



Exploring knowledge domains and future research directions in 3D printed concrete: a bibliometric and systematic review

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Abstract

3D printed concrete (3DPC) is an advanced additive manufacturing technique which aids in creating complex structures with precision and efficiency. This innovative technology offers substantial benefits, including minimised material waste, enhanced project completion speed, and the capability to fabricate complex and distinctive designs. While significant progress has been made, existing review studies primarily address specific domains such as materials, technical and non-technical challenges, rheological parameters, and modelling. However, limited research has explored quantitative data on leading countries and institutions, collaboration networks, profiles of influential authors, and key journals. Furthermore, there is a lack of comprehensive qualitative insights into the managerial, sustainability and environmental, and economic aspects of 3DPC, as well as advancements in material compatibility, mix design methods, and applications of emerging technologies. This study addresses these gaps by conducting a bibliometric and systematic review of 3DPC research from 2015 to 2024, with data sourced from Web of Science and Scopus. The bibliometric analysis revealed a steady growth in 3DPC studies, with annual publications increasing by over 800% between 2018 and 2024, and major contributions from China (28%), Australia (10%), and the USA (7%). Tongji University emerged as the leading institution, accounting for 8% of the total publications. The systematic review discusses the key advancements in technology and structural development while uniquely focusing on the managerial aspects of 3DPC. By integrating bibliometric and qualitative insights, this review provides a comprehensive understanding of the current state and future potential of 3DPC, offering valuable guidance for researchers and practitioners aiming to advance this transformative technology.

Keywords 3D printed concrete · Mix design · Material properties · Construction · Sustainability · Systematic review · Bibliometric analysis

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Introduction

Three-dimensional printing (3DP) also known as additive manufacturing (AM), is a computer-aided, layer-by-layer material deposition technique that facilitates the fabrication of complex geometries without the need for moulds, bracings, or formwork [1]. The technology emerged in the mid-1980s with the introduction of stereolithography (SLA) by Charles Hull [2]. Subsequent developments included Fused Deposition Modelling (FDM), powder bed fusion, Contour Crafting (CC) and inkjet printing [3]. While 3DP is widely used in automotive, prototyping and biomedical fields, its adoption in construction has been comparatively slower [2]. 3DP construction employs digital models to layer materials like concrete or polymers systematically, revolutionising building processes through precision, customisation, and efficiency [4]. AM techniques are often referred to interchangeably as rapid prototyping or free-form construction [5]. This emerging technology offers several advantages over traditional construction methods, including waste reduction, elimination of formwork, lower energy use, faster project timelines, reduced labour requirements, and enhanced design flexibility, thereby supporting more sustainable practices [4–6].

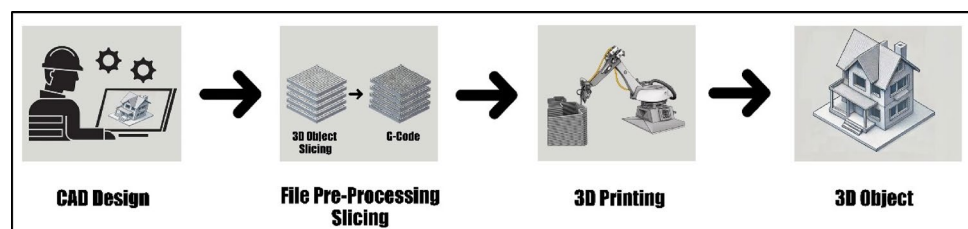
3DP process begins CAD modelling, exported in STL format. A slicing program generates the G-code to guide the printer during printing [7], as depicted in Fig. 1. The era of construction 3DP began in 1997 when Pegna from Rensselaer Polytechnic Institute first applied 3DP technology to construction [2]. In the same year, Khoshnevis developed the contour crafting (CC) technique at the University of Southern California, further promoting AM in construction. Since then, research has advanced in material development, printer optimisation, and application-specific solutions. Notable milestones include Concrete Printing at Loughborough University (2003), Dini's D-Shape system, and Gosselin's selective deposition for ultra-high-performance concrete [4, 8]. These advancements have paved the way for more automated and efficient construction systems.

These technologies have enabled the fabrication of large-scale construction elements and even entire buildings. The first residential building was made in 2014, marking the first commercial use of AM techniques [9]. By 2016, the technology had progressed to allow the on-site construction of entire houses. The most notable projects globally include

Dubai's single-storey office buildings, built using reinforced concrete, fibre-reinforced plastic, and glass fibre gypsum, and Apis Cor's mobile printer for cement-based residential construction [9]. An entire building can be constructed within days using 3DP. A military shelter was completed in 36 h, while Shanghai's pedestrian bridge, recognised by the Guinness World Records, is the largest 3D printed bridge to date [10]. In 2024, the world's first 3D printed mosque, covering 5600 square meters, was constructed in Saudi Arabia through a partnership between Fursan Real Estate Company and Guanli, a Chinese firm specialising in 3DP for construction [11]. Although significant progress has been made, 3DP in construction is still in its early stages, with ongoing research focused on enhancing printer capabilities and developing advanced construction materials.

Recently, numerous studies have been conducted to comprehensively review various aspects and applications of 3DPC innovations, highlighting its multifaceted impact on the construction sector. Among these, Salazar et al. [12] explored the opportunities and challenges associated with AM in the construction sector, specifically focusing on 3DP with cementitious materials. They concluded that technological advancements in this area are increasing, indicating promising future directions for the field. Concurrently, Du Plessis et al. [10] examined the viability of complexity and biologically inspired design in 3DPC, focusing on the implications for construction technology and materials. They highlighted the future directions for integrating bio-inspired approaches into 3DPC applications. Similarly, Ngo et al. [3] thoroughly overviewed 3DP techniques in the context of key methods applied, materials used, and its contemporary condition and applications in various industries. Building on this, Chen et al. [13] conducted a comprehensive review of 3DP geopolymer systems, focusing on the influence of raw materials on processability attributes such as flowability and thixotropy, as well as on microstructural characteristics. Moreover, Ahmad et al. [14] reviewed the developments and challenges in 3DP technology for sustainable construction practices. Similarly, Hamidi et al. [15] examined reinforcement techniques in 3DP for cementitious composites and highlighted their critical role in advancing the technology. Following this, Shakor et al. [16] examined 3DP with cement-based materials (CBMs), focusing on concrete mixes and evaluating their key properties. Additionally, Khan et al. [17] analysed the state of the art

Fig. 1 3D printing process



and practice in 3DPC, covering its historical development, material innovations, equipment, and computational modelling. In addition, Sadhu et al. [5] conducted a systematic review of recent 3DPC technologies for construction, analysing methods, software, materials, and both technical and non-technical factors. The study highlighted its significance and key applications in large scale projects. Jandyal et al. [18] reviewed various 3DP processes, outlined their advantages and limitations and detailed the materials compatible with each, contributing to a deeper understanding of 3DP technologies. Furthermore, Khan et al. [19] reviewed the impact of nanomaterials on the fresh and hardened properties of 3D printed cement-based materials, examining their optimal and maximum dosages in mix designs. The findings suggest that nanomaterials enhance thixotropic behaviour and structural development, acting as thickeners.

These review articles collectively address the significant and recent developments of 3DPC within the construction industry, focusing on specific domains such as materials, technical and nontechnical challenges, rheological parameters, modelling approaches, and the main methods employed. Despite substantial progress and extensive research, a clear gap remains in the existing body of knowledge. To date, few studies have explored quantitative data on leading countries and institutions contributing to 3DPC research, collaboration networks, profiles of key authors, and the main journals and conferences disseminating this knowledge. Moreover, comprehensive qualitative insights into emerging areas such as material optimisation, mix design innovations, and the sustainability, environmental, economic, and managerial aspects of 3DPC remain limited. To address these gaps, this review provides an extensive bibliometric and systematic analysis of 3DPC. It maps existing knowledge domains, identifies pivotal areas requiring innovation, and highlights underexplored topics essential for the development of robust and sustainable 3DPC technologies. The findings contribute to the establishment of standardised methodologies for evaluating 3DPC properties and performance while offering valuable directions for future research and development. This review aims to provide a holistic overview of the current research landscape and the multifaceted potential of 3DPC in transforming the construction industry. The specific objectives of this study are:

1. Quantitatively analyses the contributions of leading countries and institutions driving research on 3DPC.
2. Profile key authors, collaborative networks, and the primary journals and conferences disseminating 3DPC knowledge.
3. Highlight qualitative insights into new frontiers in the application of 3DPC technology, advancements in materials, material properties, effects of materials on

3DPC properties, advancements in mix design methods, sustainability, environmental, economic, and managerial aspects of 3DPC.

4. Evaluate the practical implementation and future potential of 3DPC technology.

To support the rationale of the study, the scientific significance of each objective is outlined, emphasising their contribution to both foundational knowledge and future advancements in 3DPC research. The quantitative assessment of contributions from leading countries and institutions enables the identification of prominent research regions, leading academic hubs, and variations in the global distribution of scholarly output. The analysis of key authors, collaborative networks, and primary publication sources provides insight into the intellectual structure of the field and the processes through which knowledge is generated and disseminated. Furthermore, the synthesis of qualitative evidence related to material innovations, mix design methodologies, and sustainability considerations promotes a comprehensive understanding that integrates technical performance with environmental, economic, and managerial dimensions. Finally, the evaluation of practical implementation and long-term potential underscores the relevance of 3DPC in advancing sustainable, efficient, and digitally enabled construction practices. These objectives contribute to the advancement of scientific understanding, guide future research priorities, and support evidence-based decision making across academic, industrial, and policy making domains.

The structure of this paper is organised as follows: Section “[Methodology](#)” describes the methodology employed in this study. Section “[Bibliometric analysis results](#)” presents the bibliometric analysis results, offering insights into trends, collaborations, and key contributors in 3DPC research. Section “[New Frontiers in the application of 3D printed concrete technology](#)” explores new frontiers in the application of 3DPC technology and advancements in material development. Section “[Material properties of 3D printable concrete](#)” examines the material properties critical to 3DPC performance, followed by Section “[Effect of materials on 3D printed concrete properties](#)”, which evaluates the effects of materials on the properties of 3DPC. Section “[Mix design methods for 3D printed concrete](#)” discusses mix design methods, focusing on innovations and optimisation techniques. Section “[Sustainability, environmental, economic, and managerial aspects of 3D printed concrete](#)” evaluates the sustainability, environmental, economic, and managerial impacts of 3DPC. The paper concludes with Section “[Conclusion](#)” summarising the key findings and Section “[Recommendations for future studies](#)” providing

recommendations for future research and development in this field.

Methodology

This study aims to explore the knowledge domains and establish a future research agenda for 3DPC in the construction industry by systematically analysing the existing literature. The review employs a mixed-method approach, combining systematic and bibliometric analyses to ensure a comprehensive investigation. The systematic review provides a broad overview of the research landscape, offering insights into trends, challenges, and advancements in 3DPC. Unlike narrative literature reviews, which often focus on descriptive findings and may be subject to selection bias, this approach ensures a more structured and unbiased synthesis of the literature. While a bibliometric analysis complements this by quantifying publication attributes, utilising citation analysis to construct a citation graph a visual representation of the connections between documents. This method is instrumental in identifying influential works, key contributors, and collaborative networks in the field. Together, these approaches provide a robust foundation for understanding the state of 3DPC research and shaping future directions.

Data collection source

The primary sources of literature for this study were the Scopus and Web of Science (WoS) databases, selected for their extensive coverage of peer-reviewed articles across multiple disciplines, which ensures a high-quality and comprehensive review [20]. This selection facilitated an in-depth investigation into the current research landscape on 3DPC. The review included journal articles, conference papers and review articles. To maintain relevance as well as quality, only peer-reviewed documents written in English and explicitly focused on 3DPC or related AM processes with concrete were considered. The analysis focused on publications from 2015 to 2024. This time frame was selected to provide understanding of the most recent developments in the domain of 3DPC, reflecting both the current state of the art and the evolution of the field over the past decade.

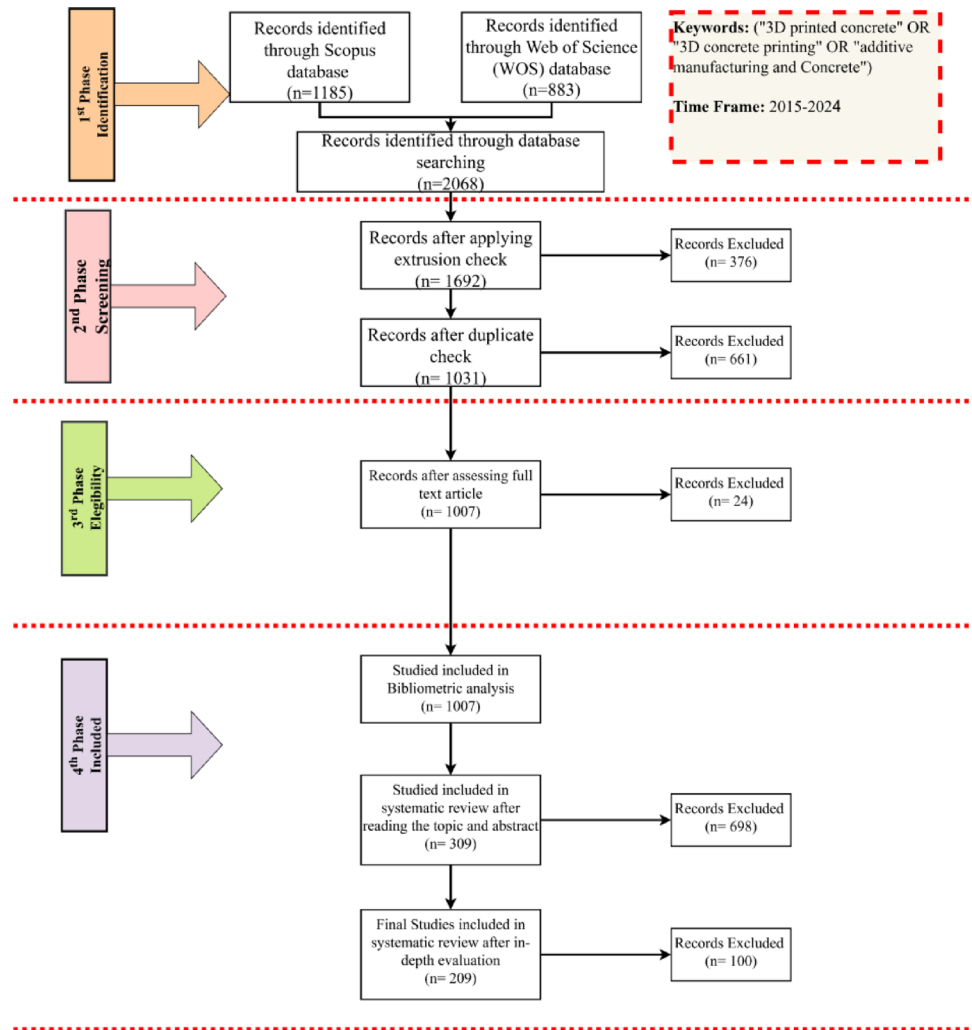
The review process adhered to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines [21]. The search string combining the keywords “3D printed concrete,” “3D concrete printing,” or “additive manufacturing and concrete” was entered into the Scopus and WOS search engines. This preliminary search resulted in 1186 documents from the Scopus database and 883 from the WoS database, as depicted in Fig. 2. After applying filters for year, document type, language, and subject area to

both databases, the counts were narrowed down to 945 for Scopus and 747 for WoS, totalling 1692 documents. Subsequently, the Scopus dataset was exported as a “BibTeX” file and the WoS dataset as a “Plain text” file. Both the files were merged into a single “.xlsx” file using R-Studio software to remove duplicates from both databases. A total of 661 documents were identified as duplicates. After their removal, 1031 documents remained for further screening. The next phase involved a detailed evaluation of the remaining documents. A full-text screening excluded 24 documents due to inappropriate document types. This left 1007 documents eligible for bibliometric analysis. For the systematic review, a more focused screening process was employed to ensure relevance to the objectives of the study. Documents were assessed based on their topics, abstracts and introductions to determine their alignment with the research focus. Through this process, 698 documents were excluded as irrelevant or unsuitable for inclusion. A total of 309 documents were subsequently examined in detail for the systematic review. However, upon in-depth evaluation, around 100 of these studies were excluded due to overlapping ideas, repetitive information or similar case studies that did not contribute additional insights to the analysis. Consequently, the final selection comprised 209 unique and highly relevant documents included in the review. This stepwise screening process ensured that the included documents were rigorously evaluated, providing a robust foundation for the bibliometric and systematic review analyses of 3DPC research. The approach highlights both the scope and detail of the study, ensuring a comprehensive understanding of the knowledge domains and future directions in this evolving field.

Data analysis tools

For the analysis of the collected literature from the Scopus and WOS, we utilised VOSviewer and Biblioshiny software, focusing on studies published between 2015 and 2024. To construct and visualise bibliometric networks i.e., co-authorship, citation, and co-occurrence networks, VOSviewer was employed. This facilitated the identification of key researchers, influential articles, and emerging trends within the knowledge domain. Biblioshiny, an R-based tool, developed by Professor Massimo Aria in 2017, can be used for a more comprehensive bibliometric analysis, enabling the exploration of data through interactive visualisations [22]. It provided insights into publication trends, thematic evolution, and research hotspots in the field of 3DPC. The use of Biblioshiny facilitated the efficient processing of data extracted from the WOS and Scopus databases. Prior to the execution of biblioshiny, the bibliometrix package was installed via RStudio using the CRAN repository command “*install.packages(“bibliometrix”)*”. Following installation,

Fig. 2 PRISMA flow diagram of the search strategy



the library was invoked within the R environment using ‘*library(bibliometrix)*’, thereby enabling access to its comprehensive suite of functions. To initiate the biblioshiny application, the command ‘*biblioshiny()*’ was entered. This function call prompted the default web browser, such as Google Chrome, to initiate the biblioshiny web interface.

Bibliometric analysis results

This section presents the findings of the bibliometric review of the 1007 documents on 3DPC published from 2015 through 2024. Table 1 provides the key descriptive details of the dataset, analysed using Biblioshiny [22].

Mapping the research landscape of 3DPC: trends, key sources, and leading journals

The analysis of 3DPC research from 2015 to 2024 indicates a significant upward trajectory, with annual publications rising

from 1 in 2015 to 37 in 2018 and reaching a peak of 341 in 2024, indicating increasing scholarly interest in the field, as depicted in Fig. 3. The most prolific journals include *Construction and Building Materials* (131 articles) and *Cement and Concrete Composites* (72 articles), while other notable contributors, such as the *Journal of Building Engineering* and *Cement and Concrete Research*, also show substantial research output, as depicted in Fig. 4. Citation analysis further identifies *Construction and Building Materials* (6182 citations) and *Cement and Concrete Research* (5774 citations) as the most influential, signifying their pivotal roles in advancing knowledge in 3DPC, as depicted in Fig. 5. This upward trend, coupled with key sources and citation patterns, reflects the field’s evolving research landscape and its growing impact on construction innovation.

Table 1 Descriptive information about the datasets

Main information	
Description	Results
<i>Main information about data</i>	
Timespan	2015:2024
Sources (Journals, Books, etc.)	215
Documents	1007
Annual growth rate %	64.66
Document average age	2.34
Average citations per doc	23.66
References	18,663
<i>Document contents</i>	
Keywords plus (ID)	2361
Author's keywords (DE)	2324
<i>Authors</i>	
Authors	1955
Authors of single-authored docs	16
<i>Authors collaboration</i>	
Single-authored docs	18
Co-authors per doc	4.53
International co-authorships %	22.74
<i>Document types</i>	
Article	723
Review	93
Proceedings papers	45
Conference paper	129
Other	17

Leading countries and institutions in 3D printed concrete research

A deeper look into the geographical distribution of 3DPC research, as depicted in Fig. 6, reveals that China, Australia, and the USA are the leading countries driving the growth of

this technology. The volume of publications from these countries reflects their significant investment and commitment to advancing 3DPC materials and techniques in the construction industry.

China leads with 282 publications and 4768 total citations (TC), showcasing its strong academic presence and institutional support in this field. Australia follows with 101 articles and 2750 citations, demonstrating significant contributions to 3DPC technologies, particularly in research focused on material performance and sustainability. The USA, with 74 articles and 830 citations as illustrated in Table 2, also plays a pivotal role in exploring the economic feasibility and implementation of 3DPC in large-scale projects.

On an institutional level, several universities and research centres have been at the forefront of 3DPC research. The Tongji University in China emerges as the leading institution, contributing 80 publications to the field. Other notable contributors include Swinburne University of Technology (57 articles), Hebei University of Technology (57 articles), and Nanyang Technological University (51 articles) as depicted in Fig. 7. These institutions are pivotal in developing new materials, printing techniques, and design methodologies to optimise the use of 3DPC in construction. Their research focuses on overcoming challenges such as mix design, material performance, and sustainability, establishing them as leaders in the field.

Leading researchers and the intellectual framework of the knowledge on 3D printed concrete

Zupic et al. [23] define intellectual structure as the schools of thought representing key research methodologies within a knowledge domain. This analysis identifies the most prolific

Fig. 3 Annual trends in article publications

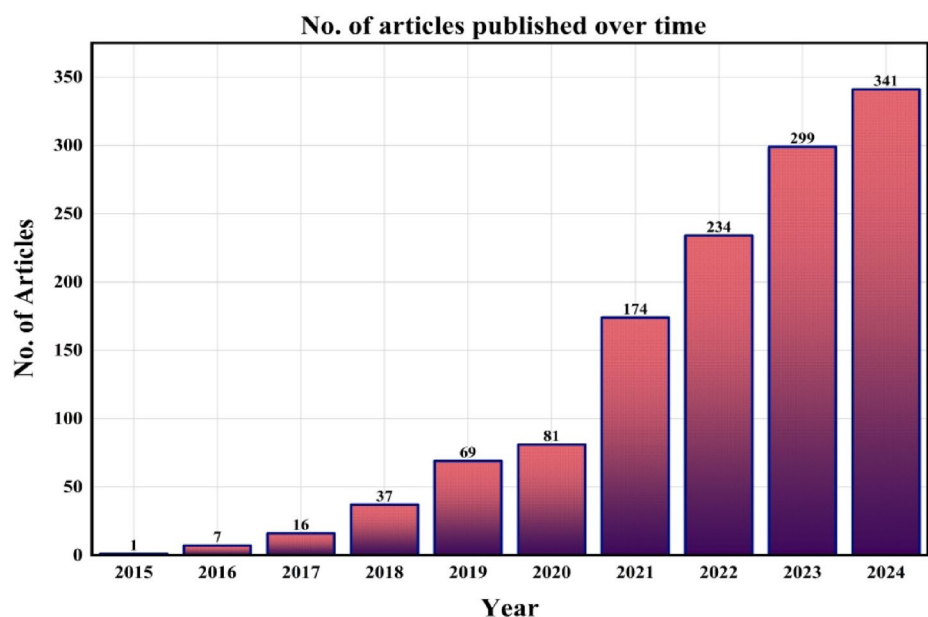


Fig. 4 Source of production over time

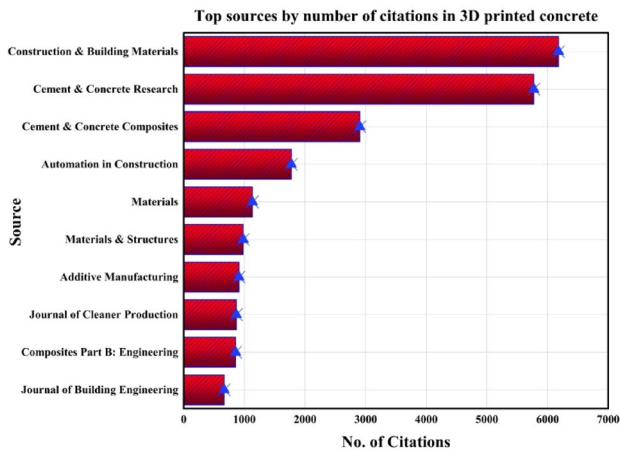
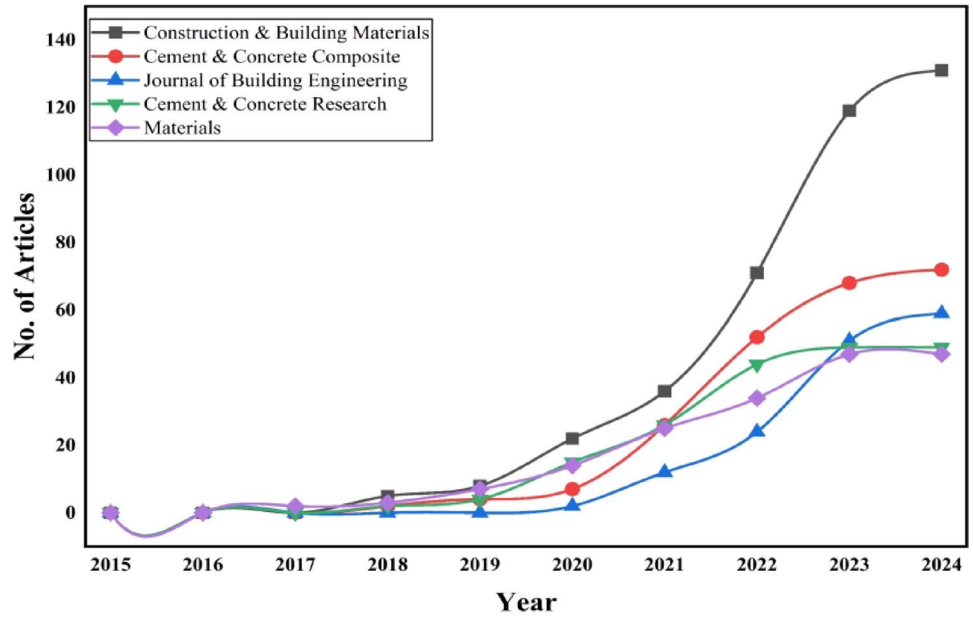
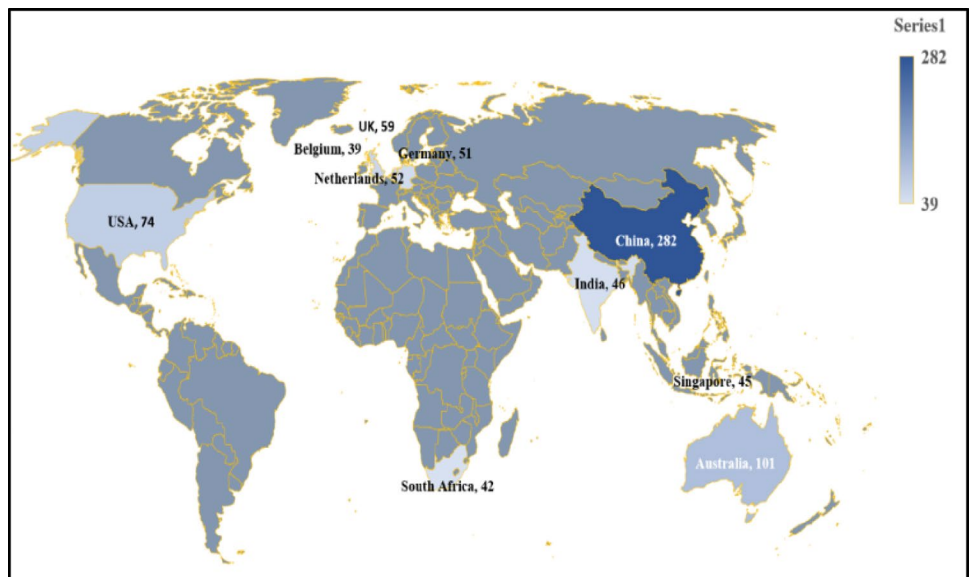


Fig. 5 Leading journals ranked by citation counts

Fig. 6 Geographical distribution of leading countries in publications



authors in field of 3DPC, including Sanjay J. (59 articles), Zhang Y. (51), Wang L. (47), Ma G. (46), and Panda B. and Xiao J. (40 each), as shown in Fig. 8. The impact of these leading authors, evaluated through metrics such as the h-index, g-index, m-index, total citations (TC), and number of publications (NP), is detailed in Table 3. Sanjay J., Tan M., and Ma G., active since 2016, stand out for their substantial citation counts and significant contributions to the field. Panda B. exemplifies a commendable balance between publication volume (40) and total citations (3479). Emerging researchers such as Li Z. and Xiao J., who began contributing in 2019, have rapidly established themselves as influential figures in 3DPC.

These authors have significantly contributed to the development of intellectual framework of 3DPC through studies

Table 2 Leading countries by total citations

Country	TC	Average article citations
China	4768	19.30
Singapore	3942	87.60
Netherlands	3041	58.50
Australia	2750	34.00
Germany	1231	24.10
South Africa	1150	27.40
Belgium	1042	26.70
France	839	36.50
USA	830	15.70
Switzerland	507	39.00
United Kingdom	475	19.80

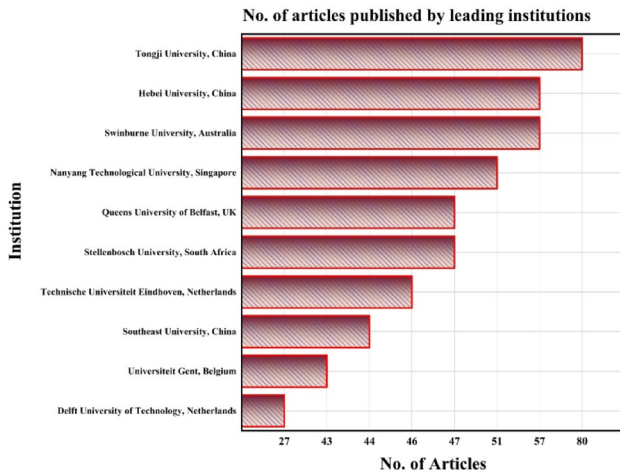


Fig. 7 Leading institutions in article publication

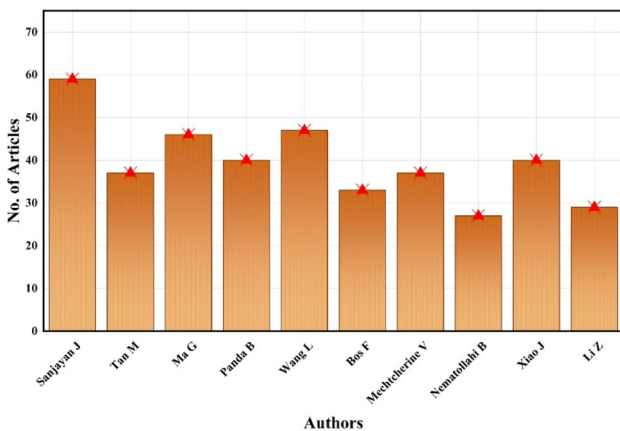


Fig. 8 Top authors by number of papers published

focusing on material properties, construction processes, and innovative applications. Citation analysis reveals that Sanjayan J. and Tan M. have received significant recognition, reflecting their pioneering work in mix design, sustainability, and 3DP technologies.

Key words analysis and topic trends over time

Keyword analysis offers insights into the relational structures and focal areas within 3DPC research [24]. Using the Biblioshiny web interface, general keywords (Fig. 9), and author keywords (Fig. 10) were generated to analyse their frequency within the dataset. The principal keywords identified in this research field are 3D printing, concrete printing, concrete, 3D concrete printing, digital fabrication, digital construction, additive manufacturing, compressive strength, construction, concrete mixtures, and yield stress. Trend analysis, as depicted in Fig. 11, shows a significant shift towards 3DPC. Although research on 3DPC began around 2015, it remained limited in the early years. The rise in scholarly attention from 2019 to 2024 on topics such as crack propagation, self-compacting concrete, sustainability, AI in mix design, and green materials reflects a transformative, technology-oriented approach in the construction industry.

The bibliometric analysis served as the first step in understanding the research landscape of 3DPC, providing a high-level categorisation of existing studies and identifying key trends in the field. Building on these insights, a systematic review was conducted to explore these trends in greater depth. The systematic review focused on critical topics, including new frontiers in the application of 3DPC Concrete technology, material properties of printable concrete, effects of materials on 3DPC, mix design methods, and the sustainability, environmental, economic, and managerial aspects of 3DPC.

By analysing 209 selected articles, the systematic review offered a detailed examination of these areas, bridging the gap between high-level bibliometric findings and in-depth exploration. This two-step approach ensures a comprehensive analysis of the advancements, challenges, and future opportunities for research on 3DPC.

Table 3 Top authors by total number of citations

Author	NP	TC	h_index	g_index	m_index	PY
Sanjayan J	59	3059	28	55	3.5	2017
Tan M	37	3801	24	37	2.67	2016
Ma G	46	1755	22	41	3.14	2018
Panda B	40	3479	22	40	2.45	2016
Wang L	47	1687	21	41	3	2018
Bos F	33	3031	20	33	2.23	2016
Mechtcherine V	37	1780	19	37	2.37	2017
Nematollahi B	27	1568	18	27	2.25	2017
Xiao J	40	1246	18	35	3	2019
Li Z	29	1227	17	29	2.43	2018

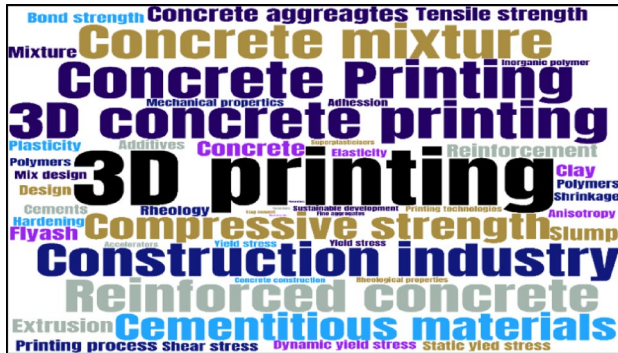


Fig. 9 Top 50 keywords plus on 3D printed concrete

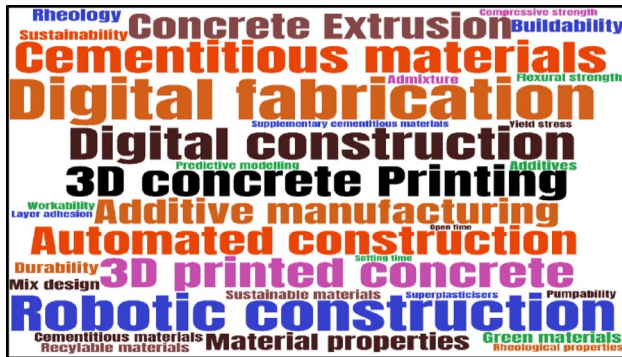


Fig. 10 Top 30 author keywords on 3D printed concrete

New Frontiers in the application of 3D printed concrete technology

Recent advancement in 3D printed concrete applications

3DPC is an advancing technology that has the capability to transform the construction sector. It enables faster, more efficient, and sustainable building solutions. Innovations such as robotic arms [24–26] and gantry systems [26, 27] have significantly enhanced precision and speed. Mobile 3DP construction robots (M3DPC-Rob) have further expanded applications with real-time monitoring and zero-turning

radius capabilities [29]. Recent advancements in this area have resulted in numerous innovative projects that are transforming construction methods. Table 4 summarise these advancements and reflect the potential of 3DPC across various domains. The figures included in this table have been reprinted with the permission of their respective copyright holders.

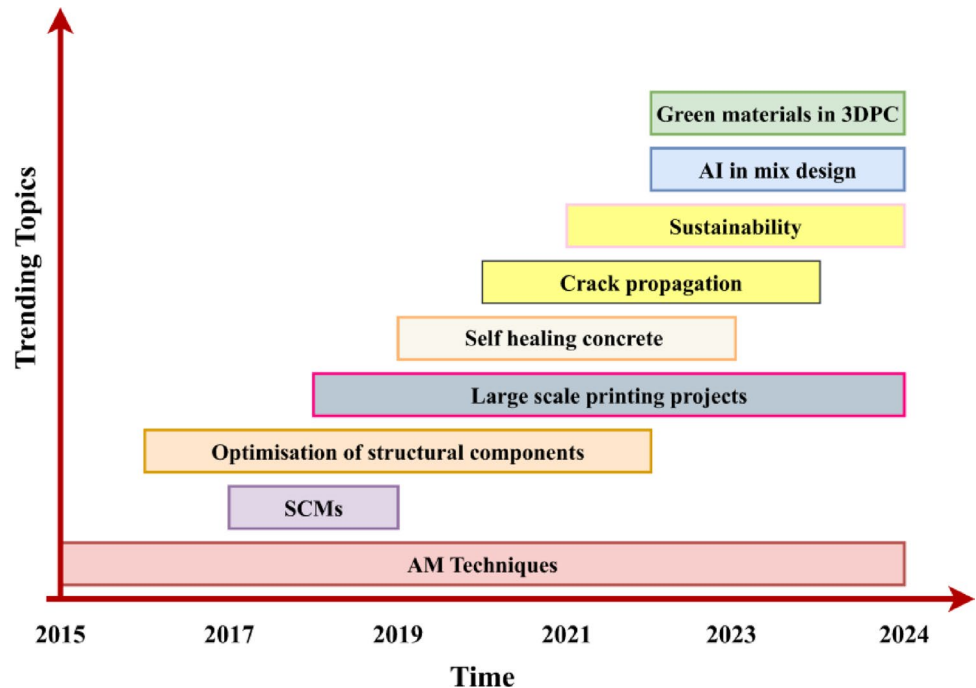
Material advancement

Material advancement is currently a hot trending topic in the field of 3DPC, as researchers aims to enhance the rheology, mechanical performance, durability, and sustainability of printed structures [38]. Notable innovations include the incorporation of recently developed materials such as calcined clay, biochar, metakaolin, Recycled bricks, and London clay into concrete mixes [39–41]. These additives have significantly improved the mechanical properties and overall performance of the concrete. By integrating such environmentally friendly materials, researchers are not only aiming to enhance structural integrity but also to promote sustainability in construction practices [42]. Table 5 summarises the material advancements that have recently emerged in the field of 3DPC. Ongoing research continues to focus on optimising the material compositions to fully unlock the potential of 3DPC and expand its applications across the construction industry.

Material properties of 3D printable concrete

3DP in construction diverges from traditional methods by utilising specialised materials that can endure the unique demands of extrusion and layering processes while maintaining essential mechanical properties. CBMs, which have significantly evolved since the mid-1960s, continue to dominate 3DP due to their high mechanical strength, cost-effectiveness, and favourable inherent qualities [63]. Unlike conventional concrete, 3D printed CBMs require tailored properties to meet the specific challenges of AM. These

Fig. 11 Trending topics over time



include sufficient flowability during extrusion, shape retention after deposition, and adequate load-bearing capacity to support subsequent layers without traditional formwork. These characteristics are critical to preventing structural failures and enabling successful layer by layer construction.

Fresh state properties

Flowability, extrudability, buildability, and open time are critical properties of concrete essential for 3DP. These characteristics determine how smoothly the material passes through the printing nozzle, enables layer stacking, and forms the intended structure [19].

Flowability

The concept of flowability in 3DPC describes the seamless motion of the material mixture within the printer system, ensuring a continuous and uninterrupted flow. This concept is closely related to pumpability, as the pump must be designed to handle mixtures with varying water-to-cement (W/C) ratios and aggregate sizes [19]. The W/C ratio is a key design factor that governs the flow characteristics of mixtures. Additionally, the inclusion of superplasticiser admixtures exerts a notable influence on this property, with the type and dosage of admixture being the predominant factors [7]. Optimum workability is crucial for 3DPC, as it enables the smooth transport of material to the printing head. Furthermore, the material must exhibit sufficient rigidity upon extrusion to maintain the integrity of the printed filaments [64].

Pumpability significantly influences several aspects of printing, including surface finish, ink flow, print consistency, printability, and the final quality of the printed object. The quantification of pumpability is determined using the pumpability index, defined as the ratio of the flow rate of the mixture (concrete) to that of water, as presented in Eq. 1 [19]. This index correlates directly with the slump-flow values and inversely with the pumping speed required to achieve the desired flow. Essential characteristics of a pumpable mixture include low plastic viscosity and moderate yield stress, which together facilitate an efficient and successful printing process [64].

$$\text{Pumpability Index} = \frac{\text{Flow Rate of concrete}}{\text{Flow Rate rate of water}} \quad (1)$$

Extrudability

Extrudability, also referred to as printability, describe the ability of a pump to discharge materials through a nozzle without altering its inherent characteristics [63]. This property is mainly influenced by the composition and particle size distribution of the dry components in the mixture [64]. For effective extrusion, maintaining a lower dynamic yield stress and reduced plastic viscosity is crucial, as this enables smooth material flow. However, excessively lowering these rheological parameters can cause undesirable effects such as uncontrolled flow or sagging [65].

Table 4 Advancements in 3D printed concrete and their relevance across construction domains




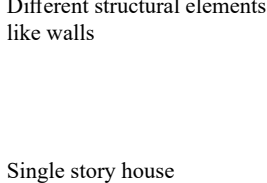



Area	Specific advancement	Description	Output 3D printed product	Reference
Technological advancement	Robotic arm precision	Development of the robotic arm for 3DP cement mortar to ensure the accuracy of the robotic arm in laying cement mortar layers to achieve adequate layer binding and structural integrity Has the capability to print objects with an area of up to 640 m ² and a height of up to 9.5 m	Modular lattice structural panels 	[25–27]
	Gantry system speed	Development of a framed gantry robot (FGR) specifically for 3DPC The RIC-M1 PRO and COBOD COD2 offers quick setup and modular efficiency	Produced various 3D printed, multi-layer concrete elements in different shapes Wall 	[27, 28]
	Mobile 3D printing	A mobile 3DP construction robot (M3DPC-Rob) is developed Real-time monitoring and adjustments for better printing quality Realize movement in all directions and rotate with zero turning radius	Wall units and curve units 	[29, 30]
Building and infrastructure	Nozzle	A customized 3D concrete printer with an ultra-thin diameter nozzle (6 mm) and fully sealed extrusion system was developed to enhance precision in three-dimensional printable concrete COBOD BOD2 and Delta WASP 3MT CONCRETE printer have typical nozzle diameters reaching up to 30 mm	Different structural elements like walls 	[31, 32]
	First 3D printed house	First 3D printed house built by WinSun company in 2014 were approximately 200 m ²	Single story house 	[9]
	Tallest building	The world's tallest building, with a total height of 9.9 m and a total floor area of 345 m ² , was constructed in Saudi Arabia in cooperation with COBOD in 2022	Three story villa 	[33]
	Largest 3D printed building	Dubai Municipality in UAE collaborated with Apis Cor to construct the tallest 3D-printed structure in 2019, which measures 9.5 m in height and spans an area of 640 square meters	Entire building 	[34]

Table 4 Advancements in 3D printed concrete and their relevance across construction domains






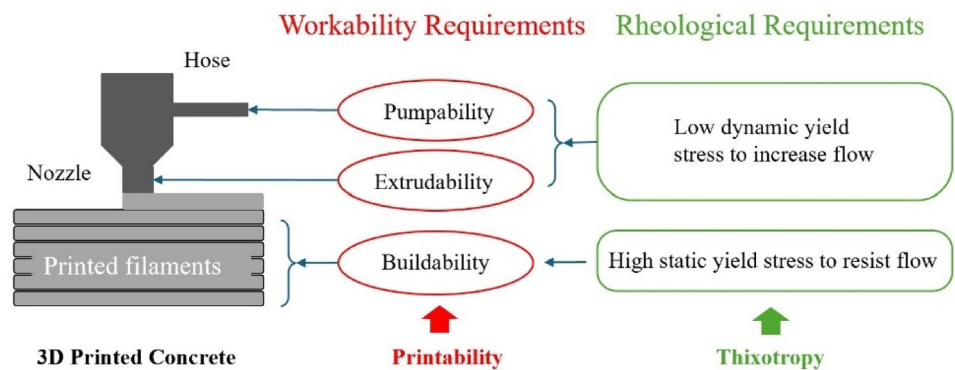
Area	Specific advancement	Description	Output 3D printed product	Reference
	World's first 3D-printed neighborhood	The US based nonprofit New Story has collaborated with ICON to construct the world's first 3D-printed neighborhood in 2022	Village 	[35]
	First 3D-printed bus stop	The UAE has effectively constructed a 3D-printed concrete bus stop in 2020, with dimensions of 4.5 × 2 × 2.3 m, and it was printed in less than 10 h	Bus stop 	[36]
	Masjid	The world's first 3D printed Masjid, named Abdul Aziz Abdullah Sharbatly, covering 5600 m ² , was constructed in Saudi Arabia through a partnership between Fursan Real Estate Company and Guanli in 2024	Entire masjid 	[11]
Bridges	First 3D-printed concrete bridge	The first 3D-printed concrete bridge in Gemert, Netherlands which is primarily meant to be used by cyclists, spanning meters in length 8	8 m Long cyclist bridge 	[12]
	World's longest pedestrian bridge	The construction of the world's longest 3DPC pedestrian bridge in Shanghai, China, spanning 26.3 m in length and 3.6 m in width	Largest pedestrian bridge 	[10]
	Bridge	Spain introduced its own achievement in this arena with the construction of a 12-m-long pedestrian bridge in the park of Castilla-La Mancha in Alcobendas, Madrid	12 m Long pedestrian bridge 	[37]

Table 5 Key material advancements in 3D printed concrete and their roles in improving structural quality and environmental impact

Category	Material advancement	Impact on 3D concrete printing	Reference
Green materials	Geopolymer concrete	Use of metakaolin, micro-silica, slag, and fly ash enhance pumpability, printability, and buildability Lower Portland cement usage, reducing environmental impact and offering a sustainable alternative	[43–45]
	Limestone calcined clay cement (LC3)	Use of LC3 enhances durability, reduces anisotropy in mechanical properties, and improves compressive strength Can replace 40–50% of OPC with minimal impact on compressive strength LC3 significantly reduces energy use and carbon emissions, supporting environmental sustainability	[38, 46, 47]
	Biochar	Biochar enhances chemical stability, lowers conductivity, limits flammability, aids curing, and supports carbon capture, potentially reducing CO ₂ emissions by up to 43% Adding 10% biochar by weight of cement optimises shape retention, surface finish, and compressive strength in printed structures	[48–50]
	Rice Husk Ash (RHA)	Enhance the initial yield stress and structuration rate Incorporation of RHA as a 20% cement replacement maintains the flowability and workability required for 3D printing RHA in 3DPC reduces environmental impact by repurposing agro-industrial waste and lowering CO ₂ emissions from cement production	[51, 52]
Recycled materials	Recycled aggregates	Mechanical strength for the recycled plastic eco-aggregate, recycled glass, recycled concrete, recycled brick, slag, recycled rubber aggregate is lower than the sand aggregates concrete, yet the flow properties of the former is better than the latter	[53–56]
Ultra-high-performance materials	Ultra-high-performance concrete (UHPC)	Use of steel fibre and silica fumes enhance Compressive strength, tensile splitting strength, and flexural strength and durability properties of 3D printed concrete UHPC enabled the 3DP of bridge components and walls	[57–60]
Self-healing materials	Self-healing concrete	Bi-component healing agents (epoxy resin, sodium silicate with nano-silica/nano-lime) stored in 3D printed modified tetrahedral units (d-TETs) with coaxial ligaments Enhances durability, allows multiple healing cycles, improves strength/stiffness recovery, and extends material shelf life Crack widths of 0.35 mm cause rupture of d-TETs to release healing agents	[61, 62]

Fig. 12 Rheological requirements for 3D printed concrete: balancing pumpability, extrudability, and buildability



Buildability

Buildability is critical in 3DPC, reflecting the ability of material to be efficiently printed while maintaining the stability and reliability of the printed structure [5]. A high static yield stress is essential, enabling the material to preserve vertical stability, support overhangs, and retain fine details. In contrast, higher plastic viscosity minimises segregation, ensures a controlled flow, improves adhesion between the layers and stabilises the printed layers [19]. The buildability of a mix depends on several factors, including setting time, the interval between layers, green strength, and interlayer bonding capacity [64]. The critical height (H), defined by

the Eq. (2), represents the maximum height beyond which a structure may experience buckling or plastic collapse.

$$H = \frac{8EI}{3\varrho gA} \tag{2}$$

where H, E, I, ϱ , A, and g represent the printed height (buildability), modulus of elasticity, inertia, density of the mix, printed filament’s surface area, and gravitational acceleration, respectively.

Open time

The open time, a crucial parameter for successful 3DPC, refers to the duration during which the material remains workable and retains its intended properties [66]. This parameter is determined using a slump flow test or Vicat apparatus to assess the material's flowability at defined interval [67]. Once established, it can be used to determine acceptable slump values, spreading diameters for flowability, and penetration resistance ranges for structural build-up behaviour.

In the fresh state, 3DPC exhibits conflicting requirements. The material requires low plastic viscosity and optimal yield stress to ensure efficient pumpability and extrudability, whereas high static yield stress is essential for maintaining buildability, as shown in Fig. 12. Additionally, the printing speed must be carefully calibrated to optimise bond strength and cost efficiency, ensuring that the fresh layers bond effectively. The printing speed should be neither too high nor too low to achieve proper interlayer adhesion.

Hardened state properties

The hardened state material properties for 3DPC include compressive strength, Flexural Strength, and interlayer layer bond strength.

Compressive strength

Compressive strength refers to the ability of a printed object to resist compressive load without undergoing deformation or failure. This mechanical property is crucial for ensuring the structural integrity and durability of 3D printed components [68]. The compressive strength of 3D printed objects is influenced by factors including the reinforcement material, print orientation, reinforcement pattern, and layer height. The strength requirements for 3DPC are not significantly different from those for traditional concrete. Researchers have successfully developed 3DPC with both low (8 Mpa) and high (100 Mpa) strengths, enabling a wide range of applications [69, 70]. However, despite these advancements, challenges persist in meeting the durability requirements of 3DPC elements.

Flexural strength

Flexural strength measures a material's resistance to bending forces without breaking. It specifies the maximal stress that a material can withstand before it fractures under a bending load. The Flexural strength of 3D printed objects

is affected by various factors, including material type, infill pattern, density, layer height, and raster orientation [71].

Interlayer bond strength

The interlayer bond strength in 3DPC, which is crucial for structural durability, refers to the adhesion between successive layers. Weak bonding can significantly compromise the overall strength of the printed structure [64]. This property is influenced by the rheological characteristics of the binder, the interval between depositions, the nozzle-to-surface distance, and the printing speed [72].

Effect of materials on 3D printed concrete properties

Various materials have been investigated to determine their effects on 3DPC in both fresh and hardened states. The incorporation of fly ash in 3D printed CBMs has shown diverse effects, enhancing shape stability, early strength, and stiffness while reinforcing the internal structure and improving polymer bonding for better insulation [12, 73, 74]. This addition promotes eco-friendliness, improving sustainability without compromising material performance [74]. Fly ash influences the compressive strength, setting time, moisture control, extent of efflorescence, and thermal conductivity of geopolymer paste. However, incorporating fly ash into 3DPC can present limitations such as retardation of the hydration reaction, low early-age strength development, and reduced yield stress, which are not ideal for the 3DP process [75].

The addition of metakaolin (MK) enhances the properties of 3DPC by improving rheology, buildability, early performance, and mechanical strength [12, 76, 77]. The utilisation of MK in 3DPC presents several limitations, including uncertain long-term durability due to anisotropic behaviour, a slow chemical reaction affecting structural build-up and buildability, reduced workability from low packing density, increased water demand, and potential impacts on extrusion capacity and overall buildability through interactions with other components [76–80]. Limestone powder can improve the thermal behaviour of concrete mixtures by enhancing volumetric heat capacity and reducing thermal conductivity. It also improves viscosity and maintains good fluidity over time while enhancing the extrusion capability and buildability of concrete [78, 81]. However, it has been observed that incorporating limestone powder into concrete mixtures may reduce buildability, decrease yield stress development, retard stiffening, diminish anisotropic

Table 6 Effect of different materials on 3D printed concrete properties

Materials	Properties of 3DPC										References	
	Workability	Extrudability	Buildability	Compressive Strength	Flexural Strength	Yield Stress	Viscosity	Durability	Carbon Footprint	Inter-layer bond stress		Shrinkage
Fly ash	↑	↑	↑	↑	-	↓	↓	↑	↓	↑	↓	[86–89]
Metakaolin	↑	-	↑	↑	-	-	-	↑	↓	-	-	[79, 87, 88, 90, 91]
Limestone powder	↑	↑	↑	↑	↑	↓	-	↑	↓	-	-	[81, 92–95]
Silica fume	↑	↑	↑	↑	-	↑	-	↑	↓	-	-	[81, 86, 96–99]
Ground granulated blast furnace slag	↑	-	↑	↑	↑	-	-	↑	↓	-	↓	[87, 88, 99, 100]
Coarse aggregate	↓	↓	↑	↑	↑	↓	↑	↑	-	↓	↓	[101–105]
Recycled plastic	↑	-	↓	↓	↓	↑	↓	-	↓	↑	-	[56, 106]
eco-aggregate (Resin8)	↓	-	↑	↑	-	↑	-	-	↓	-	-	[50, 52, 96, 107]
Rice husk ash	↓	-	↑	↑	-	↑	-	-	↓	-	-	[108–112]
Recycled sand	↑	↑	↑	↓	↓	-	-	-	↓	-	↑	[113, 114]
superplasticiser	↑	↑	-	-	-	↑	↓	-	-	-	-	[115–118]
Graphene Oxide	↑	-	↑	↑	↑	-	-	↑	-	-	↓	[73, 119–121]
Steel Slag	↑	-	↑	↓	↓	↓	-	↑	↓	-	↑	[122, 123]
Styrene butadiene Rubber (SBR)	↑	-	↑	↑	↑	-	-	↑	-	↑	↑	[39, 124, 125]
Biochar	-	↑	↓	↑	-	-	-	-	↓	-	↓	[94, 106, 126]
Calced clay	↑	↑	↑	-	↑	-	-	↑	↓	-	-	

behaviour, and decrease the compressive strength of printed specimens. [77, 82]. Silica fume can modify the rheological properties, notably enhancing the flowability and pumpability of 3DPC [83]. This addition optimises pore sphericity, resulting in improved thermal insulation and durability [84]. Furthermore, silica fume is a potential cement replacement that effectively mitigates crack formation and enhances the overall buildability of the material [74]. However, silica fumes may adversely affect the workability and shrinkage of concrete [85]. In Sect. 5, the material behaviour of 3DPC was discussed in terms of workability, flowability, extrudability, buildability, open time, and compressive, flexural and interbond strength, Table 6 summarises the effect of different materials that influence these 3DPC properties.

Mix design methods for 3D printed concrete

The rapid advancement of 3DPC construction necessitates optimised mix design strategies to meet specific performance requirements. A 3DPC mixture must exhibit adequate flowability, extrudability, buildability, green strength, and balanced setting times to maintain printability [127]. These requirements make mix design particularly challenging, especially when incorporating complex compositions with admixtures [64, 127]. Key rheological properties such as extrudability, buildability, and early-age strength are influenced by factors including the activator-to-binder ratio, mix density, and viscosity [128].

Empirical methods for mix design in 3DPC include trial-and-error approaches, laboratory testing, and predictive modelling. [129, 130]. Table 7 summarises prominent mix design approaches, highlighting their role in optimising concrete rheology through adjustments in key ingredients such as cement, sand, admixtures, and water. Laboratory tests, including slump flow, V-funnel, and buildability tests, are used to evaluate the fresh properties and printability of concrete [130].

Predictive models such as Gaussian Process Regression, Decision Tree Regression, Support Vector Machine, and XGBoost offer advanced methods for forecasting mechanical properties like compressive, flexural and tensile strengths based on input parameters, including water content, cement type, aggregates, and fibres [129, 131]. These models enhance the efficiency and quality of 3DPC while reducing experimental and computational efforts. The trial-and-error approach, although empirical, remains a practical and effective method for determining optimal mix ratios, as depicted in Fig. 13. This approach allows iterative refinement to meet the specific requirements of 3DPC applications.

Sustainability, environmental, economic, and managerial aspects of 3D printed concrete

3DPC represents a significant advancement in construction technologies, offering substantial benefits in terms of sustainability, environmental performance, and economic and managerial impacts.

Sustainability and environmental impact of 3D printed concrete

Sustainability has emerged as a key focus in the construction sector, which accounts for a substantial portion of global resource consumption and environmental impact. 3DPC offers a sustainable alternative by reducing material waste, optimising resource use, and lowering carbon emissions, thereby contributing to environmental sustainability [145]. The incorporation of low-impact materials, such as geopolymers and earth-based substances, enhances the sustainability of structures [146]. Geopolymers, for instance, have been shown to produce approximately 80% less carbon emissions compared to Portland cement production [147]. Furthermore, the inclusion of recycled materials such as eco-aggregate (Resin8) in concrete mixtures not only reduces the carbon footprint but also enhances key properties such as flowability and interlayer bond strength [56]. Additionally, the use of calcined clay, recycled sand, and industrial by-products including silica fume, fly ash, slag, plastic waste, and rice husk ash can partially replace cement, thereby further decreasing the carbon footprint associated with conventional concrete production [56, 86, 87].

In addition to its sustainability benefits, 3DPC offers cost savings over conventional construction methods by reducing water usage and energy consumption [148]. The combination of recycled aggregates and insulating materials in printable building components also enhances environmental performance, thereby promoting more sustainable construction practices [56, 87, 149]. When combined with high-performance concrete (HPC), 3DPC can reduce environmental impacts by nearly 50% compared to conventional construction [38]. The use of low-impact materials, including raw earth substances and geopolymers, significantly enhances the sustainability of building structures. However, several challenges remain. The cement content in 3DPC is considerably higher than in conventional concrete, with approximately 40% more cement required. Furthermore, the printing ink exhibits a greater environmental footprint than conventional cast concrete [150]. Consequently, developing strategies to mitigate the environmental impacts of 3DPC will be a critical focus of future research.

Table 7 Mix design approaches used for 3D printed concrete applications

Method used	Detail mix design approach	Key properties assessed	Reference	
Trial and error	Five different mixtures contain equal quantities of aggregate, superplasticiser (SP), water/binder ratio (W/B), and binder The optimal dosage of silica fume and nano clay was determined the variation of their respective content	Green strength Drop table flow Mini slump Rheological behavior	[132]	
	4 Mix of silica fume with different SP Dosage, 5 mix of nano clay with different SP and 6 mix of viscosity modifying agent with different SP was prepared with different materials Different water content was used to evaluate the yield stress and other properties	Yield stress Buildability Extrudability Robustness Structural build-up	[133]	
	Five printable mixtures were developed with different sand/binder and SP/binder ratio A W/B of 0.3 and fly ash to cement ratio of 0.667 was selected to achieve a slump value of 8 mm	Slump Extrudability Buildability Open time	[130]	
	Five printable mixtures were developed with different GGBS, cement, and sand ratio A SP of 0.5% by weight cement was taken Five different mix proportions of the material and specimen that For all the mixes a constant w/c i.e., 0.5 were taken	Flowability Extrudability Buildability Compressive strength	[134]	
	Three printable mixtures were developed with different Soil/cement ratio A Water/fines ratio of 0.40 was chosen to attain a compressive strength of 34 MPa Dosage of soil mass, soil/cement ratio and fines (cement+soil) were altered to determine the optimal mix proportions for printing	Extrudability Buildability	[135]	
	27 trial mixes made with different materials i.e., from ordinary Portland cement, sand, silica fume, quartz powder, ground granulated blast furnace, limestone powder, water, fly ash and viscosity modifying agent to determine printable properties Five mixes were identified for the suitable mix design of 3DPC, with proportions suitable for 3DPC while maintaining constant printing parameters	Flowability Buildability Extrudability Open time	[136]	
	Four type of formulation with different percentages of biochar, kaolin, and calcium carbonate were investigated Portland cement, sand, and superplasticiser and were taken as constant in all formulations (48%, 10%, and 2% respectively) The percentages of biochar, kaolin, and calcium carbonate were varied The W/C ratio for all mixes was 0.53	Workability Fluidity Geometric stability Surface texture	[39]	
	Factorial design	18 mixes are made with different W/B, cement, Sand/binder, sand, superplasticiser and admixtures Eight factors, including types of cement, sand, superplasticiser, W/B, admixtures dosages, and sand-to-binder ratio are investigated to determine the composition of the mixtures	Workability Buildability Compressive strength	[137]
		22 mixes are made with different quantities of fly ash, cement, sand, silica fume, and water For each mix, dynamic yield and static yield stress were calculated	Dynamic yield Static yield stress	[138]
		Evaluate the influence of different dosage of superplasticiser, fly ash, basalt fibre, and cement that are used to create statistical models for rheological and material strength properties	Rheological properties Material strength Compressive strength Flexural strength Extrudability Buildability Static yield stress	[139]

Table 7 (continued)

Method used	Detail mix design approach	Key properties assessed	Reference
Predictive modelling	Machine Learning (ML) Approach A dataset 21 input features (cement, water, cement, silica fume, fly ash, aggregate etc.) and 4 output properties (slump flow and compressive strength) were gathered from previous studies Five machine learning algorithms were used to forecast concrete properties Four 3D printed mix designs were tested for slump flow and compressive strength GPR was best for compressive strength; SVM for slump flow	-Compressive Strength - Slump Flow	[140]
	ML Approach A dataset of 23 input parameters related to concrete mix design, including binders, SCMs, and admixtures, and 3 output parameters was gathered from literature review which contain 1679 data points 3 ML models were used to predict cast and printed compressive strength in 3 direction and slump flow The BR-trained XGBoost achieved the highest R ² scores of 0.982 for cast compressive strength, 0.970, 0.972, and 0.971 for printed compressive strength in directions 1, 2, and 3, respectively, and 0.980 for slump flow	Compressive strength Slump flow Anisotropy	[141]
	ML approach A dataset of 7 input parameters related to concrete mix design, including binders, SCMs, and admixtures, and 3 output parameters was gathered from 90 research papers, resulting in 233 initial mix design samples 6 ML models were used to predict workability XGBoost achieved an R ² of 0.978 for fluidity, while PSO-XGBoost excelled with R ² values of 0.989 and 0.981 for dynamic yield stress and plastic viscosity, respectively	Fluidity Dynamic yield stress Plastic viscosity	[128]
	ML approach Data from 25 previous studies were gathered, with input parameters including silica fume, aggregates, VMA, cement, fibers, fiber properties, print speed, and nozzle area, fly ash, water, and target properties being the tensile and flexural strength of concrete W/B ranged from 0.27 to 0.67 Four machine learning models were used to forecast concrete properties The SVM model performed best, with R ² scores of 0.8893 for tensile strength and 0.8389 for flexural strength	Tensile strength Flexural strength	[142]
	Bingham model $\tau = \tau_d + \mu \frac{dy}{dt}$	Shear stress (τ) Dynamic yield stress (τ_d) Plastic viscosity (μ) Share rate ($\frac{dy}{dt}$)	[143]
	Coussot model $\tau_m = \tau_f \left(1 - \frac{\sigma}{\sigma_{\max}}\right)^{-m}$ where: (τ_m) Static yield stress of concrete/Mortar (τ_f) Static yield stress of cement paste Multivariate regression empirical model Torque viscosity = $7.89 + 1.74 \times A - 3.70 \times B + 3.96 \times C - 0.49 \times D + 2.73 \times E$ Flow resistance = $327.99 + 2.71 \times A - 194.03 \times B - 145.99 \times C + 419.18 \times D + 287.42 \times E$ Thixotropy = $3072 - 2125 \times A - 822.2 \times B - 185.1 \times C + 1345 \times D + 397.5 \times E$	Static yield stress	[144]
		Flow resistance Torque viscosity Thixotropy	[131]

The flowchart illustrated in Fig. 14, developed based on the reviewed literature and life cycle assessment (LCA) principles, outlines strategies to mitigate the environmental impacts of 3DPC [148]. However, while 3DPC reduces the environmental footprint through lower material waste and carbon emissions, it also presents certain challenges. The energy consumption of printing equipment and the scalability of sustainable materials remain concerns that must be addressed to maximise the technology's environmental benefits. Moreover, Table 8 highlights the available literature on the sustainability aspect of 3DPC.

Economic impact of 3D printed concrete

3DPC is increasingly recognised as a sustainable construction practice, offering potential cost savings and environmental benefits [163]. The economic advantages of using 3DPC for large-scale construction projects are multifaceted. It provides notable benefits in terms of geometric flexibility, enabling the design of topology-optimised structures that are not achievable with conventional construction methods [164]. Such flexibility reduces material demand and can lead to substantial cost savings [165]. Furthermore, a

Fig. 13 Trial and Error approach for the mix design of 3D printed concrete

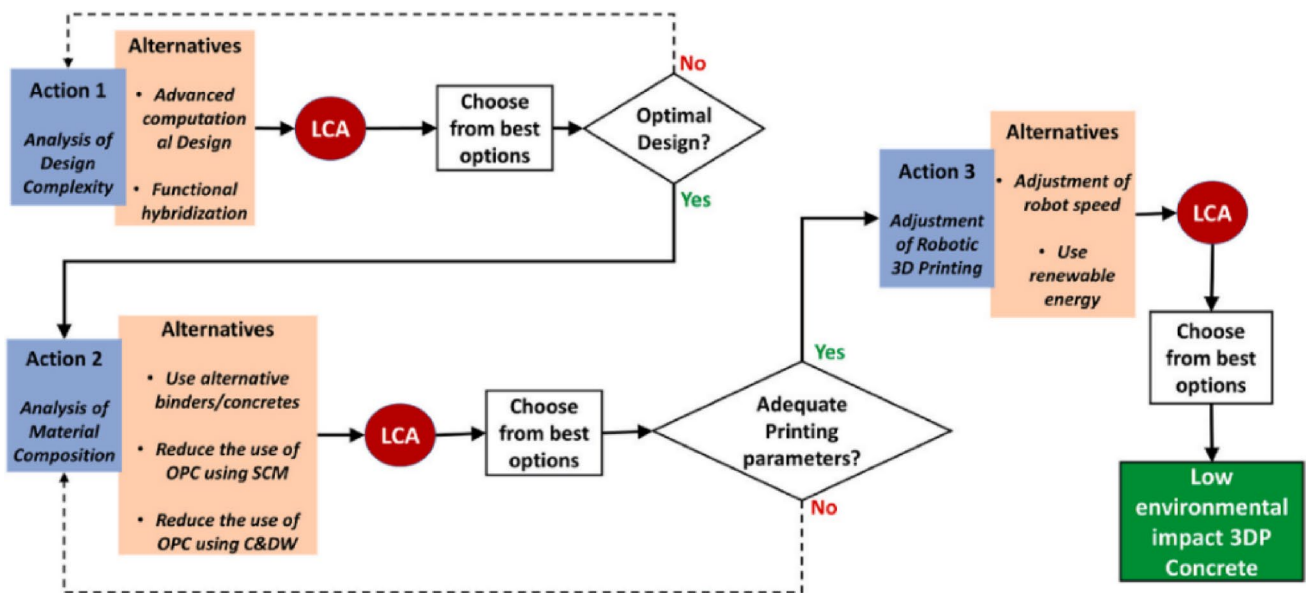
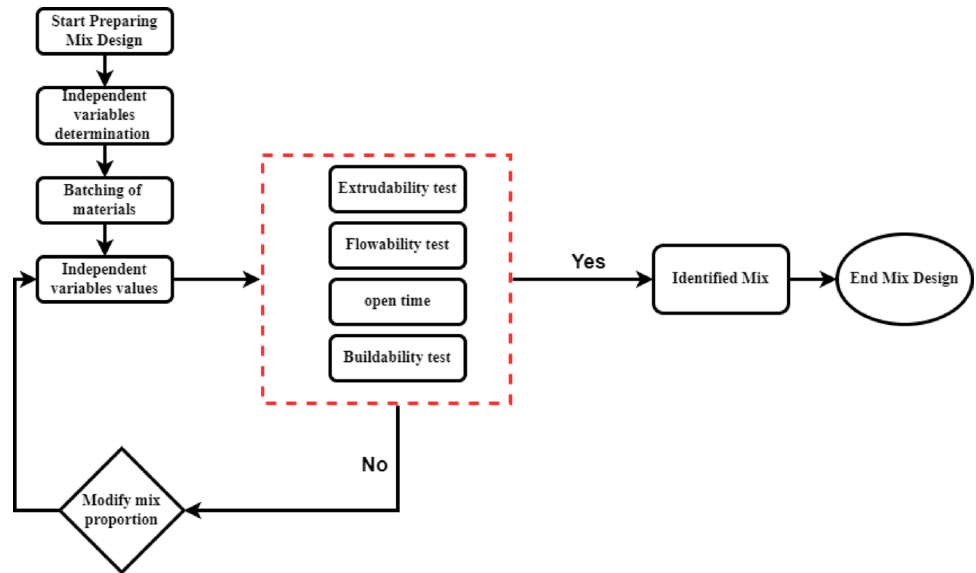


Fig. 14 LCA approach to lower the environmental impact on the 3D printed concrete. Reprinted with permission from Ref [151]

major economic advantage arises from the elimination of formwork, which can reduce overall capital expenditure by nearly 78% compared with traditional construction methods [148]. This reduction is primarily attributed to lower formwork requirements and material wastage. In conventional construction projects, more than 50% of the total cost typically results from labour and formwork expenses [166]. However, the costs associated with materials and machinery may be higher in 3DPC than in conventional methods [167].

Numerous studies have examined the economic impact of 3DPC. For instance, Markin et al. [168] estimated the costs associated with constructing exterior walls using 3D printed foam concrete, finding that material expenses contributed the most (70%) to overall direct costs, followed by

machinery (21%) and labour (9%). Besklubova et al. [169] analysed the costs related to logistics associated with 3DPC in low-rise buildings, examining materials, equipment, and waste flows. Their findings indicated that offsite 3DP incurs substantially higher logistics costs compared with onsite 3DP, while conventional construction costs are approximately 85% lower than those of offsite 3DP. This elevated cost reflects the early-stage development of 3DPC technology, anticipated to decrease as the 3DPC market matures. Munir et al. [170] compared the construction costs of 3DPC using geopolymers with traditional OPC based concrete across four stages: raw material transportation and availability, parameter selection, material pretreatment, and strength requirements. Their results showed that 3DPC with

Table 8 Review of research on sustainable aspect of 3D printed concrete

Paper reference	Scope
Chen et al. [152]	Examined low carbon 3DPC techniques, including printable concrete with reduced emissions and carbon optimisation technologies
Schutter et al. [153]	Assessed 3DPC potential for cost and environmental efficiency through material reduction and functional hybridisation
Luhar et al. [154]	Investigated using natural fibers in 3DPC to enhance lightweight properties, energy efficiency, and thermal performance
Khan et al. [155]	Evaluated the sustainability of 3DPC in terms of design flexibility, cost-effectiveness, and operational advantages
Chen et al. [150]	Reviewed eco-friendly concrete printing using accessible materials and alternative SCMs for 3DPC applications
Tinoco et al. [44]	Explored the influence of SCMs on 3DPC properties, waste reduction, and sustainable 3DP techniques
Dey et al. [156]	Highlighted by-product utilisation in 3DPC to enhance waste management and create customised material solutions
Liu et al. [157]	Investigated sustainable 3DPC materials, focusing on extrusion and optimisation for modular construction
Nodehi et al. [158]	Analysed material effects on shrinkage, freeze–thaw resistance, and thermo–durability of printed concrete
Samudrala et al. [159]	Studied the partial replacement of cement in 3DPC with slag and silica fume for improved energy efficiency
Ahmed [160]	Provided an overview of 3DPC environmental, economic, and technical aspects, emphasising material efficiency
Tu et al. [161]	Investigated the use of recycled glass and by-products to improve engineering properties in 3DPC
Alami et al. [162]	Associated 3DPC development to achieving UN Sustainable Development Goals and reducing water and energy use

Table 9 Review of research studies on the economic analysis of 3D printed concrete

Case studies	Building stories	Country	Cost						Reference
			Material cost	Labour cost	Transportation cost	Machinery cost	Printing process cost	Storage cost	
2.43 m ² small building unit	1	Singapore	✓	✓	–	✓	✓	–	[170]
350 m ² multipurpose hall	1	Jordan	✓	–	–	–	–	–	[175]
50 m ² house	1	Finland	✓	✓	✓	✓	✓	✓	[170]
219.3 m ² villa	2	UAE	✓	–	–	–	–	–	[54]
19.63 and 18 m ² small building units	1	China	✓	✓	–	–	✓	–	[177]
90 m ² house	2	UAE	✓	–	–	✓	–	–	[148]
160 m ² house	2	Germany	–	–	✓	–	✓	✓	[178]

geopolymer concrete reduced production costs by 32% and energy consumption by 50%. Allouz et al. [171] conducted a comparative study of single-storey buildings, highlighting that 3DPC can reduce material costs by up to 65% compared with conventional construction methods. Weng et al. [172] performed a comparative economic analysis between 3DPC and pre-casting methods for producing a bathroom unit, considering key cost factors such as electricity, material usage, labour, and equipment depreciation. Their results indicated that 3DPC achieved a 34% reduction in overall costs compared with traditional pre-casting metho. Aghmien et al. [54] employed a survey approach to gather perspectives from construction industry experts, revealing that the adoption of 3DPC can significantly improve cost efficiency and productivity, particularly in housing development projects.

To further assess costs, researchers considered hypothetical models for 3D printed structures. In this context, Han et al. [173] used a hypothetical cylindrical silo model with an annular wall and conical top to compare the costs of 3DPC and traditional construction techniques. Their study found

that material costs accounted for 83% of the total costs in 3DPC, while labour costs represented the largest share in conventional construction. Furthermore, they noted that the cost of 3DPC remains unaffected by geometric complexities, whereas traditional construction methods experience significant cost increases due to formwork intricacies, which also impact labour cost [173]. Abdalla et al. [174] carried out an evaluation comparing the costs associated with 3DCP and traditional construction methods. Their analysis focused on the utilisation of essential materials such as cement, additives, aggregates, steel, and concrete, as well as the use of formwork. The findings demonstrated that 3DCP can reduce capital expenditure by 78%, primarily due to the absence of formwork requirements and the more efficient use of concrete. Tobi et al. [175] explored the economic feasibility of 3D printed housing in the UK, focusing on cost comparisons with conventional construction methods. Their findings revealed that 3DP technology could potentially reduce house construction costs by approximately 35%, particularly through savings in material and labour costs associated with the construction of walls and foundations. These savings

highlight the potential of 3D printing as a viable solution to the UK's housing affordability challenges. Batikha et al. [176] performed an in-depth evaluation of several construction techniques, such as 3DCP, cast-in-place reinforced concrete, modular prefabrication, hot-rolled steel, and cold-formed steel, to assess their effects on the construction time, costs, and carbon footprint of a two-storey building. Their findings indicated that 3DPC achieved substantial decreases in overall construction duration, expenses, and environmental impact when compared to the alternative approaches.

The preceding analysis underscores the significant potential of 3DPC to achieve notable reductions in overall construction costs compared to traditional building methods. As outlined in Table 9, the current body of research on 3DPC lacks comprehensive cost evaluations that span the entire construction lifecycle, from material procurement to the final build. Furthermore, there is a growing need for detailed economic analyses that focus on critical stages of the 3DPC process, including transportation, material handling, and the actual printing operations. Conducting such assessments would offer valuable insights into the complete economic viability and advantages of 3DPC.

Management aspect of 3D printed concrete

The management aspect of 3DPC focuses on the effective integration of this transformative technology into construction workflows, requiring a re-evaluation of processes and strategies. A key advantage of 3DPC is its capacity to enhance construction management through improved planning and control [179, 180]. By eliminating auxiliary tasks such as formwork and related operations typical of conventional methods, 3DPC simplifies logistics and significantly increases labour productivity [181]. Furthermore, the automated production of large-scale concrete elements reduces reliance on skilled labours, although expertise remains essential for operating and maintaining 3D printers and producing associated components [182, 183]. The digitalisation of construction sites enabled by 3DPC also provides notable managerial benefits. Greater predictability in construction processes allows for improved control, reducing delays and enhancing efficiency. This predictability further contributes to safer working environments, as automation minimises risks associated with on-site accidents [184]. Managers play a pivotal role in integrating digital systems into project operations to ensure these technologies are effectively implemented to maximise safety and operational performance [180].

From a cost management perspective, 3DPC provides significant opportunities for savings. Formwork, which traditionally accounts for approximately one-third of total construction costs, is entirely eliminated in 3DPC processes.

This alone can result in substantial cost reductions. While 3DPC materials may initially be more expensive, the associated savings in labour and time from avoiding formwork and manual concrete pouring often offset these costs [9]. Managers must therefore reassess resource allocation strategies, focusing on how 3DPC can optimise both material and labour efficiency [185]. The adoption of 3DPC also requires substantial adjustments in supply chain management. Unlike traditional construction projects, which often involve fragmented workflows, 3DPC enables a more streamlined and flexible supply chain [186]. Additive manufacturing reduces the complexity of supply chains by allowing for localised production and minimising the need for extensive material handling [186]. Managers must coordinate diverse stakeholders, including material suppliers, equipment manufacturers, software providers, contractors, and public authorities, to ensure that the benefits of 3DPC are fully realised [180, 187]. This collaborative approach is critical to the successful implementation of the technology.

Another key consideration for managers is meeting stakeholder expectations. The efficiency, cost savings, and reduced project timelines achieved through 3DPC have been well received by stakeholders, who recognise the socio-economic benefits of this innovative approach [188]. Moreover, 3DPC's capacity to deliver customised and complex designs that meet specific client requirements further reinforces its value in modern construction projects [189]. Despite the potential and growing interest in 3DPC, very limited studies have been conducted on its management aspects, and research in this area remains relatively sparse. Existing literature primarily focuses on technical and economic dimensions, leaving significant gaps in understanding how to best manage 3DPC processes, integration, and challenges at both project and organisational levels. As the construction industry continues to evolve, there is a pressing need for further research to explore strategic frameworks, operational challenges, and innovative solutions that can enhance the management of 3DPC technologies. Future studies should aim to provide actionable insights to guide practitioners and policymakers in fully realising the potential of 3DPC. The integration of 3DP in construction, a managerial aspect of the technology, necessitates to address a range of factors that influence its adoption and implementation. Studies highlight that organisational readiness, supply chain adaptability, and compatibility with existing construction processes are critical to achieving successful 3DP integration in construction industry. Table 10 provides an overview of the key factors, success parameters, challenges, managerial responsibilities, and stakeholder impacts related to the management aspects of 3DPC integration.

Table 10 Overview of management aspects of 3D printed concrete integration

Category	Description	Influential factors or challenges in the adoption of 3DP integration in construction	Reference
Drivers	Factors encouraging the adoption of 3DPC	Elimination of formwork and auxiliary tasks increases productivity	[185, 187]
Success factors	Conditions critical to the successful management and implementation of 3DPC	Automation reduces reliance on skilled labour while maintaining quality	[190]
		Digitalisation enhances control, predictability, and safety on construction site	[184]
		Effective integration of 3DPC into workflows through planning and control	[180]
Challenges	Barriers to the adoption and implementation of 3DPC	Comprehensive workforce training for equipment operation and maintenance	[191]
		Alignment and collaboration among stakeholders: suppliers, designers, contractors, and public authorities	[192]
		Strategic cost management: savings on formwork offset higher material costs	[193]
Management implications	Managerial responsibilities and adjustments required for successful 3DPC adoption	Resistance to change within organisations and among stakeholders	[194]
		Lack of technical expertise for operating and maintaining 3DPC systems	[189]
		Uncertainty regarding regulatory requirements and certification processes for 3D-printed components	[6]
Stakeholder impact	Effect of 3DPC on key stakeholders and their satisfaction	Initial high costs for materials and equipment compared to conventional methods	[195]
		Updating supply chain models to support localised production and streamline logistics	[185, 186]
		Adopting new project scheduling methods to account for faster timelines enabled by 3DPC	[180]
Stakeholder impact	Effect of 3DPC on key stakeholders and their satisfaction	Balancing short-term operational disruptions with long-term benefits of 3DPC	[15]
		Improved efficiency and cost savings lead to higher satisfaction among clients and contractors	[188]
		Enables stakeholders to meet client-specific design requirements and customise projects more effectively	[196]
		Socio-economic benefits include faster project delivery and reduced resource wastage	[196]

Conclusion

This review paper examines recent advancements in 3DPC and its transformative potential in the building and construction industry. A bibliometric analysis of 1007 journal articles highlights key trends, including publication growth, core journals, influential authors, leading countries and institutions, highly cited papers, keyword usage, and emerging research directions. Additionally, a systematic review of 309 journal articles delves deeper into the techniques, materials, and applications of 3DPC, alongside its sustainability, environmental, and economic impacts. The findings reveal significant progress in 3DPC, driven by innovative research and the growing engagement of leading researchers and institutions. This review provides valuable insights into the potential of 3DPC to revolutionise construction through sustainable, cost-effective, and innovative practices. Recommendations for future research emphasise material optimisation, sustainability-focused innovations, and the practical implementation of 3DPC technologies to meet the demands of modern construction. Key findings are:

- The rise of 3DPC represents a transformative shift in the construction industry, characterised by significant research growth, particularly between 2021 and 2023. The journal *Construction and Building Materials* leads the field with 132 publications, followed by *Cement and Concrete Composites and Materials*. Prominent

contributors to this domain include Sanjayan J., Zhang Y., Wang L., and Ma G.

- Key terms such as “3D printing,” “concrete printing,” “compressive strength,” and “construction industry” dominate the discourse. Recent years have seen increasing focus on “crack propagation,” “self-compacting concrete,” “sustainability,” “AI in mix design,” and “green materials for 3DP processes”, reflecting evolving research priorities.
- China, Australia, and the USA emerged as the leading contributing countries, with China accounting for 28% of total publications, while Tongji University was identified as the most active institution, contributing approximately 8% of the global research output.
- The field has experienced an increase of over 800% in publication output between 2018 and 2024, reflecting the rapidly growing academic interest in 3DPC technologies
- 3DPC offers significant advantages in construction, including reduced material waste, elimination of formwork, lower energy consumption, and enhanced sustainability. The technology also enables faster project delivery, reduced labour dependency, and greater architectural flexibility, supporting innovation and growth in the modern construction industry.
- Recent advancements in 3DPC have demonstrated its practical viability across a range of construction applications, including residential buildings, infrastructure,

and pedestrian bridges. These advancements showcase the technology's ability to enhance design adaptability, reduce material waste, accelerate project timelines, and support cost-effective construction. Notable implementations, such as the creation of the world's first 3DP neighbourhood and long-span pedestrian bridges, illustrate the broad utility and transformative impact of 3DPC. Furthermore, ongoing progress in printable materials continues to improve both the mechanical performance and environmental sustainability of 3DP structures, reinforcing its role as a foundational innovation in modern construction practice

- The use of SCMs such as fly ash, metakaolin, silica fume, and ground granulated blast furnace slag significantly enhances the sustainability and performance of 3DPC. These materials improve key properties including compressive strength, durability, and rheological behaviour while reducing cement demand and environmental impact. However, their effectiveness varies depending on dosage, compatibility, and mix design, highlighting the need for standardised guidelines and optimisation frameworks.
- 3DPC contributes to environmental sustainability by reducing construction waste and enabling low carbon material alternatives, yet its full ecological benefits depend on optimised mix designs and lifecycle-based evaluation.
- Current mix design practices in 3DPC predominantly rely on trial-and-error methods, which lack scientific rigour and optimisation. This highlights the need for adopting data-driven or artificial intelligence-based frameworks to enhance the precision, efficiency, and repeatability of mix proportioning.
- 3DPC has the potential to reduce overall construction costs through decreased material usage, reduced labour requirements, and shorter project timelines. However, the high initial investment in equipment and limited standardisation currently constrain its widespread economic feasibility, indicating the need for further cost benefit analyses and scalable implementation strategies
- Effective integration of 3DPC in construction projects requires new management strategies, including the adaptation of workflows, workforce reskilling, and digital coordination between design and production, to overcome current implementation challenges and support industry wide adoption.

Recommendations for future studies

As 3DP technology progresses, its potential to revolutionise the building and construction industry becomes increasingly evident. This technology facilitates the printing of complex shapes and structures, offers extensive customisation options, and significantly reduces material waste. However, several challenges need to be overcome to enable its widespread adoption in the construction sector. To this end, it is essential to propose and implement strategic recommendations that optimise the printing process and fully realise its benefits.

- Material incompatibility and high costs due to the technology being in initial phase remain a significant challenge. Research is needed to enhance the efficiency and compatibility of the 3DP process with a broader range of materials and processes.
- Reliance on trial-and-error mix designs highlights the need for validated, application-specific formulations to improve precision and expand 3DPC applicability in construction.
- Incorporating SCMs, mineral additives, and chemical admixtures into 3DPC can improve setting times and early-age properties. However, research must determine optimal quantities to prevent issues with interlayer adhesion and pumpability, establishing appropriate dosages across varied scenarios.
- Identifying the physical and technical limits of 3DPC is crucial. Research should define boundaries such as structural dimension extremes, feasibility of complex shapes, and operational range under diverse environmental conditions.
- Innovative materials designed to accelerate construction, improve mechanical properties, and minimise environmental impacts are needed. Research into hybrid composites and eco-friendly alternatives can significantly enhance 3DPC quality and sustainability.
- Exploring underexplored aspects such as reinforcement methods, self-compacting concrete, and other construction-specific factors is essential to advance the practical implementation of 3DP in the construction industry.
- Stakeholders' involvement and satisfaction is less hence efforts should focus on increasing awareness through media campaigns, workshops, and live demonstrations. Educational initiatives should be developed to build a skilled workforce, complemented by pilot projects that showcase the practical applications, efficiency, and cost-effectiveness of 3DP. Additionally, partnerships between educational institutions, industry leaders and government can provide internships and real-world experience.

- There is much less focus on managerial side, hence specific frameworks should be developed for managing 3DPC projects, focusing on scheduling, resource allocation, and risk management dedicated to this technology. Conduct detailed studies on cost estimation, budgeting, and financial risk analysis in 3DPC to guide stakeholders in decision-making.
- Encourage cross-disciplinary collaborations i.e. between construction managers, architects, material scientists, and software developers to design more efficient and sustainable 3DPC systems.
- Future research should move beyond technical aspects and focus on practical applications, such as reducing tool use, minimising material waste, and mitigating construction risks. Success in 3D-printed structures depends on optimising the properties of fresh concrete, making it crucial to identify and refine concrete mixes suited for 3DP.

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Data availability Data is available in the supplementary materials.

Declarations

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors. During the preparation of this work the authors used ChatGpt and Grammarly in order for the language enhancement. After using this tool/service, the authors reviewed and edited the content as needed and takes full responsibility for the content of the publication.

Informed consent Not applicable, as the study does not involve human subjects.

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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References

1. Ning X, Liu T, Wu C, Wang C (2021) 3D printing in construction: current status, implementation hindrances, and development agenda. *Adv Civil Eng*. <https://doi.org/10.1155/2021/6665333>
2. Žujović M, Obradović R, Rakonjac I, Milošević J (2022) 3D printing technologies in architectural design and construction: a systematic literature review. *Buildings*. <https://doi.org/10.3390/buildings12091319>
3. Ngo TD, Kashani A, Imbalzano G, Nguyen KTQ, Hui D (2018) Additive manufacturing (3D printing): a review of materials, methods, applications and challenges. *Compos B Eng* 143:172–196. <https://doi.org/10.1016/j.compositesb.2018.02.012>
4. Pan Y, Zhang Y, Zhang D, Song Y (2021) 3D printing in construction: state of the art and applications. *Int J Adv Manuf Technol* 115:1329–1348. <https://doi.org/10.1007/s00170-021-07213-0>
5. Akman A, Sadhu A (2024) Recent development of 3D-printing technology in construction engineering. *Pract Period Struct Des Constr*. <https://doi.org/10.1061/ppscfx.sceng-1278>
6. Tu H, Wei Z, Bahrami A, Ben Kahla N, Ahmad A, Özkılıç YO (2023) Recent advancements and future trends in 3D concrete printing using waste materials. *Dev Built Environ*. <https://doi.org/10.1016/j.dibe.2023.100187>
7. Şahin HG, Mardani-Aghabaglou A (2022) Assessment of materials, design parameters and some properties of 3D printing concrete mixtures; a state-of-the-art review. *Constr Build Mater* 316(December):2021. <https://doi.org/10.1016/j.conbuildmat.2021.125865>
8. El-Sayegh S, Romdhane L, Manjikian S (2020) A critical review of 3D printing in construction: benefits, challenges, and risks. *Arch Civ Mech Eng* 20:1–25. <https://doi.org/10.1007/s43452-020-00038-w>
9. Besklubova S, Skibniewski MJ, Zhang X (2021) Factors affecting 3D printing technology adaptation in construction. *J Constr Eng Manag*. [https://doi.org/10.1061/\(asce\)co.1943-7862.0002034](https://doi.org/10.1061/(asce)co.1943-7862.0002034)
10. du Plessis A, Babafemi AJ, Paul SC, Panda B, Tran JP, Broeckhoven C (2020) Biomimicry for 3D concrete printing: A review and perspective. *Addit Manuf* 38(December):2021. <https://doi.org/10.1016/j.addma.2020.101823>
11. World's First 3D Printed Mosque Completed in Saudi Arabia—3D natives. Available: <https://www.3dnatives.com/en/worlds-first-3d-printed-mosque-completed-in-saudi-arabia-130320244/#1>. Accessed 27 January 2025
12. Robayo-Salazar R, de Gutiérrez R, Villaquirán-Caicedo MA, DelvastoArjona S (2023) 3D printing with cementitious materials: Challenges and opportunities for the construction sector. *Autom Constr* 146:104693. <https://doi.org/10.1016/j.autcon.2022.104693>
13. Chen K, Liu Q, Chen B, Zhang S, Ferrara L, Li W (2024) Effect of raw materials on the performance of 3D printing geopolymer: a review. *J Build Eng* 84:108501. <https://doi.org/10.1016/j.jobe.2024.108501>
14. Tabassum T, Ahmad Mir A (2023) A review of 3d printing technology-the future of sustainable construction. *Mater Today Proc* 93:408–414. <https://doi.org/10.1016/j.matpr.2023.08.013>
15. Hamidi F, Aslani F (2019) Additive manufacturing of cementitious composites: materials, methods, potentials, and challenges. *Constr Build Mater* 218:582–609. <https://doi.org/10.1016/j.conbuildmat.2019.05.140>
16. Shakor P, Nejadi S, Paul G, Malek S (2019) Review of emerging additive manufacturing technologies in 3d printing of cementitious materials in the construction industry. *Front Built Environ*. <https://doi.org/10.3389/fbuil.2018.00085>

17. Khan MS, Sanchez F, Zhou H (2020) 3-D printing of concrete: beyond horizons. *Cem Concr Res*. <https://doi.org/10.1016/j.cemconres.2020.106070>
18. Jandyal A, Chaturvedi I, Wazir I, Raina A, Ul Haq MI (2021) 3D printing—a review of processes, materials and applications in industry 4.0. *Sustain Oper Comput* 3:33–42. <https://doi.org/10.16/j.susoc.2021.09.004>
19. Khan SA, Ghazi SMU, Amjad H, Imran M, Khushnood RA (2023) Emerging horizons in 3D printed cement-based materials with nanomaterial integration: a review. *Constr Build Mater* 411:134815. <https://doi.org/10.1016/j.conbuildmat.2023.134815>
20. Martín-Martín A, Orduna-Malea E, Thelwall M, Delgado López-Cózar E (2018) Google scholar, web of science, and scopus: a systematic comparison of citations in 252 subject categories. *J Informetr* 12(4):1160–1177. <https://doi.org/10.1016/j.joi.2018.09.002>
21. Moher D, Liberati A, Tetzlaff J, Altman DG (2010) Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *Int J Surg* 8(5):336–341. <https://doi.org/10.1016/j.ijsu.2010.02.007>
22. Aria M, Cuccurullo C (2017) Bibliometrix: an R-tool for comprehensive science mapping analysis. *J Informetr* 11(4):959–975. <https://doi.org/10.1016/j.joi.2017.08.007>
23. Zupic I, Čater T (2015) Bibliometric methods in management and organization. *Organ Res Methods* 18(3):429–472. <https://doi.org/10.1177/1094428114562629>
24. Ellegaard O, Wallin JA (2015) The bibliometric analysis of scholarly production: how great is the impact? *Scientometrics* 105(3):1809–1831. <https://doi.org/10.1007/s11192-015-1645-z>
25. Leong Z, Chen R, Xu Z, Lin Y, Hu N (2023) Robotic arm three-dimensional printing and modular construction of a meter-scale lattice façade structure. *Eng Struct* 290:116368. <https://doi.org/10.1016/j.engstruct.2023.116368>
26. Brousek J, Petr T, Mendricky R (2023) Displacement analysis of large-scale robotic arm for printing cement mortar using photogrammetry. *Machines* 11(1):1–16. <https://doi.org/10.3390/machines11010037>
27. Puzatova A, Shakor P, Laghi V, Dmitrieva M (2022) Large-scale 3D printing for construction application by means of robotic arm and gantry 3D printer: a review. *Buildings*. <https://doi.org/10.3390/buildings12112023>
28. Sahai R, Bisht RS, Singh S, Panigrahi SK (2024) Design analysis and development of a gantry robot for multi-layer 3-D concrete printing with simulation and experimental validation. *Mech Based Des Struct Mach* 0(0):1–30. <https://doi.org/10.1080/15397734.2024.2377266>
29. gang Qi L et al (2022) Mobile 3D printing techniques for construction engineering: outdoor navigation and printing quality control. *Struct Eng Int* 32(2):203–210. <https://doi.org/10.1080/10168664.2022.2025749>
30. Shen J, Li Y, Zhang X, Li Y, Huang C, Luo W (2024) Three-dimensional printable concrete by an ultra-thin nozzle and fully sealed extrusion. *Buildings*. <https://doi.org/10.3390/buildings14071958>
31. Shahzad Q, Abbas N, Akbar M, Sabi E, Thomas BS, Arshid MU (2024) Influence of print speed and nozzle diameter on the fiber alignment in 3D printed ultra-high-performance concrete. *Front Mater* 11:1–18. <https://doi.org/10.3389/fmats.2024.1355647>
32. The world's tallest 3D printed building | COBOD International. Available: <https://cobod.com/the-worlds-tallest-3d-printed-building-is-now-in-saudia-arabia/>. Accessed 27 January 2025
33. Apis Cor builds world's largest 3D-printed building in Dubai. Available: <https://www.dezeen.com/2019/12/22/apis-cor-worlds-largest-3d-printed-building-dubai/>. Accessed: 27 January 2025
34. This is the world's first 3D-printed neighborhood | by Varun Cheedalla | TechTalkers | Medium. Available: <https://medium.com/techtalkers/worlds-first-3d-printed-neighborhood-b4fe807829d5>. Accessed 27 January 2025
35. MEED | Acciona builds Middle East's first 3D-printed bus stop Available: <https://www.meed.com/acciona-builds-middle-east-s-first-3d-printed-bus-stop>. Accessed 27 January 2025.
36. Menna C et al (2020) Opportunities and challenges for structural engineering of digitally fabricated concrete. *Cem Concr Res* 133:106079. <https://doi.org/10.1016/j.cemconres.2020.106079>
37. Hajare DM, Gajbhiye TS (2022) Additive manufacturing (3D printing): recent progress on advancement of materials and challenges. *Mater Today Proc* 58(2022):736–743. <https://doi.org/10.1016/j.matpr.2022.02.391>
38. Vergara LA, Perez JF, Colorado HA (2023) 3D printing of ordinary Portland cement with waste wood derived biochar obtained from gasification. *Case Stud Constr Mater* 18:e02117. <https://doi.org/10.1016/j.cscm.2023.e02117>
39. Dhandapani Y, Marsh ATM, Rahmon S, Kanavaris F, Papakosta A, Bernal SA (2023) Suitability of excavated London clay as a supplementary cementitious material: mineralogy and reactivity. *Mater Struct* 56(10):1–21. <https://doi.org/10.1617/s11527-023-02260-3>
40. Christen H, van Zijl G, de Villiers W (2022) The incorporation of recycled brick aggregate in 3D printed concrete. *Clean Mater*. <https://doi.org/10.1016/j.clema.2022.100090>
41. Gamage K, Fawzia S, Zahra T, Teixeira MBF, Ramli Sulong NH (2024) Advancement in sustainable 3D concrete printing: a review on materials, challenges, and current progress in Australia. *Buildings*. <https://doi.org/10.3390/buildings14020494>
42. Kondepudi K, Subramaniam KVL (2021) Formulation of alkali-activated fly ash-slag binders for 3D concrete printing. *Cem Concr Compos*. <https://doi.org/10.1016/j.cemconcomp.2021.103983>
43. Zaid O, El Ouni MH (2024) Advancements in 3D printing of cementitious materials: a review of mineral additives, properties, and systematic developments. *Constr Build Mater*. <https://doi.org/10.1016/j.conbuildmat.2024.136254>
44. Dey D, Srinivas D, Panda B, Suraneni P, Sitharam TG (2022) Use of industrial waste materials for 3D printing of sustainable concrete: a review. *J Clean Prod* 340:130749. <https://doi.org/10.1016/j.jclepro.2022.130749>
45. Ibrahim KA, van Zijl GPAG, Babafemi AJ (2023) Influence of limestone calcined clay cement on properties of 3D printed concrete for sustainable construction. *J Build Eng*. <https://doi.org/10.1016/j.jobe.2023.106186>
46. Al-Noaimat YA et al (2023) 3D printing of limestone-calcined clay cement: a review of its potential implementation in the construction industry. *Results Eng* 18:101115. <https://doi.org/10.1016/j.rineng.2023.101115>
47. Bhattacharjee S et al (2021) Sustainable materials for 3D concrete printing. *Cem Concr Compos*. <https://doi.org/10.1016/j.cemconcomp.2021.104156>
48. Akinyemi BA, Adesina A (2020) Recent advancements in the use of biochar for cementitious applications: a review. *J Build Eng* 32:101705. <https://doi.org/10.1016/j.jobe.2020.101705>
49. Senadheera SS et al (2023) Application of biochar in concrete—a review. *Cem Concr Compos* 143:105204. <https://doi.org/10.1016/j.cemconcomp.2023.105204>
50. Pimentel Tinoco M, Gouvêa L, de CássiaMagalhães Martins K, Dias Toledo Filho R, Aurelio Mendoza Reales O (2023) The use of rice husk particles to adjust the rheological properties of 3D printable cementitious composites through water sorption. *Constr Build Mater* 365:130046. <https://doi.org/10.1016/j.conbuildmat.2022.130046>
51. Muthukrishnan S, Kua HW, Yu LN, Chung JKH (2020) Fresh properties of cementitious materials containing rice husk ash for

- construction 3D printing. *J Mater Civ Eng* 32(8):1–16. [https://doi.org/10.1061/\(asce\)mt.1943-5533.0003230](https://doi.org/10.1061/(asce)mt.1943-5533.0003230)
52. Ting GHA, Tay YWD, Qian Y, Tan MJ (2019) Utilization of recycled glass for 3D concrete printing: rheological and mechanical properties. *J Mater Cycles Waste Manag* 21(4):994–1003. <https://doi.org/10.1007/s10163-019-00857-x>
 53. Christen H, van Zijl G, de Villiers W (2022) The incorporation of recycled brick aggregate in 3D printed concrete. *Cleaner Mater* 4:100090. <https://doi.org/10.1016/j.clema.2022.100090>
 54. Han Y, Yang Z, Ding T, Xiao J (2021) Environmental and economic assessment on 3D printed buildings with recycled concrete. *J Clean Prod* 278:123884. <https://doi.org/10.1016/j.jclepro.2020.123884>
 55. Oosthuizen JD, Babafemi AJ, Walls RS (2023) 3D-printed recycled plastic eco-aggregate (Resin8) concrete. *Constr Build Mater*. <https://doi.org/10.1016/j.conbuildmat.2023.133712>
 56. Javed A, Mantawy IM, Azizinamini A (2021) 3D-printing of ultra-high-performance concrete for robotic bridge construction. *Transp Res Record J Transp Res Board* 2675(7):307–319. <https://doi.org/10.1177/03611981211011645>
 57. Sucharda O, Gandel R, Cmiel P, Jerabek J, Bilek V (2024) Utilization of high-performance concrete mixtures for advanced manufacturing technologies. *Buildings*. <https://doi.org/10.3390/buildings14082269>
 58. Yao Y, Zhang J, Sun Y, Pi Y, Wang J, Lu C (2024) Mechanical properties and failure mechanism of 3D printing ultra-high performance concrete. *Constr Build Mater* 447:138108. <https://doi.org/10.1016/j.conbuildmat.2024.138108>
 59. Fan D et al (2023) Intelligent design and manufacturing of ultra-high performance concrete (UHPC)—a review. *Constr Build Mater*. <https://doi.org/10.1016/j.conbuildmat.2023.131495>
 60. De Nardi C, Gardner R, Cristofori D, Ronchin L, Vavasori A, Jefferson T (2023) Advanced 3D printed mini-vascular network for self-healing concrete. *Mater Des*. <https://doi.org/10.1016/j.matdes.2023.111939>
 61. Wan Z, Xu Y, Zhang Y, He S, Šavija B (2022) Mechanical properties and healing efficiency of 3D-printed ABS vascular based self-healing cementitious composite: experiments and modelling. *Eng Fract Mech*. <https://doi.org/10.1016/j.engfracmech.2022.108471>
 62. Bishar Hussein A, Bishar Hussein A (2021) Review paper on 3D printing concrete technology and mechanics from industrial aspect. *Int J Eng Appl Sci Technol* 5(12):39–48. <https://doi.org/10.33564/ijeast.2021.v05i12.006>
 63. Zhang C et al (2021) Mix design concepts for 3D printable concrete: a review. *Cem Concr Compos*. <https://doi.org/10.1016/j.cemconcomp.2021.104155>
 64. Li VC et al (2020) On the emergence of 3D printable engineered, strain hardening cementitious composites (ECC/SHCC). *Cem Concr Res*. <https://doi.org/10.1016/j.cemconres.2020.106038>
 65. Zhou W, McGee W, Zhu H, Gökçe HS, Li VC (2022) Time-dependent fresh properties characterization of 3D printing engineered cementitious composites (3DP-ECC): on the evaluation of buildability. *Cem Concr Compos*. <https://doi.org/10.1016/j.cemconcomp.2022.104704>
 66. Ma G, Li Z, Wang L (2018) Printable properties of cementitious material containing copper tailings for extrusion based 3D printing. *Constr Build Mater* 162:613–627. <https://doi.org/10.1016/j.conbuildmat.2017.12.051>
 67. Pan Z, Si D, Tao J, Xiao J (2023) Compressive behavior of 3D printed concrete with different printing paths and concrete ages. *Case Stud Constr Mater*. <https://doi.org/10.1016/j.cscm.2023.e01949>
 68. Markin V, Nerella VN, Schröfl C, Guseynova G, Mechtcherine V (2019) Material design and performance evaluation of foam concrete for digital fabrication. *Materials*. <https://doi.org/10.3390/ma12152433>
 69. Nerella VN, Hempel S, Mechtcherine V (2019) Effects of layer-interface properties on mechanical performance of concrete elements produced by extrusion-based 3D-printing. *Constr Build Mater* 205:586–601. <https://doi.org/10.1016/j.conbuildmat.2019.01.235>
 70. Parikh HH, Chokshi S, Chaudhary V, Khan A, Mistry J (2023) Flexural response of 3D printed wood dust reinforced polymer composite. *Mater Today Proc*. <https://doi.org/10.1016/j.matpr.2023.06.375>
 71. Ma G, Salman NM, Wang L, Wang F (2020) A novel additive mortar leveraging internal curing for enhancing interlayer bonding of cementitious composite for 3D printing. *Constr Build Mater* 244:118305. <https://doi.org/10.1016/j.conbuildmat.2020.118305>
 72. Dey D, Srinivas D, Panda B, Suraneni P, Sitharam TG (2022) Use of industrial waste materials for 3D printing of sustainable concrete: a review. *J Clean Prod*. <https://doi.org/10.1016/j.jclepro.2022.130749>
 73. Melichar J, Žižková N, Brožovský J, Mészárosová L, Hermann R (2022) Study of the interaction of cement-based materials for 3D printing with fly ash and superabsorbent polymers. *Buildings*. <https://doi.org/10.3390/buildings12112008>
 74. Yang H, Che Y (2022) Recycling of aggregate micro fines as a partial replacement for fly ash in 3D printing cementitious materials. *Constr Build Mater* 321:126372. <https://doi.org/10.1016/j.conbuildmat.2022.126372>
 75. Jaji MB, Ibrahim KA, van Zijl GPAG, Babafemi AJ (2023) Effect of anisotropy on permeability index and water absorption of 3D printed metakaolin-based geopolymer concrete. *Mater Today Proc*. <https://doi.org/10.1016/j.matpr.2023.06.394>
 76. Xu Z et al (2023) Effects of additives on the mechanical properties, rheology, and printing properties of Pcc-based 3DPMs. *Ceram Int* 49(17):28354–28368. <https://doi.org/10.1016/j.ceramint.2023.06.090>
 77. Diniz HAA, Martinelli AE, Cabral KC, Ferreira RLdaS, da Silva IFD (2023) Synergistic effects of the use of metakaolin, sand and water on the properties of cementitious composites for 3D printing. *Constr Build Mater*. <https://doi.org/10.1016/j.conbuildmat.2022.130277>
 78. Duan Z, Li L, Yao Q, Zou S, Singh A, Yang H (2022) Effect of metakaolin on the fresh and hardened properties of 3D printed cementitious composite. *Constr Build Mater* 350:128808. <https://doi.org/10.1016/j.conbuildmat.2022.128808>
 79. Jaji MB, Ibrahim KA, van Zijl GPAG, Babafemi AJ (2023) Thixotropic characterisation of slag modified 3D printable metakaolin based geopolymer composite. *Mater Today Proc*. <https://doi.org/10.1016/j.matpr.2023.03.530>
 80. Srinivas D, Dey D, Panda B, Sitharam TG (2022) Printability, thermal and compressive strength properties of cementitious materials: a comparative study with silica fume and limestone. *Materials*. <https://doi.org/10.3390/ma15238607>
 81. Chen Y, Zhang Y, He S, Liang X, Schlangen E, Çopuroğlu O (2023) Improving structural build-up of limestone-calcined clay-cement pastes by using inorganic additives. *Constr Build Mater*. <https://doi.org/10.1016/j.conbuildmat.2023.131959>
 82. Kanagasuntharam S, Ramakrishnan S, Muthukrishnan S, Sanjayam J (2023) Effect of magnetorheological additives on the buildability of 3D concrete printing. *J Build Eng*. <https://doi.org/10.1016/j.jobeb.2023.106814>
 83. Liu C, Zhang Y, Banthia N (2023) Unveiling pore formation and its influence on micromechanical property and stress distribution of 3D printed foam concrete modified with hydroxypropyl methylcellulose and silica fume. *Addit Manuf* 71(April):103606. <https://doi.org/10.1016/j.addma.2023.103606>

84. Hamada HM et al (2023) Effect of silica fume on the properties of sustainable cement concrete. *J Mater Res Technol* 24:8887–8908. <https://doi.org/10.1016/j.jmrt.2023.05.147>
85. Cui W et al (2023) Study of 3D printed concrete with low-carbon cementitious materials based on its rheological properties and mechanical performances. *J Sustain Cem Based Mater* 12(7):832–841. <https://doi.org/10.1080/21650373.2023.2189172>
86. Shilar FA, Ganachari SV, Patil VB, Bhojaraja BE, Yunus Khan TM, Almakayee N (2023) A review of 3D printing of geopolymer composites for structural and functional applications. *Constr Build Mater* 400(July):132869. <https://doi.org/10.1016/j.conbuildmat.2023.132869>
87. Colyn M, van Zijl G, Babafemi AJ (2024) Fresh and strength properties of 3D printable concrete mixtures utilising a high volume of sustainable alternative binders. *Constr Build Mater*. <https://doi.org/10.1016/j.conbuildmat.2024.135474>
88. Li X, Bai C, Qiao Y, Wang X, Yang K, Colombo P (2022) Preparation, properties and applications of fly ash-based porous geopolymers: a review. *J Clean Prod* 359(April):132043. <https://doi.org/10.1016/j.jclepro.2022.132043>
89. Jaji MB, van Zijl GPAG, Babafemi AJ (2024) Durability and pore structure of metakaolin-based 3D printed geopolymer concrete. *Constr Build Mater* 422:135847. <https://doi.org/10.1016/j.conbuildmat.2024.135847>
90. Diniz HAA, Martinelli AE, Cabral KC, Ferreira RLDS, da Silva IFD (2023) Synergistic effects of the use of metakaolin, sand and water on the properties of cementitious composites for 3D printing. *Constr Build Mater* 366:130277. <https://doi.org/10.1016/j.conbuildmat.2022.130277>
91. Jia Z, Kong L, Jia L, Ma L, Chen Y, Zhang Y (2024) Printability and mechanical properties of 3D printing ultra-high performance concrete incorporating limestone powder. *Constr Build Mater* 426:136195. <https://doi.org/10.1016/j.conbuildmat.2024.136195>
92. Yang H, Che Y, Shi M (2021) Influences of calcium carbonate nanoparticles on the workability and strength of 3D printing cementitious materials containing limestone powder. *J Build Eng* 44:102976. <https://doi.org/10.1016/j.job.2021.102976>
93. Chen Y, He S, Zhang Y, Wan Z, Çopuroğlu O, Schlangen E (2021) 3D printing of calcined clay-limestone-based cementitious materials. *Cem Concr Res* 149:106553. <https://doi.org/10.1016/j.cemconres.2021.106553>
94. Wang D, Shi C, Farzadnia N, Shi Z, Jia H, Ou Z (2018) A review on use of limestone powder in cement-based materials: mechanism, hydration and microstructures. *Constr Build Mater* 181:659–672. <https://doi.org/10.1016/j.conbuildmat.2018.06.075>
95. Bhushan Jindal B, Jangra P (2023) 3D printed concrete: a comprehensive review of raw material's properties, synthesis, performance, and potential field applications. *Constr Build Mater*. <https://doi.org/10.1016/j.conbuildmat.2023.131614>
96. Lucen H, Long L, Shipeng Z, Huanghua Z, Jianzhuang X, Chi-Sun P (2024) The synergistic effect of greenhouse gas CO₂ and silica fume on the properties of 3D printed mortar. *Compos B Eng* 271:111188. <https://doi.org/10.1016/j.compositesb.2023.111188>
97. Liu C et al (2021) Influence of hydroxypropyl methylcellulose and silica fume on stability, rheological properties, and printability of 3D printing foam concrete. *Cem Concr Compos* 122:104158. <https://doi.org/10.1016/j.cemconcomp.2021.104158>
98. Bayat H, Kashani A (2023) Analysis of rheological properties and printability of a 3D-printing mortar containing silica fume, hydrated lime, and blast furnace slag. *Mater Today Commun*. <https://doi.org/10.1016/j.mtcomm.2023.107128>
99. Ahmed GH, Askandar NH, Jumaa GB (2022) A review of large-scale 3DCP: material characteristics, mix design, printing process, and reinforcement strategies. *Structures* 43:508–532. <https://doi.org/10.1016/j.istruc.2022.06.068>
100. Liu Y, Wang L, Yuan Q, Peng J (2023) Effect of coarse aggregate on printability and mechanical properties of 3D printed concrete. *Constr Build Mater* 405:133338. <https://doi.org/10.1016/j.conbuildmat.2023.133338>
101. Wang X et al (2022) Optimization of 3D printing concrete with coarse aggregate via proper mix design and printing process. *J Build Eng* 56:104745. <https://doi.org/10.1016/j.job.2022.104745>
102. Wu Y et al (2021) Study on the rheology and buildability of 3D printed concrete with recycled coarse aggregates. *J Build Eng*. <https://doi.org/10.1016/j.job.2021.103030>
103. Sasikumar A, Balasubramanian D, Senthil Kumaran MS, Govindaraj V (2023) Effect of coarse aggregate content on the rheological and buildability properties of 3D printable concrete. *Constr Build Mater*. <https://doi.org/10.1016/j.conbuildmat.2023.131859>
104. Rahul AV, Mohan MK, Schutter GD, Tittelboom KV (2021) 3D printable concrete with natural and recycled coarse aggregates: rheological, mechanical and shrinkage behaviour. *Cem Concr Compos* 125:104311. <https://doi.org/10.1016/j.cemconcomp.2021.104311>
105. Babafemi AJ, Norval C, Kolawole JT, Chandra Paul S, Ibrahim KA (2023) 3D-printed limestone calcined clay cement concrete incorporating recycled plastic waste (RESIN8). *Results Eng* 22:102112. <https://doi.org/10.1016/j.rineng.2024.102112>
106. Faleschini F, Trento D, Masoomi M, Pellegrino C, Zanini MA (2023) Sustainable mixes for 3D printing of earth-based constructions. *Constr Build Mater* 398:132496. <https://doi.org/10.1016/j.conbuildmat.2023.132496>
107. Zou S, Xiao J, Ding T, Duan Z, Zhang Q (2021) Printability and advantages of 3D printing mortar with 100% recycled sand. *Constr Build Mater*. <https://doi.org/10.1016/j.conbuildmat.2020.121699>
108. Ding T, Xiao J, Zou S, Wang Y (2020) Hardened properties of layered 3D printed concrete with recycled sand. *Cem Concr Compos*. <https://doi.org/10.1016/j.cemconcomp.2020.103724>
109. Ding T, Xiao J, Zou S, Yu J (2021) Flexural properties of 3D printed fibre-reinforced concrete with recycled sand. *Constr Build Mater*. <https://doi.org/10.1016/j.conbuildmat.2021.123077>
110. Ding T, Xiao J, Qin F, Duan Z (2020) Mechanical behavior of 3D printed mortar with recycled sand at early ages. *Constr Build Mater*. <https://doi.org/10.1016/j.conbuildmat.2020.118654>
111. Zhang H, Xiao J (2021) Plastic shrinkage and cracking of 3D printed mortar with recycled sand. *Constr Build Mater*. <https://doi.org/10.1016/j.conbuildmat.2021.124405>
112. Tramontin Souza M et al (2022) Role of chemical admixtures on 3D printed Portland cement: Assessing rheology and buildability. *Constr Build Mater* 314:125666. <https://doi.org/10.1016/j.conbuildmat.2021.125666>
113. de Matos PR, Zat T, Lima MM, da S. Andrade Neto J, Souza MT, Rodríguez ED (2023) Effect of the superplasticizer addition time on the fresh properties of 3D printed limestone calcined clay cement (LC3) concrete. *Case Stud Constr Mater*. <https://doi.org/10.1016/j.cscm.2023.e02419>
114. Liu J, Tran P, Ginigaddara T, Mendis P (2023) Exploration of using graphene oxide for strength enhancement of 3D-printed cementitious mortar. *Addit Manuf Lett*. <https://doi.org/10.1016/j.addlet.2023.100157>
115. Zhou GX et al (2020) 3D printing geopolymer nanocomposites structure: Graphene oxide size effects on a reactive matrix. *Carbon N Y* 164:215–223. <https://doi.org/10.1016/j.carbon.2020.02.021>
116. Liu S, Lu F, Chen Y, Dong B, Du H, Li X (2022) Efficient use of graphene oxide in layered cement mortar. *Materials*. <https://doi.org/10.3390/ma15062181>
117. Inayath Basha S, Ur Rehman A, Aziz MA, Kim JH (2023) Cement composites with carbon-based nanomaterials for 3D concrete

- printing applications – a review. *Chem Record*. <https://doi.org/10.1002/tcr.202200293>
118. Ma G, Yan Y, Zhang M, Sanjayan J (2022) Effect of steel slag on 3D concrete printing of geopolymer with quaternary binders. *Ceram Int* 48(18):26233–26247. <https://doi.org/10.1016/j.ceramint.2022.05.305>
 119. Sheng G, Li C, Jin S, Bai Q (2023) Effects of steel slag powder as a cementitious material on compressive strength of cement-based composite. *Minerals*. <https://doi.org/10.3390/min13070869>
 120. Yu Q et al (2023) Investigation of the rheological and mechanical properties of 3D printed eco-friendly concrete with steel slag. *J Build Eng*. <https://doi.org/10.1016/j.jobe.2023.106621>
 121. Kim KK, Yeon J, Lee HJ, Yeon JH (2019) Dimensional stability of SBR-modified cementitious mixtures for use in 3D additive construction. *Appl Sci*. <https://doi.org/10.3390/app9163386>
 122. Kim KK, Yeon J, Lee HJ, Yeon KS (2019) Strength development characteristics of SBR-modified cementitious mixtures for 3-dimensional concrete printing. *Sustainability*. <https://doi.org/10.3390/su11154164>
 123. Falliano D, Restuccia L, Ferro GA (2022) Biochar addition for 3DCP: a preliminary study. *Proc Struct Integr* 41:699–703. <https://doi.org/10.1016/j.prostr.2022.05.079>
 124. Yang X, Wang XY (2021) Strength and durability improvements of biochar-blended mortar or paste using accelerated carbonation curing. *J CO2 Util* 54:101766. <https://doi.org/10.1016/j.jcou.2021.101766>
 125. Chen Y, Romero Rodriguez C, Li Z, Chen B, Çopuroğlu O, Schlangen E (2020) Effect of different grade levels of calcined clays on fresh and hardened properties of ternary-blended cementitious materials for 3D printing. *Cem Concr Compos* 114:103708. <https://doi.org/10.1016/j.cemconcomp.2020.103708>
 126. Xu Z, Zhang D, Li H, Jin H, Cai X, Tian Z (2023) Mix design and 3D printing correlation performance of Pcc-based 3DPM. *Compos Struct* 320:117229. <https://doi.org/10.1016/j.compstruct.2023.117229>
 127. Chandra Paul S, Basit MA, Hasan NMS, Dey D, Panda B (2023) “3D printing of geopolymer mortar: Overview of the effect of mix design and printing parameters on the strength. *Mater Today Proc*. <https://doi.org/10.1016/j.matpr.2023.04.292>
 128. Ali A et al (2023) Machine learning-based predictive model for tensile and flexural strength of 3D-printed concrete. *Materials*. <https://doi.org/10.3390/ma16114149>
 129. Pham TL, Zhuang XJ, Nguyen THT, Nguyen PA, Trinh DT, Do TQ (2023) 3D printable concrete: mixture design and laboratory test methods. *Minist Sci Technol Viet* 65(1):3–8. [https://doi.org/10.31276/vjste.65\(1\).03-08](https://doi.org/10.31276/vjste.65(1).03-08)
 130. Weng Y, Lu B, Li M, Liu Z, Tan MJ, Qian S (2018) Empirical models to predict rheological properties of fiber reinforced cementitious composites for 3D printing. *Constr Build Mater* 189:676–685. <https://doi.org/10.1016/j.conbuildmat.2018.09.039>
 131. Zhang Y, Zhang Y, Liu G, Yang Y, Wu M, Pang B (2018) Fresh properties of a novel 3D printing concrete ink. *Constr Build Mater* 174:263–271. <https://doi.org/10.1016/j.conbuildmat.2018.04.115>
 132. Rahul AV, Santhanam M, Meena H, Ghani Z (2019) 3D printable concrete: mixture design and test methods. *Cem Concr Compos* 97:13–23. <https://doi.org/10.1016/j.cemconcomp.2018.12.014>
 133. Rahmat NF, Ali N, Abdullah SR, Abdul Hamid NA, Salleh N, Shahidan S (2023) Fresh properties and flexural strength of 3D printing sustainable concrete containing GGBS as partial cement replacement. *IOP Conf Ser Earth Environ Sci* 1205(1):33–41. <https://doi.org/10.1088/1755-1315/1205/1/012042>
 134. Daher J, Kleib J, Benzerzour M, Abriak NE, Aouad G (2023) The development of soil-based 3D-printable mixtures: a mix-design methodology and a case study. *Buildings*. <https://doi.org/10.3390/buildings13071618>
 135. Ambily PS, Rajendran N, Kaliyavaradhan SK (2023) Mix design, optimization and performance evaluation of extrusion-based 3D printable concrete. *Proc Inst Civ Eng Construct Mater*. <https://doi.org/10.1680/jcoma.23.00077>
 136. Sergis V, Ouellet-Plamondon CM (2022) Automating mix design for 3D concrete printing using optimization methods. *Digit Discov* 1(5):645–657. <https://doi.org/10.1039/d2dd00040g>
 137. Liu Z, Li M, Weng Y, Wong TN, Tan MJ (2019) Mixture design approach to optimize the rheological properties of the material used in 3D cementitious material printing. *Constr Build Mater* 198:245–255. <https://doi.org/10.1016/j.conbuildmat.2018.11.252>
 138. Kaushik S, Sonebi M, Amato G, Das UK, Perrot A (2023) Optimisation of mix proportion of 3D printable mortar based on rheological properties and material strength using factorial design of experiment. *Materials*. <https://doi.org/10.3390/ma16041748>
 139. Malik UJ, Riaz RD, Rehman SU, Usman M, Riaz RE, Hamza R (2024) Advancing mix design prediction in 3D printed concrete: predicting anisotropic compressive strength and slump flow. *Case Stud Constr Mater* 21:e03510. <https://doi.org/10.1016/j.cscm.2024.e03510>
 140. Rehman SU, Riaz RD, Usman M, Kim IH (2024) Augmented data-driven approach towards 3D printed concrete mix prediction. *Appl Sci*. <https://doi.org/10.3390/app14167231>
 141. Liu Y et al (2024) Machine learning driven fluidity and rheological properties prediction of fresh cement-based materials. *Materials*. <https://doi.org/10.3390/ma17225400>
 142. Chen M et al (2020) Yield stress and thixotropy control of 3D-printed calcium sulfoaluminate cement composites with metakaolin related to structural build-up. *Constr Build Mater*. <https://doi.org/10.1016/j.conbuildmat.2020.119090>
 143. Zhang C, Deng Z, Chen C, Zhang Y, Mechtcherine V, Sun Z (2022) Predicting the static yield stress of 3D printable concrete based on flowability of paste and thickness of excess paste layer. *Cem Concr Compos*. <https://doi.org/10.1016/j.cemconcomp.2022.104494>
 144. Heywood K, Nicholas P (2023) Sustainability and 3D concrete printing: identifying a need for a more holistic approach to assessing environmental impacts. *Architect Intell*. <https://doi.org/10.1007/s44223-023-00030-3>
 145. Roux C, Archez J, Le Gall C, Saadé M, Féraille A, Caron JF (2024) Towards sustainable material: optimizing geopolymer mortar formulations for 3D printing: a life cycle assessment approach. *Sustainability*. <https://doi.org/10.3390/su16083328>
 146. Xia M, Nematollahi B, Sanjayan J (2019) Printability, accuracy and strength of geopolymer made using powder-based 3D printing for construction applications. *Autom Constr* 101:179–189. <https://doi.org/10.1016/j.autcon.2019.01.013>
 147. Abdalla H, Fattah KP, Abdallah M, Tamimi AK (2021) Environmental footprint and economics of a full-scale 3d-printed house. *Sustainability*. <https://doi.org/10.3390/su132111978>
 148. Vasudevans S, Poornima V, Balachandran M (2020) Influence of admixtures on properties of concrete and optimization using response surface methodology. *Mater Today Proc* 24:650–661. <https://doi.org/10.1016/j.matpr.2020.04.319>
 149. Zhao Z et al (2023) A critical review on reducing the environmental impact of 3D printing concrete: material preparation, construction process and structure level. *Constr Build Mater*. <https://doi.org/10.1016/j.conbuildmat.2023.133887>
 150. Tinoco MP, de Mendonça ÉM, Fernandez LIC, Caldas LR, Reales OAM, Toledo Filho RD (2022) Life cycle assessment (LCA) and environmental sustainability of cementitious materials for 3D concrete printing: a systematic literature review. *J Build Eng* 52:104456. <https://doi.org/10.1016/j.jobe.2022.104456>
 151. Chen Y, Veer F, Çopuroğlu O (2017) A critical review of 3D concrete printing as a low CO₂ concrete approach. *Heron* 62(3):167–194

152. De Schutter G, Lesage K, Mechtcherine V, Nerella VN, Habert G, Agusti-Juan I (2018) Vision of 3D printing with concrete—technical, economic and environmental potentials. *Cem Concr Res* 112:25–36. <https://doi.org/10.1016/j.cemconres.2018.06.001>
153. Luhar S et al (2020) Sustainable and renewable bio-based natural fibres and its application for 3d printed concrete: a review. *Sustainability*. <https://doi.org/10.3390/su122410485>
154. Khan SA, Koç M, Al-Ghamdi SG (2021) Sustainability assessment, potentials and challenges of 3D printed concrete structures: a systematic review for built environmental applications. *J Clean Prod*. <https://doi.org/10.1016/j.jclepro.2021.127027>
155. Chen Y, He S, Gan Y, Çopuroğlu O, Veer F, Schlangen E (2022) A review of printing strategies, sustainable cementitious materials and characterization methods in the context of extrusion-based 3D concrete printing. *J Build Eng*. <https://doi.org/10.1016/j.jobbe.2021.103599>
156. Liu J, Nguyen-Van V, Panda B, Fox K, Du Plessis A, Tran P (2022) Additive manufacturing of sustainable construction materials and form-finding structures: a review on recent progresses. *3D Print Addit Manuf* 9(1):12–34. <https://doi.org/10.1089/3dp.2020.0331>
157. Nodehi M, Aguayo F, Nodehi SE, Gholampour A, Ozbakkaloglu T, Gencel O (2022) Durability properties of 3D printed concrete (3DPC). *Autom Constr* 142:104479. <https://doi.org/10.1016/j.autcon.2022.104479>
158. Samudrala M, Mujeeb S, Lanjewar BA, Chippagiri R, Kamath M, Ralegaonkar RV (2023) 3D-Printable concrete for energy-efficient buildings. 1–16
159. Ahmed GH (2022) A review of ‘3D concrete printing’: materials and process characterization, economic considerations and environmental sustainability. *J Build Eng* 66:105863. <https://doi.org/10.1016/j.jobbe.2023.105863>
160. Tu H, Wei Z, Bahrami A, Kahla NB, Ahmad A, Özkılıç YO (2023) Recent advancements and future trends in 3D concrete printing using waste materials. *Dev Built Environ*. <https://doi.org/10.1016/j.dibe.2023.100187>
161. Hamdan M, Anshari M, Ahmad N, Ali E (2023) Public policy’s role in achieving sustainable development goals, pp 1–370. <https://doi.org/10.4018/978-1-6684-8903-1>
162. Nguyen-Van V, Li S, Liu J, Nguyen K, Tran P (2023) Modelling of 3D concrete printing process: a perspective on material and structural simulations. *Addit Manuf*. <https://doi.org/10.1016/j.adma.2022.103333>
163. Ooms T, Vantghem G, Van Coile R, De Corte W (2021) A parametric modelling strategy for the numerical simulation of 3D concrete printing with complex geometries. *Addit Manuf*. <https://doi.org/10.1016/j.addma.2020.101743>
164. Vantghem G, De Corte W, Shakour E, Amir O (2020) 3D printing of a post-tensioned concrete girder designed by topology optimization. *Autom Constr* 112:103084. <https://doi.org/10.1016/j.autcon.2020.103084>
165. Li W, Lin X, Bao DW, Xie YM (2022) A review of formwork systems for modern concrete construction. *Structures* 38:52–63. <https://doi.org/10.1016/j.istruc.2022.01.089>
166. Mohan MK, Rahul AV, van Dam B, Zeidan T, De Schutter G, Van Tittelboom K (2022) Performance criteria, environmental impact and cost assessment for 3D printable concrete mixtures. *Resour Conserv Recycl* 181:106255. <https://doi.org/10.1016/j.resconrec.2022.106255>
167. Markin V, Krause M, Otto J, Schröfl C, Mechtcherine V (2021) 3D-printing with foam concrete: from material design and testing to application and sustainability. *J Build Eng*. <https://doi.org/10.1016/j.jobbe.2021.102870>
168. Besklubova S, Tan BQ, Zhong RY, Spicsek N (2022) Logistic cost analysis for 3D printing construction projects using a multi-stage network-based approach. *Autom Constr* 151:104863. <https://doi.org/10.1016/j.autcon.2023.104863>
169. Munir Q, Kärki T (2021) Cost analysis of various factors for geopolymer 3d printing of construction products in factories and on construction sites. *Recycling*. <https://doi.org/10.3390/recycling6030060>
170. Allouzi R, Al Azhari W, Allouzi R (2020) Conventional Construction and 3D Printing: a Comparison Study on Material Cost in Jordan. *J Eng* 2020:1424682. <https://doi.org/10.1155/2020/1424682>
171. Weng Y et al (2020) Comparative economic, environmental and productivity assessment of a concrete bathroom unit fabricated through 3D printing and a precast approach. *J Clean Prod*. <https://doi.org/10.1016/j.jclepro.2020.121245>
172. Aghimien D, Aigbavboa C, Aghimien L, Thwala WD, Ndlovu L (2020) Making a case for 3D printing for housing delivery in South Africa. *Int J Hous Mark Anal* 13(4):565–581. <https://doi.org/10.1108/IJHMA-11-2019-0111>
173. Abdalla H, Fattah KP, Abdallah M, Tamimi AK (2021) Environmental footprint and economics of a full-scale 3d-printed house. *Sustainability (Switzerland)* 13(21):1–19. <https://doi.org/10.3390/su132111978>
174. Tobi ALM, Omar SA, Yehia Z, Al-Ojaili S, Hashim A, Orhan O (2018) Cost viability of 3D printed house in UK. *IOP Conf Ser Mater Sci Eng* 319(1):012061. <https://doi.org/10.1088/1757-899X/319/1/012061>
175. Batikhia M, Jotangia R, Baaj MY, Mousleh I (2021) 3D concrete printing for sustainable and economical construction: a comparative study. *Autom Constr* 134:104087. <https://doi.org/10.1016/j.autcon.2021.104087>
176. Weng Y et al (2020) Comparative economic, environmental and productivity assessment of a concrete bathroom unit fabricated through 3D printing and a precast approach. *J Clean Prod* 261:121245. <https://doi.org/10.1016/j.jclepro.2020.121245>
177. Besklubova S, Tan BQ, Zhong RY, Spicsek N (2023) Logistic cost analysis for 3D printing construction projects using a multi-stage network-based approach. *Autom Constr* 151:104863. <https://doi.org/10.1016/j.autcon.2023.104863>
178. Hossain MA, Zhumabekova A, Paul SC, Kim JR (2020) A review of 3D printing in construction and its impact on the labor market. *Sustainability* 12(20):1–21. <https://doi.org/10.3390/su12208492>
179. Wu P, Zhao X, Baller JH, Wang X (2018) Developing a conceptual framework to improve the implementation of 3D printing technology in the construction industry. *Archit Sci Rev* 61(3):133–142. <https://doi.org/10.1080/00038628.2018.1450727>
180. Lowke D, Dini E, Perrot A, Weger D, Gehlen C, Dillenburger B (2017) Particle-bed 3D printing in concrete construction – possibilities and challenges. *Cem Concr Res* 112:50–65. <https://doi.org/10.1016/j.cemconres.2018.05.018>
181. Kloft H et al (2020) Influence of process parameters on the inter-layer bond strength of concrete elements additive manufactured by Shotcrete 3D printing (SC3DP). *Cem Concr Res* 134:106078. <https://doi.org/10.1016/j.cemconres.2020.106078>
182. Spicsek N, Besklubova S, Skibniewski MJ (2024) Impact of 3D printing technology on meeting construction 5.0 criteria. In: *Proceedings of the creative construction conference*
183. Tahmasebinia F et al (2020) Criteria development for sustainable construction manufacturing in construction industry 4.0: theoretical and laboratory investigations. *Constr Innov* 20(3):379–400. <https://doi.org/10.1108/CI-10-2019-0103>
184. Adaloudis M, Bonnin Roca J (2021) Sustainability tradeoffs in the adoption of 3D concrete printing in the construction industry. *J Clean Prod* 307:127201. <https://doi.org/10.1016/j.jclepro.2021.127201>
185. Ayyagari R, Chen Q, de García Soto B (2023) Quantifying the impact of concrete 3D printing on the construction supply chain.

- Autom Constr 155:105032. <https://doi.org/10.1016/j.autcon.2023.105032>
186. Besklubova S, Spicak N, Zhong RY, Kravchenko E, Skibniewski MJ (2024) A framework for the acceptance of 3D printing technology in construction. *Int J Appl Sci Eng* 21(4):1–25. [https://doi.org/10.6703/IJASE.202409_21\(4\).001](https://doi.org/10.6703/IJASE.202409_21(4).001)
187. Al-Raqeb H, Ghaffar SH (2025) 3D Concrete printing in Kuwait: stakeholder insights for sustainable waste management solutions. *Sustainability (Switzerland)* 17(1):200. <https://doi.org/10.3390/su17010200>
188. El-Sayegh S, Romdhane L, Manjikian S (2020) A critical review of 3D printing in construction: benefits, challenges, and risks. *Arch Civ Mech Eng* 20(2):1–25. <https://doi.org/10.1007/s43452-020-00038-w>
189. Handfield RB, Aitken J, Turner N, Boehme T, Bozarth C (2022) Assessing adoption factors for additive manufacturing: insights from case studies. *Logistics*. <https://doi.org/10.3390/logistics6020036>
190. Spicak N, Besklubova S, Skibniewski MJ (2023) Benchmarking critical success factors in construction projects utilizing 3D printing technology. *Int J Appl Sci Eng*. [https://doi.org/10.6703/IJASE.202312_20\(4\).001](https://doi.org/10.6703/IJASE.202312_20(4).001)
191. Shivendra BT et al (2024) A Path towards SDGs: Investigation of the Challenges in Adopting 3D Concrete Printing in India. *Infrastructures (Basel)* 9(9):1–19. <https://doi.org/10.3390/infrastructure9090166>
192. Porulselvi K et al (2023) Comprehensive review on 3D concrete printing. *Mater Sci Technol*. <https://doi.org/10.10543/f0299.2023.41799>
193. Mogaji IJ, Mewomo MC, Toyin JO (2023) Key barriers to the adoption of 3D printing innovation in construction: a review of empirical studies. In: *International conference on construction in the 21st century*, vol. 2023-May, no. September, 2023
194. Ambily PS, Kaliyavaradhan SK, Rajendran N (2024) Top challenges to widespread 3D concrete printing (3DCP) adoption—a review. *Eur J Environ Civ Eng* 28(2):300–328. <https://doi.org/10.1080/19648189.2023.2213294>
195. Ma J, Samarasinghe DAS, Rotimi JOB, Zuo K (2024) Supply chain landscape of 3D printed buildings: a stakeholder decision support framework. *Buildings*. <https://doi.org/10.3390/buildings14061811>
196. Adamtsevich L, Pustovgar A, Adamtsevich A (2024) Assessing the prospects and risks of delivering sustainable urban development through 3D concrete printing implementation. *Sustainability*. <https://doi.org/10.3390/su16219305>

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