbon footprint by 8.3% while enhancing structural performance [78]. The use of low-carbon cementitious mixtures (e.g., geopolymers, recycled aggregates) in 3DPC can lower emissions to 113–305 kg CO_2/m^3, compared to traditional mixtures (330–680 kg CO_2/m^3) [77]. 3DP enables formwork-free construction and topology-optimized designs, reducing material waste by depositing concrete only where structurally necessary [77,79]. A pilot project using calcined clay and biochar-augmented mixtures achieved enhanced material efficiency by improving hydration and reducing cement content [78]. Computational design tools for 3DPC allow architects to create complex geometries with minimal material use, though comprehensive quantitative data (e.g., a potential 25% improvement) is often omitted in studies [79]. Dubai's 3D Printing Strategy aims to deploy 3DP in 25% of new buildings by 2030, emphasizing waste reduction and labor savings [77]. LCA comparisons indicate that 3DPC reduces waste by 10–30% in structural components like walls and pillars compared to traditional methods [77,79]. 3DPC eliminates formwork and reduces manual labor, though exact percentages (e.g., 20%) are not quantified in the provided sources [79]. According to Alami et al. [67], 3DCP offers significant cost and resource savings: labor expenses may decrease by ~60%, and associated traditional construction costs by up to 78%. In traditional concrete construction, reinforcing steel accounts for 49% of the environmental impact, while concrete itself contributes 19%. In contrast, 3DPC's superior environmental performance stems from its elimination of reinforcing steel bars [67]. Alhumayani et al. [7] corroborate this, highlighting 3DPC's reduced environmental footprint due to its lack of steel reinforcement.

Textile Reinforced Mortars (TRMs) are novel composites considered a viable alternative to Fiber Reinforced Polymers (FRPs) for strengthening structural elements. TRMs exhibit superior fire resistance, enhanced environmental compatibility, and improved structural safety compared to FRPs, owing to their strong substrate bond and diverse failure modes. Jahangir et al. [80] calibrated TRM-concrete bond models to predict bond strength using a database of 221 experimental direct shear tests. Their simplified model, refined via soft computing, achieved an R-value of 0.6909 and NMAE of 12.62% for various fiber types and geometries. Janfada et al. [81] evaluated Steel Reinforced Polymer (SRP) and Steel Reinforced Grout (SRG) composites for column strengthening. The CNR-DT200 standard best predicted SRP-confined column strength (R=0.7671, MAPE=7.39%). SRP models outperformed SRG models, likely because existing models are designed for FRPs, not TRMs. Onyelowe et al. [82] investigated agro-industrial by-products (e.g., fly ash [FA], rice husk ash [RHA]) in sustainable concrete production. Using Artificial Neural Networks (ANN) and Evolutionary Polynomial Regressions (EPR), they predicted the mechanical/hydraulic properties of FA- and RHA-based concrete and developed a smart mix design tool. Onyelowe et al. [83] analyzed 192 Ultra-High Performance Concrete (UHPC) mixes to reduce lab testing reliance. A life cycle assessment identified Mix C-783 (87 kg/m^3 RHA) as environmentally optimal, but Mix C-300 (75 kg/m^3 RHA) was preferred for balancing strength and sustainability. Their ANN-BP model (Backpropagation) most accurately predicted compressive strength (R=0.989, R^2=0.979, MAPE=4.95%), outperforming previous models.

4.4. 3DPC: Potentials and Challenges

Large-scale implementation of additive manufacturing of concrete, or 3D concrete printing, presents issues for the construction industry, as Figure 8 illustrates. The scarcity of knowledge and information on this technology is one of the primary challenges. To achieve successful adoption, however, further study is necessary as Additive Manufacturing of Concrete opens up new possibilities. The ability of the printed concrete to pass easily through pipes during the printing process is known as pumpability, and it is one of the important topics that require further investigation. The capacity of the concrete to be precisely extruded via nozzles is known as extrudability, and it is still another crucial factor. For printed concrete to stay in the desired shape after extrusion, buildability is essential. The last factor to consider is shape retentivity, which guarantees that the concrete has the strength to support stresses from higher layers without buckling [84]. Building components and homes may be quickly constructed with 3DP technology by successfully solving issues like pumpability, extrudability, buildability, and form retentivity. In addition to maximizing resource utilization and reducing waste, this can result in considerable cost reductions for building projects [84]. To completely realize the promise of 3D concrete printing in the construction industry, more research and development in these domains are necessary.

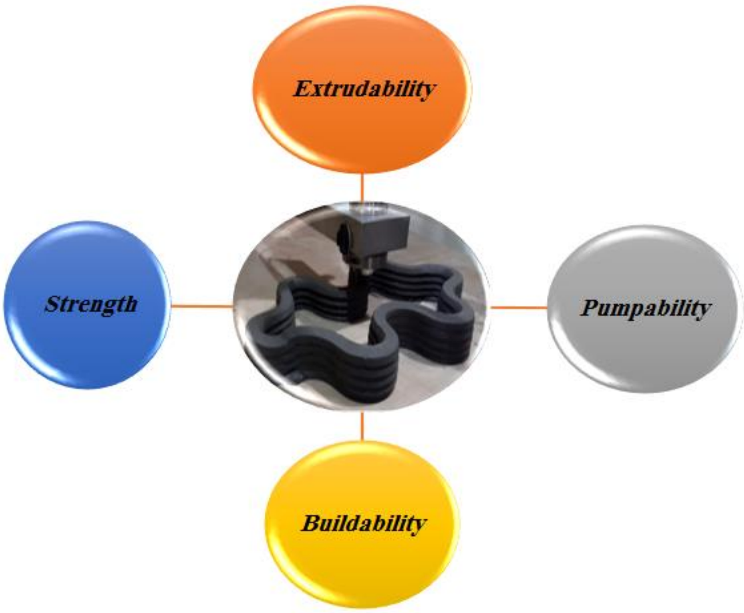

Fig. 8. Challenges in 3D Printable Concrete (3DPC) [47].

Recent research has brought to light the difficulties facing 3DP technology for concrete, including the complexity of cement-based materials [23]. For extrusion, the material must have an appropriate thixotropy, meaning it should be sufficiently pumpable and fluid for extrusion, show maximum workability and flowability for layer placement, and maintain its shape after deposition [23]. In addition, it has been highlighted that 3DP technology offers benefits to the construction industry, such as shorter construction times, higher productivity, and improved system dependability [85]. Moreover, the use of

3DPC in the construction industry holds the potential to alleviate several problems faced by traditional construction techniques, including limited industrialization, environmental pollution, and excessive raw material consumption [16]. The benefits of 3DP technology in the construction industry have been emphasized by Alhumayani et al. [7]. These benefits include less waste, a smaller carbon footprint, and a wide range of customization options. Xing et al. [54] state that issues with material and production constraints must be resolved for 3DP concrete technology. Using alternative material systems requires consideration of specific elements, such as material development and intuition, in addition to fundamental qualities [54]. Furthermore, according to Zechmeister et al. [86], the mechanical properties of the material demonstrate that the material system significantly affects design boundary conditions including component size, span, connection type, and number. The limitations of the materials and manufacturing techniques highlight the need for further research and advancement in the field of concrete technology for three-dimensional printing. According to Hu et al. [53], there are three primary areas of concentration for current research on 3DP materials in the construction business. They fall into three primary categories: (1) the quality of concrete produced with the use of 3DP and construction technology; (2) the benefits of 3DP for the environment, economy, and society; and (3) the use of 3DP in conjunction with building project management methodologies. These research topics provide light on many facets of the use of 3DP in the building industry. The AEC sector has had to adjust in light of the pressing need to solve the global climate problem. For example, Denmark has established emission threshold restrictions for newly constructed buildings, with the aim of bringing them down from 12 kg CO_2eq/m^2/year to 7.5 kg CO_2eq/m^2/year by 2029. Furthermore, Heywood & Nicholas [79] and Eriksen & Kamari [87] have suggested a voluntary standard of 5 kg CO_2eq/m^2/year. Life life cycle assessments (LCAs), are now an essential component of the design process in order to evaluate the environmental effect of a structure throughout its whole life cycle. Based on the extraction of raw materials, construction, use, and disposal, LCAs evaluate the environmental impact of a structure. According to Flatt and Wangler [88], experts are now disputing the sustainability of 3DCP. Some have claimed that the technology's sustainable attributes may be seen in the reduction of formwork requirements and material optimization [79,89,90]. On the sustainability of 3DPC, there are, nevertheless, differing opinions within business. Though there are LCAs tools available for traditional building methods, there is a lack of tools for comparing novel manufacturing approaches in 3DCP [7,71,76,79,91]. Few studies have conducted LCAs of 3DCP components [79,91], some of which have examined individual walls and others that have examined entire structures. Applying LCAs to 3DCP causes problems with material specifications, defining system boundaries, and determining the functional unit.

The lines become increasingly blurry when it comes to 3DP concrete, raising questions like how to account for the influence of the fabrication unit and whether mixing raw materials for on-site printing counts as manufacturing or construction. Material composition, manufacturing process, and material amounts are the primary focus of current research and LCAs assessments from a cradle-to-gate perspective [89,92]. But end-of-life procedures and concrete waste must also be taken into account. Attention must be paid to the growing amount of concrete waste from building demolition and the requirement for efficient recycling methods. To fully comprehend the effects of 3DCP, environmental impact assessments must take circularity and waste minimization through 3DCP into account [8].

It is challenging to construct a consistent functional unit in 3DCP because of the variability in print width and complexity within a single project [84,92–94]. This makes it difficult to compare the LCA of 3DCP elements to traditional manufacturing methods since different studies employ different functional units, such as 1 kg of concrete, 1 m^2 of a load-bearing wall with variable depth, or a specified dimension of a detached house [95]. A uniform and adaptable method of measuring the functional unit for 3DCP is being researched to improve comparisons and guarantee significant outcomes. That being said, it is especially important in architecture to take into account a 3DCP element's total influence in relation to the broader building framework. According to Heywood and Nicholas [79], incorporating LCAs into the design process can result in a more comprehensive approach and the creation of ecologically sustainable three-dimensional concrete podiums. Salah et al. [51] state that there are opportunities to optimize material usage, increase design flexibility, and improve energy efficiency using the environmental evaluation of 3DPC. However, problems with robustness, printability, waste management, and material selection need to be solved [29,52]. Alhumayani et al. [7] state that conducting focused life cycle evaluations, promoting material innovation, and fostering collaboration and standardization are essential to overcoming these challenges. These programs will assist in making 3DPC processes more sustainable and beneficial to the environment [23].

5. Conclusion and Perspectives

The advancement of 3DP technology has significantly contributed to building industrialization and intelligent construction, yet its adoption in the industry faces challenges primarily related to the materials used in 3DPC. The unique layer-by-layer construction of 3DPC requires different mix designs than traditional concrete, and while improvements in mix designs may reduce environmental impacts, research on the material properties, durability, and resistance to corrosion is still lacking.

To enhance sustainability, researchers are exploring the use of unconventional but accessible materials, emphasizing the integration of historical building culture with practical expertise. Overall, 3DP technology offers innovative solutions to persistent construction issues, potentially increasing efficiency and reducing environmental impacts. However, further research is needed to address existing challenges and fully realize its potential.

Opportunities for 3DPC:

1. Material Optimization: Precise material placement can reduce waste and enhance resource efficiency.

2. Energy Efficiency: 3DPC may require less energy compared to traditional construction methods due to reduced labor and formwork needs.

3. Design Flexibility: The technology allows for complex designs and customization, leading to economical material use and lower environmental impact.

Challenges to Consider:

1. Material Selection: The environmental impact is highly dependent on material choices, necessitating careful evaluation of their availability and carbon footprint.

2. Printability and Durability: Ensuring the structural integrity and longevity of materials can minimize maintenance needs and associated environmental effects.

3. Waste Management: Effective management and recycling of waste generated during the 3DPC process are essential for reducing environmental impacts and promoting a circular economy.

Perspectives for Environmental Assessment:

1. Life Cycle Assessments (LCAs): Conducting LCAs specific to 3DPC can provide insights into environmental impacts throughout the material's lifecycle.

2. Material Innovation: Research should focus on alternative materials, such as bio-based or recycled options, to enhance sustainability.

3. Collaboration and Standards: Cooperation among academia, industry, and regulatory bodies is crucial for establishing standardized procedures and certifications for environmental assessments of 3DPC.

Future research directions and practical implementation strategies

Future research directions

To address the challenges associated with 3DPC and advance its adoption, the following research directions are proposed:

1. Material Innovation and Optimization

- Sustainable Binders: Develop low-carbon cementitious materials, such as geopolymers, alkali-activated binders, and biochar-augmented mixtures, to reduce reliance on Portland cement and lower embodied carbon.
- Recycled Aggregates: Investigate the use of industrial by-products (e.g., recycled sand, marble sludge, blast furnace slag) to improve resource efficiency and circularity.
- Fiber Reinforcement [96]: Optimize fiber alignment (steel, basalt, PVA) to enhance tensile strength and ductility while ensuring compatibility with printing processes.

2. Process Control and Scalability

- Rheological Properties: Establish standardized metrics for extrudability, buildability, and open time to ensure consistent print quality across mix designs.
- AI-Driven Optimization: Integrate machine learning (ML) and artificial intelligence (AI) to predict material behavior, optimize mix designs, and automate print parameter adjustments.

3. Structural Performance and Durability

- Anisotropy Mitigation: Study interlayer bonding mechanisms and develop strategies to minimize anisotropic behavior in printed structures.
- Long-Term Durability: Evaluate resistance to environmental stressors (e.g., freeze-thaw cycles, chemical corrosion) and refine curing methods for enhanced service life.

4. Environmental and Socio-Economic Impact [97]

- Comprehensive LCAs: Expand life cycle assessments (LCAs) to include end-of-life recycling, circularity, and comparisons with traditional methods using standardized functional units.
- Socio-Economic Studies: Assess job creation potential in 3DPC-related fields (e.g., digital design, equipment maintenance) and localized manufacturing benefits.

5. Regulatory and Standardization Frameworks

- Code Development: Collaborate with industry bodies (e.g., ACI, ISO) to establish design codes, safety standards, and certification protocols for 3DPC structures.
- Policy Incentives: Advocate for government subsidies and carbon credits to promote sustainable 3DPC adoption, aligning with initiatives like Dubai's 3DP Strategy.

Practical implementation strategies

To translate research advancements into industry practice, the following implementation strategies are recommended:

1. Industry-Academia Collaboration

- Pilot Projects: Partner with companies like CyBe and Winsun to test novel materials (e.g., geopolymers, recycled aggregates) in real-world applications, such as affordable housing or infrastructure repairs.
- Digital Twins: Use Building Information Modeling (BIM) to simulate 3DPC workflows, validates designs, and reduces on-site errors.

2. Workforce Training and Technology Transfer

- Skill Development: Launch training programs for architects, engineers, and laborers on 3DPC design software (e.g., CAD), printer operation, and maintenance.
- Open-Source Platforms: Share mix designs and printing parameters through collaborative databases to accelerate knowledge dissemination.

3. Sustainable Material Supply Chains

- Local Sourcing: Utilize regionally available waste materials (e.g., fly ash, rice husk ash) to reduce transportation emissions and costs.
- Circular Economy: Implement take-back programs for unused concrete paste and printed formwork to minimize waste.

4. Policy and Market Adoption

- Regulatory Sandboxes: Work with governments to create testbeds for 3DPC in public infrastructure projects, easing regulatory barriers.
- Carbon Pricing: Incentivize low-carbon 3DPC mixes through tax rebates or carbon trading schemes, as seen in Denmark's emission thresholds.

5. Advanced Manufacturing Integration

- Robotic Swarms: Deploy multiple mobile printers for large-scale projects to improve speed and scalability.
- Hybrid Techniques: Combine 3DP with prefabrication for complex components (e.g., joints, façades) to enhance structural integrity.

In general, by addressing material, structural, and regulatory challenges through targeted research and strategic industry partnerships, 3DPC can transition from a niche technology to a mainstream construction method. Practical implementation will require coordinated efforts across academia, industry, and policymakers to ensure scalability, sustainability, and socio-economic benefits.

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Conflicts of interest

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

Authors contribution statement

Marjan Salari: Investigation; Methodology; Roles/Writing – original draft.

Behnam Akhoundi: Project administration; Validation; Writing – review & editing.

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