Progress in Additive Manufacturing
https://doi.org/10.1007/s40964-025-01314-y

REVIEW

3D printing in construction: sustainable technology for building industry

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Received: 8 June 2025 / Accepted: 16 August 2025

Abstract
The adoption of 3D printing technology in the construction sector represents a transformative approach to addressing sustainability challenges, resource inefficiencies, and environmental impacts. This study explores the multifaceted potential of 3D printing as a sustainable alternative to conventional construction practices, focusing on material efficiency, architectural flexibility, labor dynamics, and environmental sustainability. Applying the PRISMA framework, the research synthesizes interdisciplinary insights from 75 high-quality journal articles across 2013–2024, emphasizing innovations in material science, digital integration, and circular economy principles. Key findings highlight that 3D printing reduces material waste by up to 60%, enhances construction speed by 50%, and enables the utilization of eco-friendly materials such as geopolymer concrete and biodegradable polymers. Despite these advancements, barriers such as scalability, high initial costs, and regulatory inconsistencies persist. This study concludes by providing lifecycle resources flow model and actionable recommendations for policymakers, industry practitioners, and researchers to foster the integration of 3D printing in construction, including standardization efforts, lifecycle assessments, and the adoption of renewable energy in printing processes. This research positions 3D printing as a cornerstone of the sustainable construction paradigm, contributing to a resilient and eco-conscious built environment.

Keywords 3D printing · Sustainable construction · 3D printed construction · Environmental impact · Economic impact · Material efficiency · 3DCP

1 Introduction

The emergence of 3D printing marks a transformative epoch in technological advancement, reshaping perceptions of traditional design and manufacturing processes [72]. Originally devised for prototyping, this technology has now permeated various domains, including the construction sector, where it promises to revolutionize outdated methods plagued by inefficiencies, high costs, and environmental impacts [70, 91]. The construction industry, often slow to adopt groundbreaking innovations, confronts mounting challenges such as resource depletion, significant carbon emissions, and administrative inefficiencies. These challenges are exacerbated by rapid urbanization, population growth, and increasing demand for sustainable infrastructure [13].

The pressing need for sustainable construction methods has catalyzed research into innovative solutions. Traditional building practices, characterized by excessive resource consumption, high energy usage, and substantial waste generation, are no longer viable. For instance, the construction

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Published online: 23 August 2025

industry accounts for 39% of global CO_2 emissions and consumes over 50% of raw materials annually, underscoring the urgency for transformative strategies [37]. This study highlights the limitations of conventional materials, such as concrete, and advocates for the integration of 3D printing as a sustainable alternative capable of meeting contemporary design and environmental demands.

This research endeavors to position 3D printing as a cornerstone of sustainable construction by exploring its multifaceted benefits. By synthesizing evidence from literature, it aims to establish how this technology can harmonize sustainability with 3D printed construction techniques. The potential of 3D printing to reduce material waste, enhance structural efficiency, and enable architectural creativity presents a compelling case for its adoption in addressing global challenges such as climate change, urban housing shortages, and resilient infrastructure development [22, 52].

2 Background

2.1 The construction waste generation

The construction industry is a significant contributor to global environmental degradation, accounting for approximately 30–40% of global resource consumption and waste generation [8]. To address this issue, the European Union has set ambitious targets, aiming to reduce raw material consumption by 30% and construction waste by 40% by 2030 [25]. Despite these efforts, the sector remains plagued by inefficiencies, including the depletion of non-renewable resources and substantial CO_2 emissions. Traditional construction methods are characterized by high energy consumption and excessive waste output, further amplifying their environmental and economic toll [11].

Research highlights that conventional concrete, a staple of the construction industry, often fails to meet modern design and sustainability demands due to its energy-intensive production and inadequate strength properties [37]. Addressing these challenges requires a paradigm shift toward innovative materials and methods that prioritize environmental sustainability. For instance, studies indicate that concrete and reinforced concrete contribute the largest share of construction waste globally, comprising toxic components that have a disproportionately harmful impact on ecosystems [26].

Figure 1 presents a comparative overview of waste generation percentages across various countries, emphasizing the global urgency of adopting sustainable practices. These data underscore the critical need for systemic reforms in construction practices to mitigate environmental impacts and align with international sustainability goals [84].

2.2 3D printing

The origins of 3D printing in the construction industry date back to its initial use for rapid prototyping in the 1980s [70]. Since then, the technology has undergone remarkable evolution, expanding its applications to become a disruptive force across numerous sectors. In the construction domain, 3D printing promises to

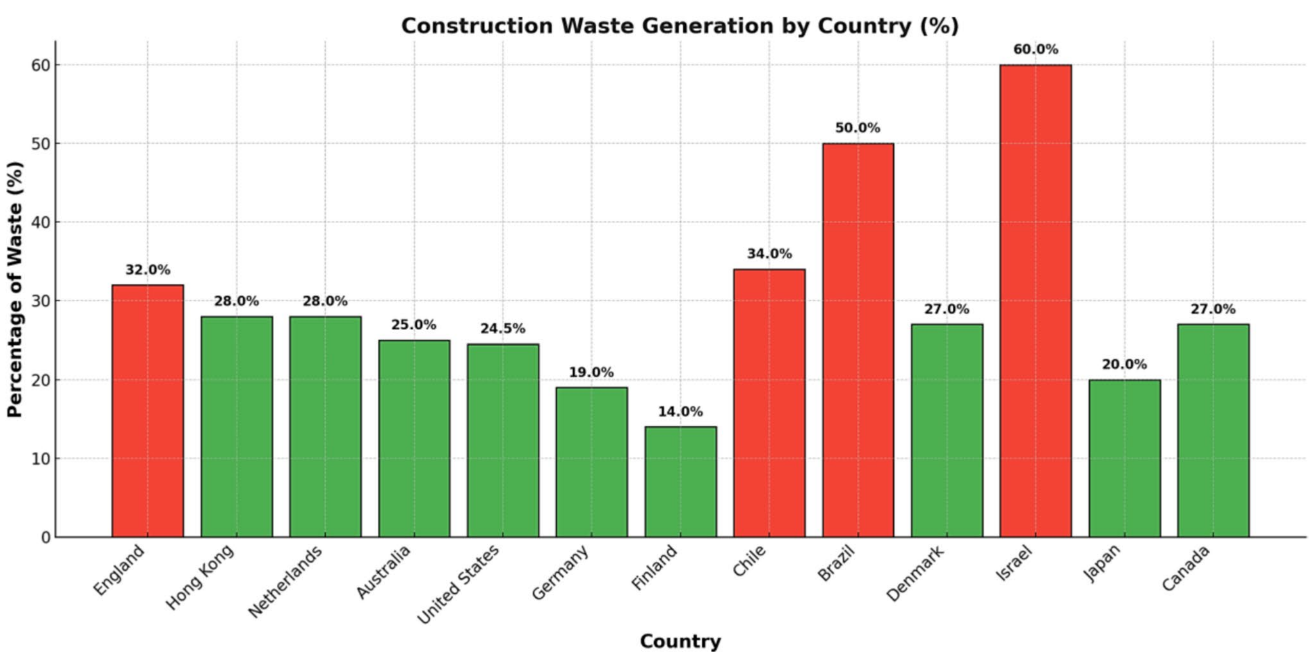

Fig. 1 Percentage of construction waste generation by countries. Adapted from [43]

revolutionize traditional methods by addressing inefficiencies, reducing material waste, and enhancing precision [52]. The transition from prototyping to large-scale applications indicates its potential to redefine modern construction practices.

3D printing technologies encompass diverse methods, each tailored to specific applications. These include stereolithography (SLA), fused deposition modeling (FDM), selective laser sintering (SLS), and digital light processing (DLP), each with distinct advantages and limitations [15, 85]. For example, SLA offers exceptional precision, making it ideal for detailed architectural models, while FDM is widely used for cost-effective and scalable construction components. The versatility of these methods enables the creation of intricate designs and custom structures [67] that would be challenging or impossible with conventional construction approaches [18].

The integration of advanced materials has further amplified the potential of 3D printing. Research highlights innovations such as biodegradable polymers, reinforced composites, and geopolymer-based concrete, which not only improve structural performance but also contribute to sustainability goals [4]. For instance, 3D printing with recycled materials significantly reduces environmental impact, aligning with circular economy principles [10].

Despite its transformative potential, 3D printing in construction faces critical challenges. Issues such as scalability, speed, material compatibility, and post-processing requirements remain significant barriers to widespread adoption [15, 36]. Addressing these challenges necessitates multidisciplinary collaboration among engineers, architects, and material scientists to optimize processes and develop standardized frameworks. The adoption of 3D concrete printing, in particular, exemplifies the convergence of sustainability and innovation. Studies show that this technology enables rapid, cost-effective construction while reducing material waste and labor requirements [35]. Moreover, its capacity to produce customized, structurally efficient designs underscores its role in advancing resilient and sustainable infrastructure. As the construction industry seeks to balance growth with environmental stewardship, 3D printing stands out as a pivotal technology. By integrating cutting-edge materials, efficient processes, and innovative designs, it offers a pathway to a more sustainable, efficient, and adaptable construction paradigm [70].

2.3 Sustainable construction practices

The principles of sustainable construction revolve around reducing environmental impacts, maximizing resource efficiency, and prioritizing societal well-being. According to Pitt et al. [59], sustainable construction practices encompass energy efficiency, waste minimization, renewable resource utilization, and the integration of green technologies into design and building processes. These efforts are further institutionalized through globally recognized certifications such as BREEAM (Building Research Establishment Environmental Assessment Method) and LEED (Leadership in Energy and Environmental Design), which advocate for environmentally responsible and resource-efficient practices [28].

Lifecycle assessments (LCA) have emerged as a cornerstone for evaluating the environmental impacts of construction materials and processes, offering insights from raw material extraction to disposal [21]. Research underscores the importance of green building materials and cutting-edge technologies, such as photovoltaic systems and advanced insulation, in achieving energy-efficient structures [23]. Circular economy principles, which emphasize reduction, reuse, and recycling, are increasingly gaining traction within the sector as a means of addressing material inefficiency and waste [60].

Despite these advances, significant barriers hinder the widespread adoption of sustainable practices. Financial constraints, resistance to change, and a lack of awareness remain critical challenges, as highlighted by Robichaud and Anantatmula [65]. Furthermore, the construction industry's fragmented structure exacerbates difficulties in achieving cohesive sustainability strategies. Addressing these barriers necessitates targeted policy interventions, financial incentives, and educational programs aimed at fostering a culture of sustainability [9].

Emerging trends highlight the integration of digital technologies, such as building information modeling (BIM) and Internet of Things (IoT), in facilitating sustainable construction. These technologies enable precise resource management, enhanced energy monitoring, and improved decision-making throughout the project lifecycle [28]. Moreover, advancements in material science, including the development of carbon-negative concrete and bio-based composites, hold promises for reducing construction carbon footprints [7, 75]. Looking ahead, the convergence of digital innovations and sustainable practices offers a roadmap for transforming the construction industry.

2.4 Rationale for exploring 3D printing as a solution to sustainable construction

Exploring 3D printing as a solution for sustainable construction is underpinned by the critical need to address the limitations of traditional construction methods. These include inefficiencies in material use, high energy consumption, and significant waste generation. The adoption of 3D printing offers several transformative advantages supported by extensive literature:

- **Material efficiency:** The precision of 3D printing allows for targeted deposition of materials, significantly reducing waste compared to conventional methods [33]. By minimizing excessive material usage, this technology directly aligns with global sustainability goals to reduce resource depletion [20].
- **Customization and design optimization:** The ability to create complex and bespoke designs, unattainable through traditional methods, highlights the architectural versatility of 3D printing [32]. Such optimization enhances structural efficiency, thereby decreasing reliance on unnecessary materials and promoting sustainable practices [52].
- **Energy efficiency:** Layer-by-layer additive manufacturing techniques used in 3D printing consume less energy compared to traditional construction processes that rely on extensive formwork and energy-intensive shaping methods [6]. This contributes to a lower carbon footprint and improved energy conservation.
- **Waste reduction:** Conventional construction processes often result in substantial waste during manufacturing, transport, and on-site assembly. In contrast, the precision and on-demand production of 3D printing align with circular economy principles by reducing waste generation and landfill contributions [31].
- **Construction speed and on-site resource reduction:** 3D printing significantly accelerates construction timelines, reducing on-site labor and associated resource consumption [57]. 3D printing should not be seen just as a method to produce sections of buildings or structures, yet, it has an important role in providing flexible support to construction. For example, 3D printing provides a rapid and bespoke way of creating jigs and fixtures, aiding the fabrication of scaffolding. This enhanced efficiency not only shortens project durations but also minimizes environmental disruption during the construction phase.
- **Adaptability to sustainable materials:** The compatibility of 3D printing with recycled and alternative materials, such as geopolymer concrete and biodegradable polymers, supports environmental sustainability [73]. Such innovations reinforce the potential of 3D printing to integrate sustainable materials into mainstream construction.

These attributes position 3D printing as a pivotal technology for transforming the construction industry. By addressing challenges in resource efficiency, waste reduction, and environmental impact, 3D printing not only fulfills contemporary sustainability demands but also sets the foundation for innovative practices in green construction.

3 Research aim and objectives

This study seeks to develop a comprehensive understanding of how 3D printing technology can revolutionize construction practices with a primary focus on sustainability. The objectives are firmly anchored in addressing the environmental, economic, and social challenges of this approach of modern construction.

1. **Environmental impact:** This research examines how 3D printing aligns with global sustainability goals by reducing resource consumption, material waste, energy usage, and overall carbon footprints. This study explores specific mechanisms through which 3D printing technology minimizes ecological harm, including precision material usage and adaptability to sustainable building materials [33].
2. **Social implications:** This study delves into the social dimensions of 3D printing adoption, including its impact on labor dynamics, skill requirements, and stakeholder involvement. By assessing its potential to alter workforce roles and foster community engagement, this research aims to shed light on the broader societal implications of this transformative technology [57].
3. **Integration of sustainable practices:** A central focus of this study is to identify pathways for embedding 3D printing into sustainable construction practices. This includes leveraging circular economy principles, accelerating project timelines, and fostering innovative, eco-friendly design solutions [20].

This research addresses critical knowledge gaps at the intersection of 3D printing and sustainable construction. By combining insights from interdisciplinary fields, it establishes a roadmap for integrating advanced manufacturing technologies into environmentally and socially responsible construction paradigms. The findings aim to catalyze industry-wide transformations, contributing to resilient, efficient, and sustainable built environments globally.

4 Review methodology

4.1 Originality

This study introduces a novel and comprehensive exploration of the intersection between 3D printing technology and sustainable construction practices. By focusing on the applications, methods, and materials associated with 3D printing, the research advances a unique perspective that blends technological innovation with ecological imperatives [15, 20]. What sets this investigation apart is its interdisciplinary approach, which integrates insights from material science, environmental studies, and construction engineering to present a holistic understanding of the subject.

In addition, this study adopts the PRISMA framework to ensure methodological rigor and precision [53]. By systematically reviewing and synthesizing existing literature, the research identifies critical gaps and proposes actionable pathways for integrating 3D printing into sustainable construction paradigms. The originality lies not only in the methodological approach but also in the emphasis on long-term sustainability, societal impacts, and practical implementation strategies.

Furthermore, this study highlights unexplored opportunities in the use of advanced materials, such as geopolymer concrete and biodegradable composites, for 3D printing applications in construction. By addressing both technical and environmental challenges, it provides a balanced and forward-thinking perspective that contributes significantly to the academic discourse and practical advancements in the field. The findings are expected to catalyze innovation and inspire future research on the transformative potential of 3D printing for creating resilient and eco-friendly built environments.

4.2 Creating the keywords and query of references

To support a comprehensive and systematic exploration of the intersection between 3D printing and sustainable construction practices, a robust list of targeted keywords has been curated. These keywords include, but are not limited to, "3D printing," "Additive manufacturing," "Sustainable construction," "Eco-friendly building," "Construction technology," "Building components," "Environmental impact," "Urban growth," "Construction sector," "Resource efficiency," "Waste reduction," "Construction operations," and "3D concrete printing." These terms were strategically selected to encompass the technological, environmental, and operational dimensions of the topic (Fig. 2).

The process of creating these keywords was guided by an iterative review of existing literature, identifying recurring themes and critical terminologies. The goal was to ensure inclusivity and relevance across academic, industrial, and environmental contexts. By leveraging these keywords, this research aims to maximize the retrieval of high-quality, domain-specific literature, facilitating a nuanced understanding of the subject matter.

4.3 PRISMA model

To ensure a systematic, transparent, and comprehensive review of the literature, the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework has been adopted as the methodological foundation for this study [48]. This approach enables structured identification, screening, and inclusion of relevant research, providing a robust basis for evaluating 3D printing's role in sustainable construction.

4.4 Identification

The identification phase involved a systematic search across prominent academic databases, including Google Scholar, IEEE Xplore, and Scopus, using carefully curated keywords such as "3D printing," "sustainable construction," "additive manufacturing," and "waste reduction." This process ensured a broad yet focused selection of studies relevant to the intersection of 3D printing and sustainability. The initial search yielded over 200 documents spanning journals, conference proceedings, and industry reports.

4.5 Screening and eligibility

The screening phase employed rigorous filters to refine the dataset by examining the titles and abstracts of identified publications. This stage eliminated irrelevant and low-quality studies, narrowing the pool to 100 high-potential documents. Eligibility assessment followed, involving a detailed review of full texts to ensure alignment with the study's objectives. This phase prioritized papers that addressed key themes such as environmental impact, energy efficiency, and material innovation in 3D printing for construction. Studies failing to meet these criteria were excluded, ensuring a robust and focused dataset.

4.6 Inclusion

The final inclusion stage selected 75 high-quality studies from reputable journals, forming the foundation for comprehensive synthesis. These studies collectively provide a nuanced understanding of 3D printing's advantages, including its potential to enhance productivity, reduce waste, and

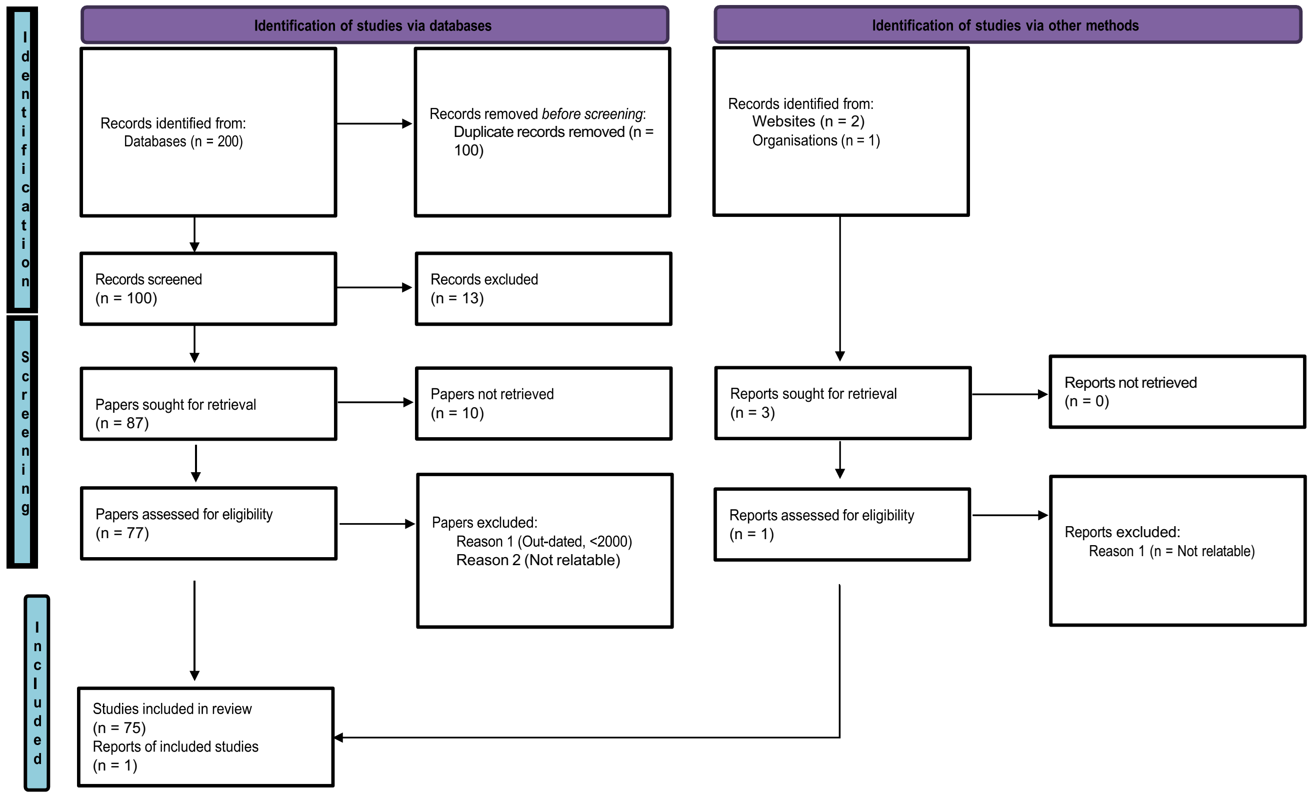

Fig. 2 PRISMA framework for the literature review

promote sustainability in construction. The selection process indicates the methodological rigor and relevance of the included literature, ensuring that the study's conclusions are both credible and impactful. The PRISMA model's structured methodology enhances the reliability and validity of this research, offering a transparent roadmap for replicability and further inquiry into the transformative potential of 3D printing in sustainable construction (Fig. 2).

4.7 Exclusion

During the systematic review process governed by the PRISMA framework, a number of studies were excluded to ensure the relevance, quality, and methodological alignment of the final dataset. The following exclusion criteria were applied:

- Outdated publications: Studies published prior to 2013 were excluded, as they do not reflect the current state of the art in 3D printing technologies and sustainable construction practices.
- Irrelevant domains: Articles not directly related to 3D printing applications in the built environment—such as studies focused on biomedical or aerospace applications—were excluded despite overlapping keywords.
- Low methodological quality: Gray literature, non-peer-reviewed articles, and studies lacking sufficient methodological transparency or empirical data were removed to maintain academic robustness.
- Language and accessibility: Publications not written in English or those inaccessible through university subscriptions or open access were excluded due to limitations in interpretability and replicability.
- Redundancy and duplicates: Multiple entries of the same study across databases were screened and removed to avoid duplication bias.

These exclusions were necessary to refine the review scope and ensure that the final sample of 75 articles and one report represents a high-quality, thematically focused, and current synthesis of research at the intersection of 3D printing and sustainable construction. By maintaining strict inclusion parameters, this study ensures methodological integrity while minimizing noise from tangential or outdated studies.

5 Descriptive analysis

A thorough investigation into the revolutionary potential of 3D printing technology within the construction sector begins with a detailed review of research on sustainable construction and 3D printing. This descriptive analysis seeks to identify trends, advancements, and emerging opportunities in leveraging 3D printing for sustainable practices.

The final collection of resources includes 75 journal articles and one report, categorized based on their publication years, as illustrated in Fig. 3. Research articles from 2013 to 2024 were prioritized, ensuring their relevance and timeliness in addressing contemporary challenges within the construction industry. Of the initial pool of over 200 journal articles reviewed, the selected pool represents the most impactful and relevant works, reflecting cutting-edge developments and practical applications of 3D printing technology.

The data reveal a significant rise in research activity from 2016 to 2019, with the highest number of selected publications occurring in 2019. This peak highlights a growing recognition of 3D printing's potential to transform the construction industry. While there was a decline in publications during 2020, the numbers rose again in subsequent years, reaching to peak of 15 journal articles in 2024, highlighting renewed interest and continued innovation in the field. This analysis underscores the importance of sustained research efforts in exploring 3D printing as a transformative tool for sustainable construction, emphasizing its capacity to address critical industry challenges such as material waste, energy consumption, and ecological impact.

6 Content analysis

Content analysis is an effective approach in analyzing and understanding textual material [40] related to the issue in the research on 3D printing in sustainable construction described above. The information used in this investigation comes from a variety of sources, including academic articles, research papers and reports, and textual materials that examine the consequences, challenges, and potential of 3D printing technology in sustainable construction.

6.1 Overview of 3D printing in construction

3D printing technology has emerged as a revolutionary force across industries, redefining production, design, and sustainability paradigms. Initially utilized for rapid prototyping in the 1980s, this technology has evolved into a transformative tool for the construction sector, offering unprecedented opportunities to address inefficiencies, reduce resource wastage, and enhance design flexibility [54]. The construction industry, traditionally resistant to technological shifts, is now embracing 3D printing as a solution to critical challenges such as excessive material consumption, high labor costs, and significant ecological impacts [35]. The increasing demand for sustainable urban development, coupled with the shrinking availability of construction resources, necessitates the integration of innovative technologies like 3D printing [56, 62]. This paradigm shift not only promises efficiency but also promotes environmentally responsible practices, aligning with global sustainability goals.

Recent advancements highlight the strategic use of gantry-type and robotic arm-type 3D printers in construction. Gantry systems, known for their stability and speed,

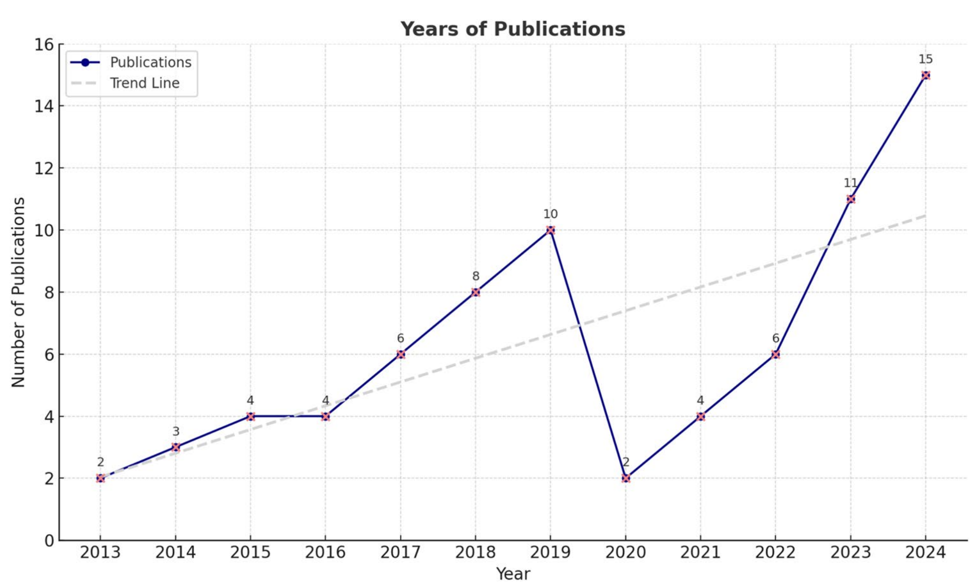

Fig. 3 Annual publication trend (2013–2024)

are ideal for large-scale projects, including residential and commercial structures [15]. In contrast, robotic arm systems offer unparalleled flexibility, enabling the creation of intricate architectural designs and customized components for smaller or medium-scale constructions [4]. Moreover, technical comparisons underscore the distinct advantages of these systems. Gantry systems excel in precision and structural integrity, while robotic arms prioritize adaptability and design complexity. Both systems significantly contribute to sustainable construction practices by minimizing material waste, optimizing resource use, and reducing construction timelines [18]. The integration of advanced materials, such as geopolymer concrete and biodegradable composites, further enhances the sustainability potential of 3D printing. These materials not only meet structural demands but also address environmental concerns by reducing embodied carbon and promoting recycling [20].

Figure 4 illustrates a detailed comparison between traditional construction methodologies and 3D printing in construction. Traditional methods involve extensive human labor at multiple stages, leading to significant time consumption and high costs. Additionally, these methods generate a considerable amount of construction waste due to inefficient material handling and on-site processes. Conversely, 3D printing technology leverages automation to fabricate structures directly from computer-aided design (3D-CAD) models, minimizing the need for human intervention and eliminating the requirement for conventional tooling, dies, formwork, and fittings [35]. The adoption of 3D printing in construction projects demonstrates remarkable efficiency in resource utilization, significant time savings, and reduced labor dependency. This advanced approach also contributes to a cleaner construction environment by drastically lowering material waste and environmental impacts. For example, 3D printing has been effectively employed in producing durable building components such as flow nozzles, showcasing its versatility and potential to transform traditional building processes [18].

Figure 5 illustrates a technical visualization of 3D printing technology applied in construction, focusing on two distinct nozzle designs and their influence on material extrusion and structure quality [18, 71]. The robotic arm actively performs the extrusion process, highlighting the intricate relationship between nozzle geometry and the resulting printed layers.

The key elements of the illustration include the following:

- Nozzle designs:

  (1) Down-flow round opening: This nozzle design (5.a) produces smooth, cylindrical layers, ideal for creating curved and seamless structures (5.c). The uniform material flow associated with round nozzles contributes to consistent layer deposition, enhancing the esthetic and structural quality of the printed object. Studies have shown that nozzle shape optimization can lead to improved flow control and reduced pressure drop, which are crucial for achieving high-quality prints [71].

  (2) Back-and-down-flow rectangular opening: This type has a rectangular design with dual-directional flow (backward and downward) (5.b). Rectangular nozzles are designed to extrude sharp-edged, compact layers, making them suitable for linear and angular forms (5.d). The specific flow dynamics of rectangular nozzles can enhance the mechanical properties of the printed material, resulting in structures with higher strength and stability. Research on extrusion nozzle shaping for engineered cementitious materials suggests that nozzle geometry can significantly impact the quality and performance of 3D-printed concrete structures. This design is advantageous for structures demanding high compaction and strength in linear or angular forms [41].

- Material extrusion: The extrusion process captures the dynamic interaction between the nozzle design and material deposition. The smooth cylindrical and compact rectangular layers showcase the adaptability of 3D printing to different construction needs.

The illustration (Fig. 5) reflects the precision and control required for scalable 3D printing in construction. It highlights the potential of additive manufacturing for efficient material usage, reduced waste, and customized structural forms. This technical visualization presents the operational principles of nozzle designs in construction-scale 3D printing, focusing on the integration of robotics and material science for optimized outcomes.

6.2 Gantry-type 3D printing in construction

Gantry-type 3D printing is a transformative technology that employs a stationary frame to direct the print head along programmed axes, enabling precise and large-scale construction applications. This technology is particularly suited for high-volume projects, such as housing developments, commercial buildings, and infrastructure, including bridges and tunnels [30]. The system's movable gantry frame, which guides the print head across designated axes, offers enhanced structural integrity and speed of construction, making it an ideal choice for large-scale projects requiring uniformity and durability.

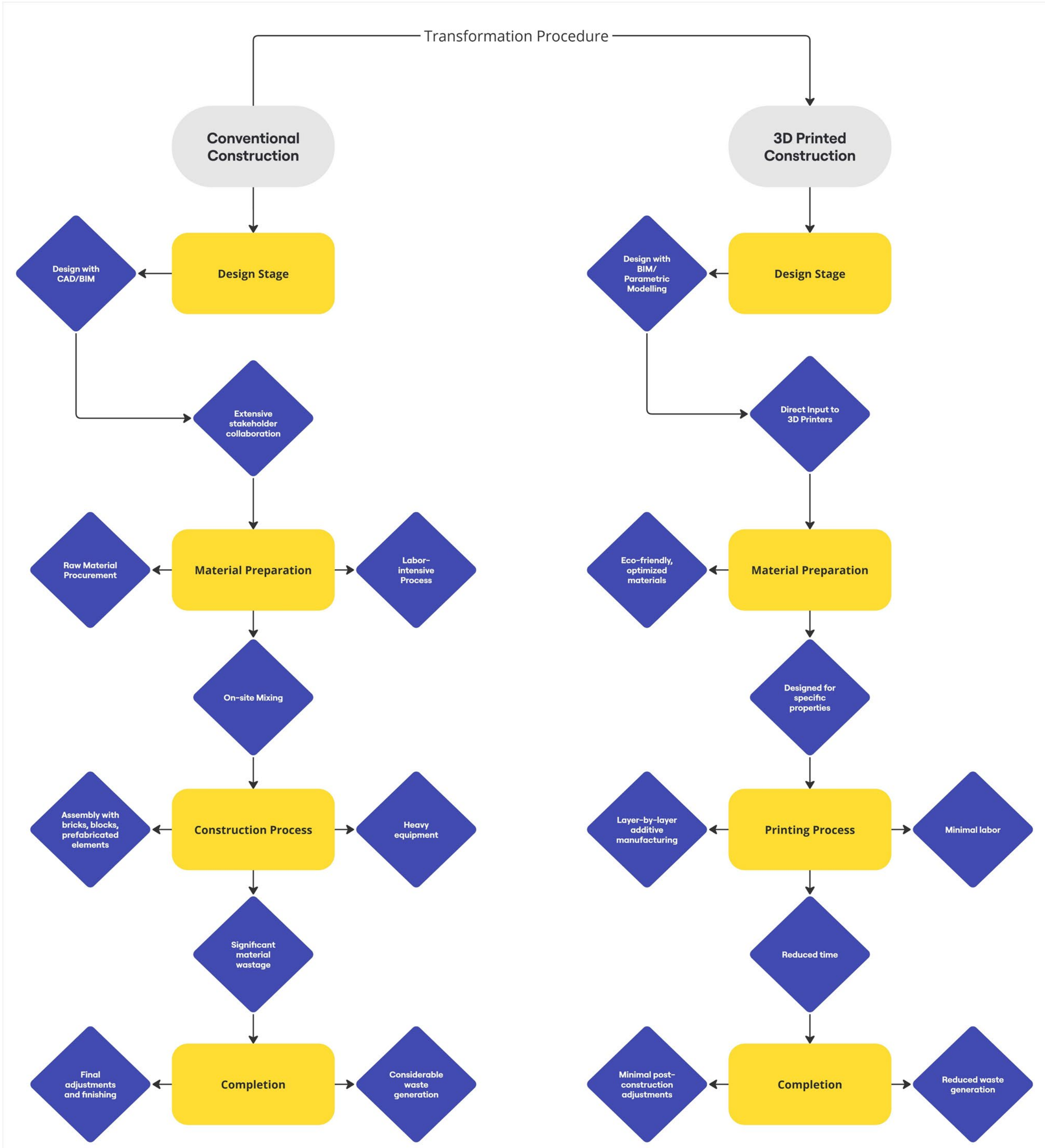

Fig. 4 Conventional construction versus 3D printing construction procedure [18, 35]

A study by Bos et al. [15] demonstrated the efficacy of gantry-type 3D printing in constructing residential buildings, showcasing its ability to significantly reduce construction times while maintaining structural precision. The system's capacity to layer materials with pinpoint accuracy minimizes waste and optimizes resource usage, aligning with sustainable construction practices [18]. Additionally, the adaptability of this technology to integrate advanced materials, such as geopolymer concrete and recycled aggregates, further enhances its environmental benefits [20]. Moreover, the gantry system's reliance on pre-programmed digital models ensures consistent and repeatable outcomes,

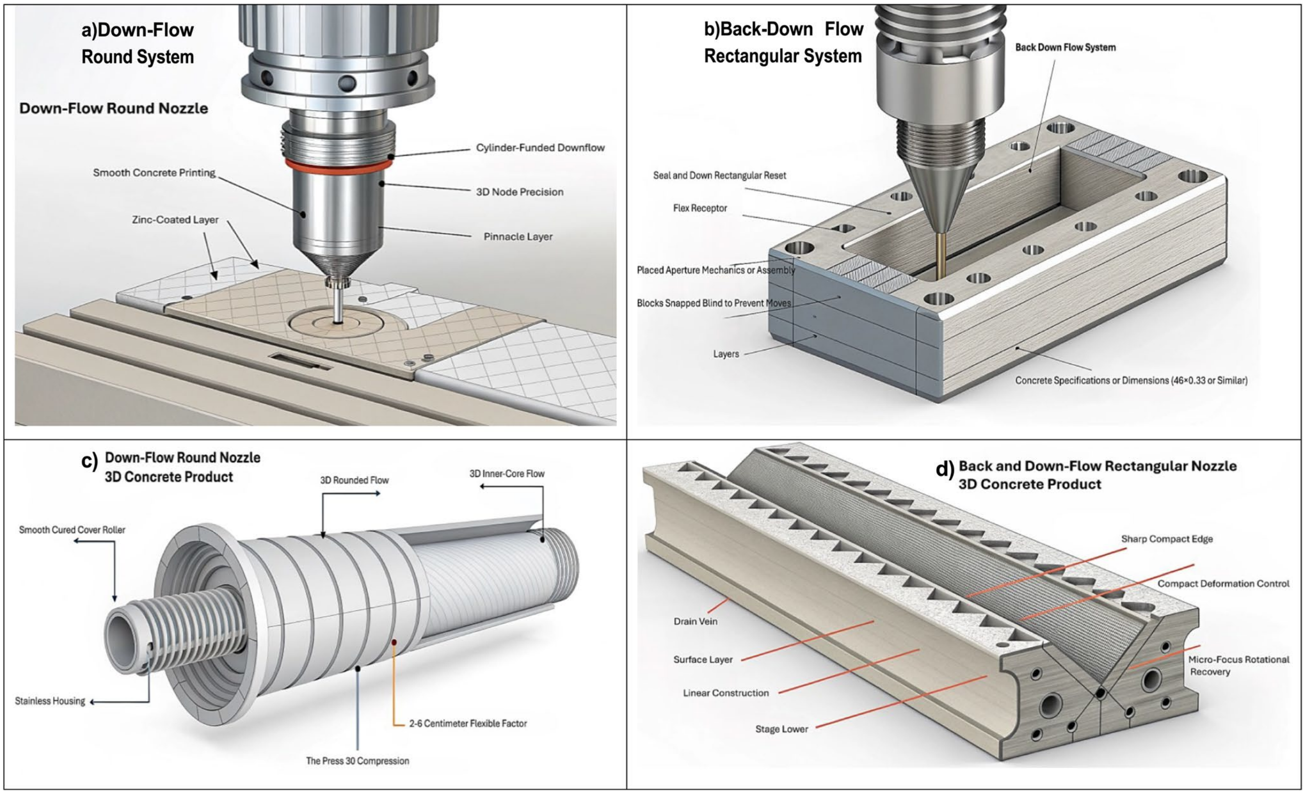

Fig. 5 **a** Down-flow round opening nozzle, **b** back-and-down-flow rectangular opening nozzle, **c** down-flow round nozzle concrete product, **d** back-and-down-flow rectangular nozzle concrete product, in 3D printing. Adapted from [18, 41, 71]

reducing human error and labor dependency [35]. This automation not only accelerates construction processes but also facilitates the creation of complex geometries that were previously unachievable with traditional methods.

In summary, gantry-type 3D printing stands out as a robust and efficient solution for modern construction challenges. Its ability to combine speed, precision, and sustainability makes it a cornerstone technology for advancing eco-friendly and high-performance building practices.

6.3 Robotic arm-type 3D printing in construction

The printing head of robotic arm-type 3D printers moves dynamically in multiple directions, providing exceptional adaptability and flexibility. This capability enables their application across a wide range of building sizes, from small to medium structures, and supports the creation of unique designs or complex architectural details [4]. Robotic arm-type 3D printing has gained significant traction as a versatile and innovative solution in modern construction. According to Wu et al. [91], robotic arms surpass gantry systems in flexibility of movement and orientation, making them particularly effective for projects that involve intricate architectural structures and custom designs.

6.3.1 Technical comparison

When evaluating the technical features of 3D printing systems, notable distinctions emerge between gantry and robotic arm technologies. Gantry systems, characterized by their larger build volumes and faster print speeds, excel in large-scale projects where speed and stability are paramount. These systems achieve exceptional accuracy due to the inherent stability of their framework, making them ideal for repetitive and high-precision tasks [15]. In contrast, robotic arm systems are distinguished by their flexibility in movement and orientation, enabling the production of diverse and intricate designs with outstanding precision [77]. This adaptability is particularly beneficial for projects with unique or non-standard requirements.

The choice between these technologies largely depends on specific project demands. Robotic arms offer superior adaptability and the ability to handle complex geometries, whereas gantry systems are best suited for applications that prioritize speed and uniformity. Both systems contribute to the advancement of 3D printing in construction, each addressing different facets of project requirements and technological capabilities. In addition to gantry and robotic arm systems, Delta-type 3D printing has emerged as a promising alternative for specific construction use cases. Based on parallel kinematic mechanisms, Delta printers feature a compact design and efficient movement profile [24], making them well suited for vertical, columnar, or repetitive prefabricated elements. They are particularly advantageous in confined on-site conditions or off-site micro-fabrication, where space constraints and energy efficiency are critical [88]. While less flexible in handling complex overhangs or multi-directional extrusion, Delta systems offer cost-effective and accurate printing within a defined operational envelope [12].

Table 1 presents a comparative analysis of gantry-type, robotic arm-type, and delta-type 3D printing in construction based on a wide range of parameters including system, speed, precision, applications, environmental impact, footprint, structural complexity, and cost efficiency. Figure 6 summarizes the specific differences between the gantry and robotic arm types, as the two most popular types of 3-D printing technology in construction. The infrastructure requirements of Gantry-type 3D printing suit a modular construction process. Modules can be 3D printed off-site and transported to the site and assembled. The printed modules can be manufactured fast and accurately. The robotic arm-type 3D printing can be applied on-site or off-site, depending on the size of the printed part and whether the robotic arm can be adequately secured on-site.

6.4 Material-focused 3D printing methods

The concept of "material efficiency" is central to sustainable construction and refers to the optimization of construction materials to minimize waste while achieving the desired outcomes. Traditional construction practices often involve overordering materials, leading to excessive waste and higher costs [10]. In contrast, 3D printing technology revolutionizes material usage by allowing precise, controlled deposition, significantly reducing waste, and enabling environmentally conscious practices [61]. 3D printing's role in promoting material efficiency can be understood through various advanced techniques (Table 2):

(1) **Extrusion-based concrete printing:**

- **Cementitious material printing:** This method employs nozzles to extrude cement and aggregates layer by layer, ensuring precision in material placement and reducing waste. By targeting only necessary areas, it minimizes material consumption and aligns with sustainability goals, such as reducing embodied carbon and waste generation (Fig. 7a, b) [29].
- **Shotcrete printing:** Concrete or mortar is projected pneumatically at high velocity onto surfaces. This technique enhances material efficiency by reducing rebound and wastage, further lowering the environmental footprint of construction activities [45].

(2) **Powder-based printing:**

- **Selective binding:** This technique applies binders selectively to powder layers, such as gypsum or sand, to form solid structures. This method reduces costs and waste by precisely targeting areas requiring binding [29].

Table 1 Comparative analysis of gantry-type, robotic arm-type, and delta-type 3D printing in construction [4, 12, 18, 24, 77]

Parameter	Gantry-type 3D printing	Robotic arm-type 3D printing	Delta-type 3D printing
System	Stationary frame moves print head along Cartesian axes	Robotic arm manipulates print head in multiple orientations and planes	Three vertical actuators move the print head using parallel kinematics
Speed	High print speed for large-scale, repetitive geometries	Variable speed depending on complexity and arm articulation	Moderate to high speed, optimized for continuous vertical builds
Precision	High positional accuracy due to mechanical stability	Influenced by arm reach and articulation resolution	High precision in central zones, slightly less accurate at outer edges
Applications	Housing modules, walls, infrastructure	Custom facades, complex geometry, artistic and organic forms	Vertical elements, columns, small-to-medium prefabricated components
Environmental impact	Reduces waste via uniform construction; suitable for prefabrication	Flexible, efficient use of materials in intricate geometries	Compact footprint, lower material use, suitable for low-carbon on-site production
Footprint	Large, requires fixed gantry structure	Flexible, can be adapted to different sites or off-site prefabrication	Small-to-medium footprint; suitable for constrained spaces
Structural complexity	Best suited for rectangular, regular geometries	Ideal for irregular, complex forms and multiaxial paths	Suitable for axisymmetric or columnar components
Cost efficiency	High throughput but requires high capital investment and setup	Moderate investment, high design flexibility	Lower cost, energy-efficient system, suitable for small to mid-scale production

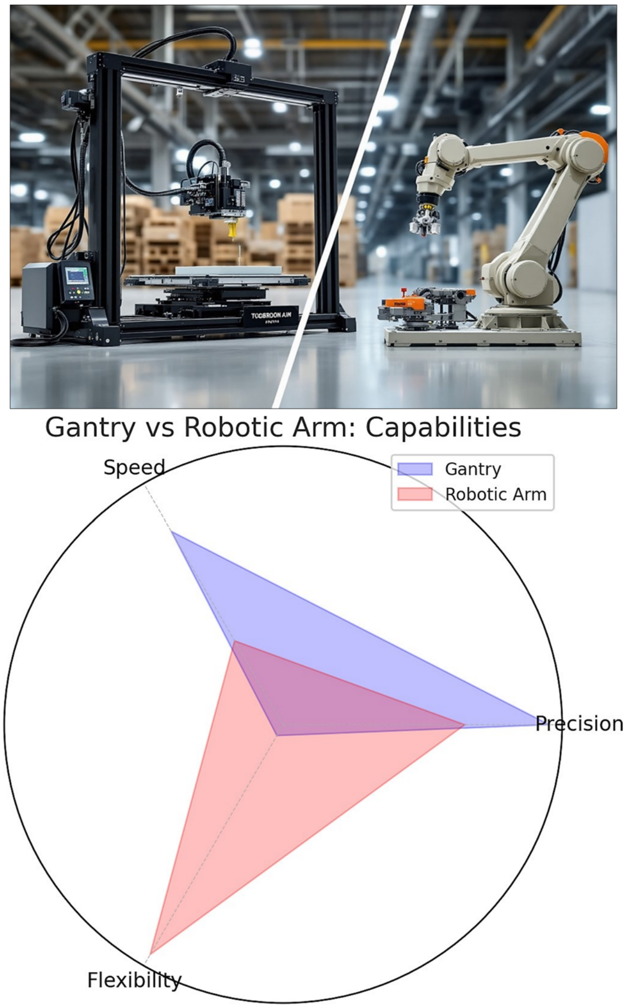

Fig. 6 Key capabilities comparison of gantry versus robotic arm [4, 18, 77]

- **Sintering:** This technology employs lasers or heat sources to fuse powder particles into cohesive forms. Sintering enhances material utilization and ensures sustainability by reducing excess material usage [16] (Fig. 8).

(3) **Plastic and polymer printing:**

- **Fused deposition modeling (FDM):** This widely used method extrudes thermoplastic polymers through heated nozzles for precise deposition, ensuring minimal material waste and maximizing efficiency [96].
- **Stereolithography (SLA):** Using ultraviolet light to cure photo-reactive polymers layer by layer, SLA achieves high precision and minimizes material overuse, aligning with environmental sustainability goals [79] (Fig. 9).

(4) **Metal printing:**

- **Direct metal laser sintering (DMLS)**: DMLS utilizes lasers to fuse metal powder particles, ensuring efficient material use and minimizing waste. This technique is particularly effective in reducing environmental impacts in metal fabrication [16].
- **Electron beam melting (EBM):** EBM uses electron beams to melt metal powders, achieving high accuracy and material efficiency while reducing waste [34].
- **Wire arc additive manufacturing (WAAM)**: WAAM uses arc welding to deposit wire filament onto the build area. It has a very high material deposition rate [82] (Fig. 10).

(5) **Composite material printing:**

- **Continuous fiber fabrication:** Incorporating continuous fibers, such as glass or carbon, into thermoplastics enhances structural strength and reduces excess material use. This innovation also enables lightweight and durable designs [52].
- **Filled polymers:** Polymers combined with metal, wood, or ceramic particles tailor material properties to specific applications, optimizing resource utilization and reducing waste [58] (Fig. 11).

(6) **Hybrid systems:**

- **Multi-material printing:** Combining different materials in a single print enables diverse material properties and optimizes overall usage, reducing waste while enhancing functional capabilities [36].
- **Integrated functional components:** Embedding sensors, wiring, or piping into printed structures during fabrication reduces the need for additional materials, streamlining construction processes and improving material efficiency [29] (Fig. 12).

Table 2 presents the summary of the illustrated 3D printing methods from the material efficiency, and suitability for construction applications point of view.

6.5 Technological evolution and progress

This section delivers the technological evolution and progress on the leading edge of 3D printing in construction, discussing a varied variety of developments aimed at boosting efficiency, lowering environmental effect, and pushing the limits of what's possible in eco-friendly building techniques.

Table 2 Material efficiency of different 3D printing methods

3D printing method	Examples	Sustainability aspect	Suitability for construction applications
Extrusion-based concrete	Cementitious printing, Shotcrete	Controlled deposition, low material waste	Highly suitable for walls, structural frames, on-site construction of housing and infrastructure
Powder-based printing	Selective Binding, Sintering	Precision binding, reduced unused powder	Suitable for decorative panels, complex forms; limited for structural loads; more appropriate for prefabs
Plastic and polymer printing	FDM, SLA	Accurate deposition, recyclable polymers	Suitable for non-structural components: HVAC ducts, formworks, cladding, architectural models
Metal printing	DMLS, EBM, WAAM	High strength, minimal waste, material recyclability	Highly suitable for joints, reinforcements, brackets, connectors in modular or hybrid systems
Composite material printing	Continuous fiber, filled polymers	Lightweight, tailored properties for durability and resilience	Suitable for insulation panels, custom furniture, light framing systems, non-load-bearing applications
Hybrid systems	Multi-material, integrated wiring/sensors	Streamlined construction, multi-functional components	Suitable for intelligent façades, integrated MEP elements, and complex assemblies requiring embedded systems

6.5.1 3D concrete printing

The revolutionary potential of 3D printing in the construction industry hinges on state-of-the-art 3D concrete printers,

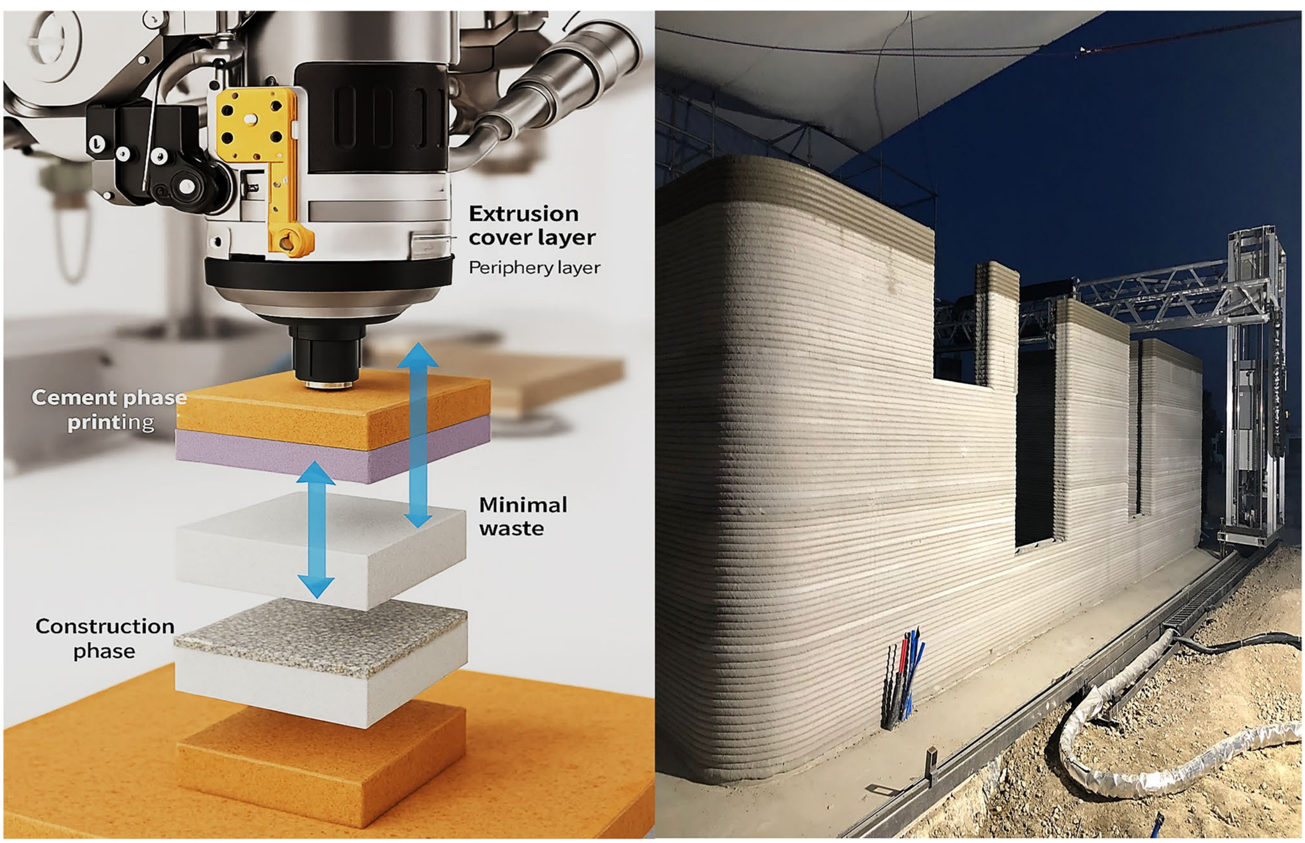

Fig. 7 **a** Extrusion-based concrete printing system, adapted from [29, 45], **b** ICON Vulcan II large-scale gantry-type 3D concrete printer actively constructing a building wall printing a full-scale wall on-site (courtesy of M3 Design via ICON) [44]

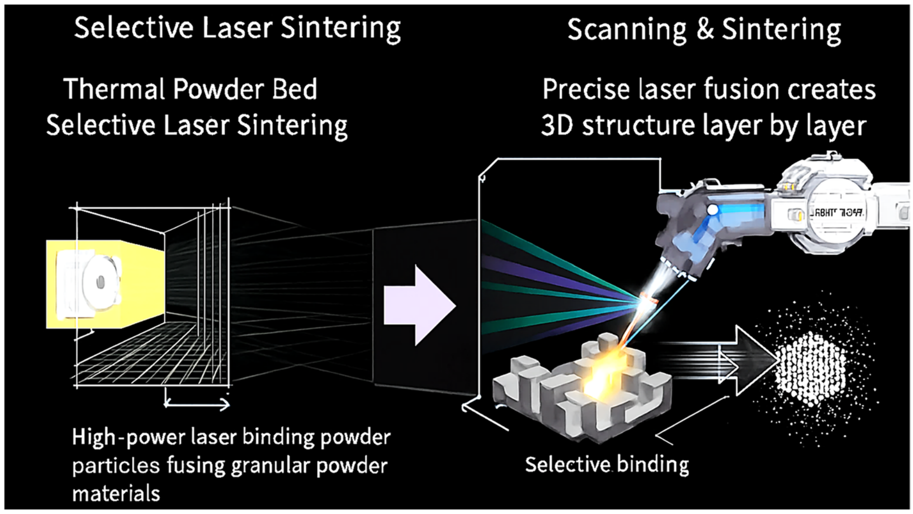

Fig. 8 Powder-based printing system. Adapted from [16, 29]

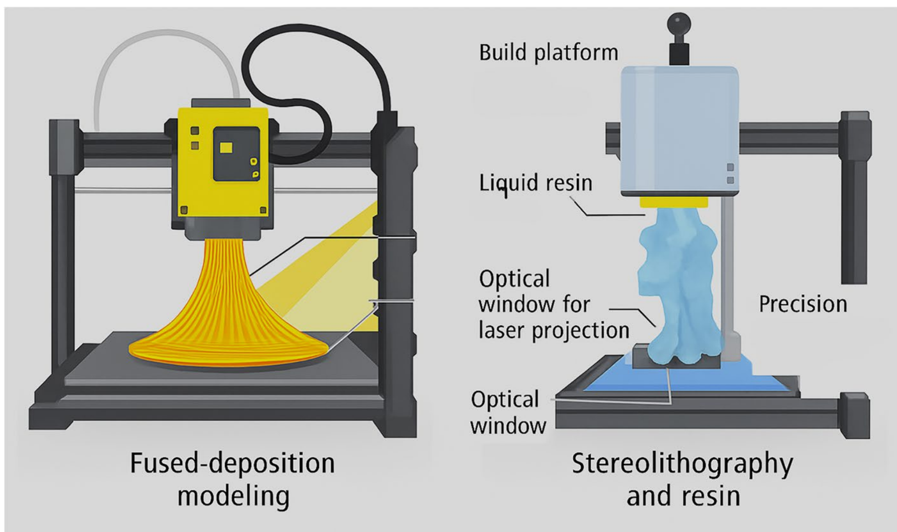

Fig. 9 Plastic/polymer-based printing system. Adapted from [79, 96]

which have undergone significant advancements in precision, reliability, and versatility [45]. Improvements in these systems directly influence their scalability, efficiency, and overall performance in building projects, demonstrating their positive impact on the construction industry [50]. Table 3 indicates the key advancements in 3D concrete printing technology.

Advances in 3D concrete printers not only enhance project-specific precision and efficiency but also contribute to broader sustainability goals. For example, material-specific advancements, such as the use of recycled aggregates and low-carbon cement blends, reduce environmental impact while ensuring structural integrity [20, 61]. Additionally, AI-driven enhancements enable predictive maintenance and optimized workflows, ensuring the long-term reliability and adaptability of these systems [16].

6.5.2 Technical enhancements

Particularly in the context of building, the materials utilized in 3D printing are constantly evolving. Table 4 looks into how 3D printing has advanced material science, with a focus on how new materials enhance important characteristics like robustness, longevity, and environmental sustainability. Assessing the quality, durability, and environmental impact of structures made by 3D printing requires an understanding of the continuous advancements in material technology. It also tackles the more general objective of improving construction methods' sustainability [55]. These novel blends improve strength and durability while also being more environmentally friendly.

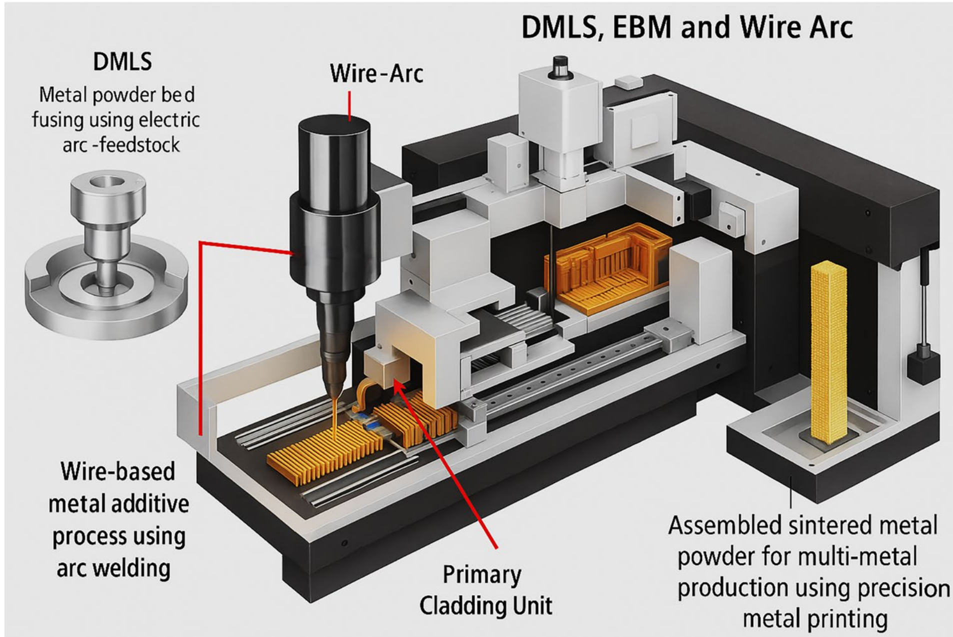

Fig. 10 Metal-based printing systems. Adapted from [16, 34, 82]

6.6 Software and digital design tools

Construction-specific software and advanced CAD (computer-aided design) tools are pivotal for effective 3D printing implementation in modern construction. These tools enhance designers' and architects' capabilities, enabling them to transform conceptual ideas into accurate 3D-printed structures. Table 5 evaluates how digital tools and software contribute to creativity, precision, and sustainability in 3D printing processes [91].

1. **BIM integration:** Software like Autodesk Revit and Bentley AECOsim facilitates seamless integration between 3D printing and BIM, ensuring comprehensive project management and precise material estimation. These tools improve project sustainability by simulating energy consumption and reducing material waste [18].
2. **Parametric and generative design:** Tools such as Rhino/Grasshopper enable the creation of complex geometries and adaptive designs through parametric modeling. Generative design algorithms optimize structures for strength and material efficiency, enhancing both functionality and environmental performance [86].
3. **Structural analysis and optimization:** Software like Trimble Tekla Structures supports detailed structural analysis, ensuring that printed designs meet safety and durability requirements. By detecting clashes and optimizing designs, these tools reduce construction errors and material overuse [42].
4. **Lifecycle and environmental assessments:** Advanced tools, including Dassault Systemes CATIA, provide lifecycle assessment capabilities, evaluating the environmental impact of materials and designs. This analysis helps architects choose eco-friendly materials and energy-efficient designs [15].

6.7 Key sustainability dimensions

With reference to the key sustainability dimensions of 3D printed buildings, both robotic arm-type and gantry-type 3D printing technologies contribute significantly to environmentally friendly construction methods. Gantry systems excel in material utilization and waste reduction [15, 18]. Similarly, robotic arm-type printing fosters the creation of customized, resource-efficient buildings that prioritize sustainable architectural designs [52].

In principle, 3D printing technologies enable precise material deposition, reducing waste compared to traditional construction methods. Extrusion-based techniques, such as cementitious material printing and shotcrete printing, ensure controlled material usage and lower environmental impact [45, 61]. The automated and streamlined processes of 3D printing consume less energy than traditional construction methods. Techniques like selective binding and sintering optimize energy use while ensuring structural integrity [93]. 3D printing supports innovative designs and complex structures, enabling architects to create sustainable and esthetically pleasing buildings [67]. Technologies including FDM and SLA offer unparalleled design freedom while reducing resource consumption [74]. The layer-by-layer approach of additive manufacturing minimizes material wastage and

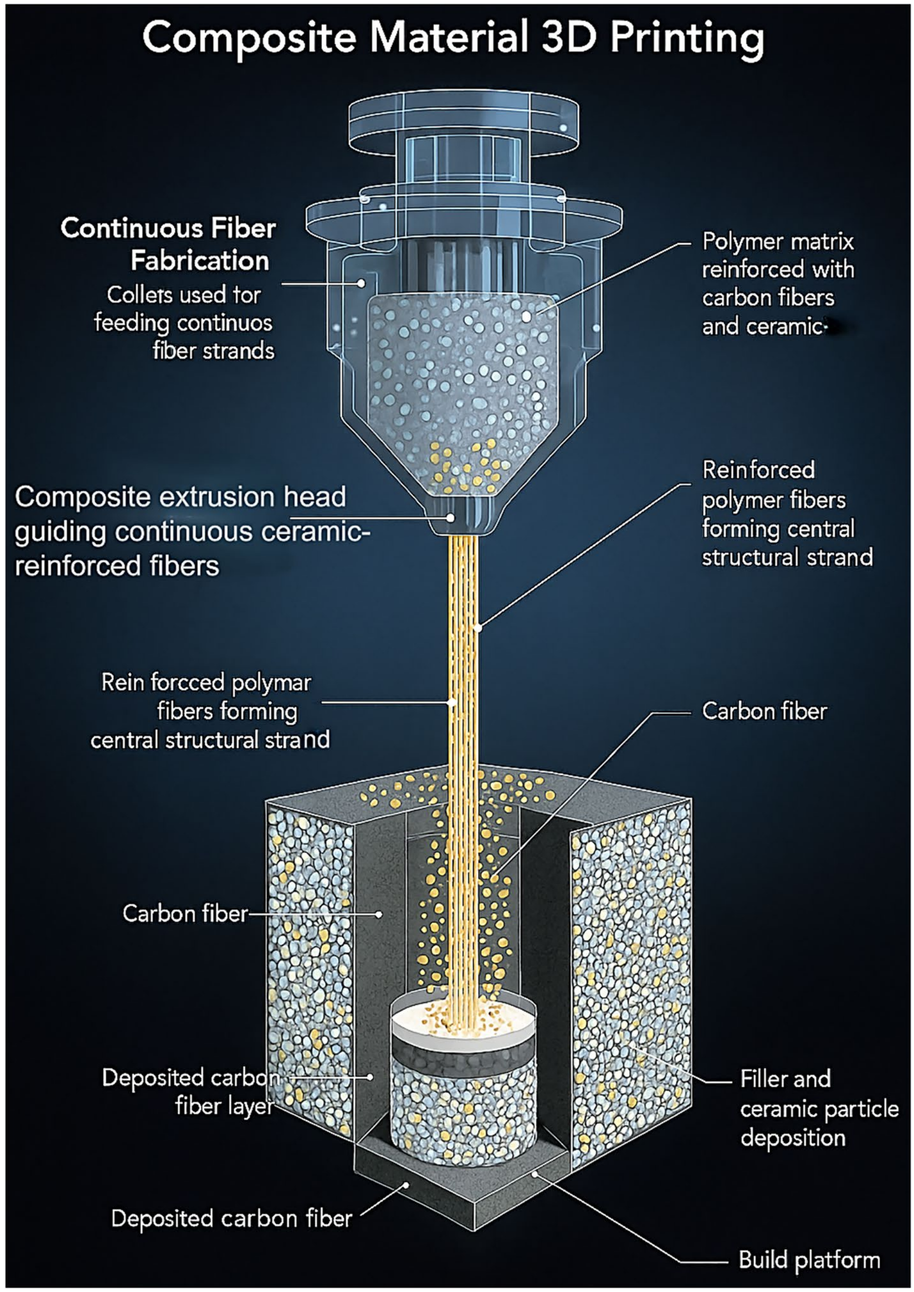

Fig. 11 Composite-based printing system. Adapted from [52, 58]

landfill contributions, aligning with circular economy principles [20]. By incorporating recycled and biodegradable materials, 3D printing reduces the carbon footprint of construction projects. This is further corroborated with DMLS and EBM to enhance material efficiency [16].

6.7.1 Environmental impacts

The evaluation of the environmental sustainability of 3D printing in construction is a multidimensional challenge requiring a thorough analysis across the entire lifecycle of 3D- printed structures, spanning material extraction, production, operation, and end-of-life disposal [4]. Emerging research demonstrates that 3D printing offers substantial opportunities to reduce carbon emissions and energy consumption, yet comprehensive assessments of its broader environmental and economic implications are essential [1] (Table 6).

(1) Material extraction

Traditional materials like Portland cement significantly contribute to greenhouse gas emissions due to the energy-intensive calcination process. Advanced materials such as

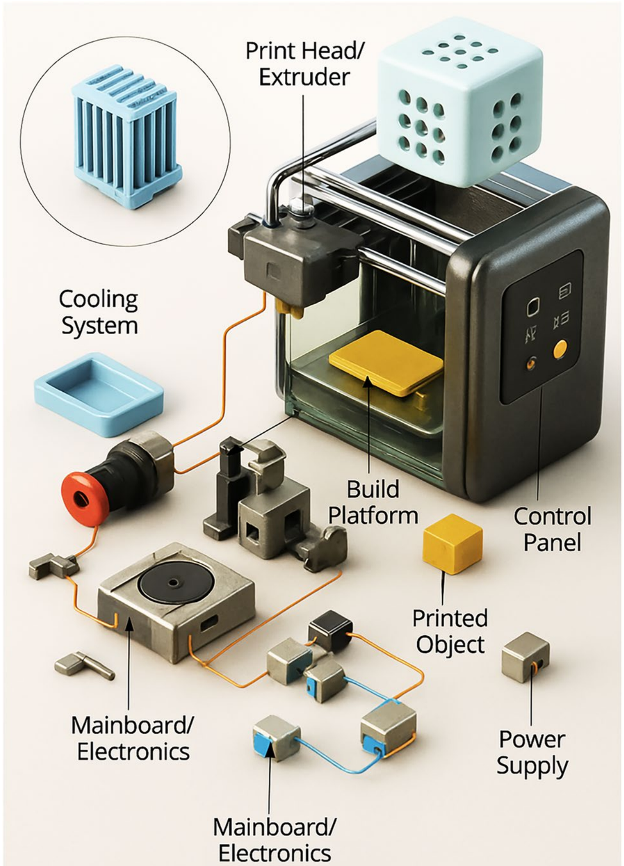

Fig. 12 Hybrid printing system. Adapted from [29, 36]

calcium sulfoaluminate cement and geopolymer binders offer potential reductions of up to 40% in embodied carbon, contingent on local sourcing and optimized material compositions [50]. Additionally, the integration of waste-derived materials (e.g., fly ash and recycled glass aggregates) and bio-based polymers have been shown to significantly enhance environmental performance. For instance, a study by Yao et al. [95] demonstrate that replacing traditional aggregates with waste-derived materials can reduce CO_2 emissions by 30–50% during production.

(2) Design and application

Advanced design processes utilizing parametric modeling and computational tools enable optimal material usage, minimizing waste. Projects employing 3D printing report waste reductions of up to 60%, enhancing both ecological and economic outcomes [18, 79]. Time efficiencies achieved in 3D printing reduce on-site emissions and operational delays, further aligning with global net-zero goals. Agustí-Juan et al. [2] noted that 3D-printed walls required 30% less energy during fabrication compared to traditional methods, primarily due to reduced material wastage and precision manufacturing.

(3) Operational phase

Enhanced thermal insulation properties of 3D-printed walls contribute to operational energy savings of 25–30% compared to conventionally built structures. Integrating passive energy-saving strategies into designs could lead to an additional 15% reduction in lifecycle operational emissions [52]. Furthermore, LCAs of 3D-printed structures highlight long-term benefits, including reduced heating and cooling energy demands. For example, models of 3D-printed buildings with optimized ventilation systems show up to a 40% decrease in lifecycle energy consumption compared to traditional construction [50].

(4) End-of-life and disposal

Closed-loop systems incorporating recyclable and biodegradable materials (e.g., eco-polymers and hybrid composites) are advancing end-of-life solutions. These systems reduce landfill waste and facilitate material recovery, aligning with circular economy principles [15, 50]. The layered

Table 3 Key advancements in 3D concrete printing technology

Aspect	Description	Technical enhancements
Accuracy	Ensures constructions fulfill intricate design specifications, crucial for complex architectural forms	Improved nozzle control, robotic precision, real-time calibration, and AI-driven feedback systems enhance precision [97]
Dependability	Guarantees consistent and high-quality output, minimizing delays and defects in project execution	Integration of advanced fault-detection algorithms and real-time monitoring systems enhances reliability [45]
Material versatility	Ability to accommodate a wide range of materials, including recycled composites, geopolymer concrete, and bio-based alternatives	Multi-material nozzles, adaptive extrusion techniques, and smart material compatibility expand application versatility [15]
Scalability	Capability to scale operations from small residential projects to large-scale infrastructure	Modular printer configurations, scalable frameworks, and adaptive systems ensure flexibility in diverse projects [20, 61]

Table 4 New technologies in 3D printing for sustainable construction

Technology	Description	Sources
3D concrete	Customized concrete mixes for improved structural performance. Reduces use of standard concrete	[19]
Recycled material usage	Integrates recycled materials into printing processes, promoting environmentally friendly practices	[55]
Machine learning integration	AI algorithms improve material utilization and efficiency. Reduces resource use through intelligent optimization	[46]
Prefabricated modular construction	Printing prefabricated components accelerates assembly, reduces energy and material usage on-site	[50]
Biodegradable structures	Creation of temporary or biodegradable structures addressing end-of-life concerns	[20]
Additive manufacturing	Reduces material waste via layer-by-layer construction, enhancing resource efficiency	[64]
Robotic arm systems	Precision in construction minimizes errors and waste, enhancing sustainability and the ability to print more complex geometries	[94]

Table 5 Software contributions to 3D printing in construction

Software/tool	Key features	Applications	Sustainability benefits
Autodesk Revit	BIM integration, clash detection, parametric modeling	Comprehensive design and material estimation	Enables energy simulation and reduces construction waste
Rhino/Grasshopper	Generative design, advanced modeling	Complex geometry creation	Optimizes material use and enhances design flexibility
Trimble Tekla Structures	Structural analysis, detailing, clash detection	Structural engineering and integration	Minimizes errors and optimizes resource utilization
Bentley AECOsim	Simulation tools, BIM authoring	Energy-efficient design and analysis	Enhances energy performance and resource efficiency
Dassault Systems CATIA	Lifecycle assessment, parametric modeling	Multidisciplinary applications	Evaluates environmental impact and supports sustainable practices

Table 6 Key environmental impacts analysis of construction 3D printing

Phase	Environmental impact	Mitigation strategies
Material extraction	Energy-intensive production and transport of specialized materials like geopolymer concrete and composites	Use of recycled or bio-based materials; localized material sourcing [20]
Design and application	Construction phase waste minimized by precise material usage and automation	Automated deposition; optimized material utilization to align with sustainability goals [18]
Operational phase	Enhanced insulation and thermal performance reduce operational energy demands	Integration of passive design and energy-efficient technologies [52]
End-of-life disposal	Challenges in recycling and dismantling large-scale structures	Innovations in biodegradable materials and closed-loop systems [15]

deposition method intrinsic to 3D printing poses challenges in dismantling structures, especially those reinforced with composites.

6.7.2 LCA methodologies and economic implications

LCAs of 3D-printed structures provide insights into environmental impacts across all stages, including raw material production, construction, operation, and end-of-life disposal. Studies by Agustí-Juan et al. [2] and Yao et al. [95] emphasize the importance of comprehensive cradle-to-grave assessments to capture the true environmental performance of 3D-printed projects. In terms of the impact assessment methods, commonly used methods like CML, ReCiPe, and TRACI offer diverse environmental metrics, including global warming potential, resource depletion, and water usage. ReCiPe, particularly at the midpoint level, is frequently employed for its broad coverage of impact categories [50].

In terms of the economic implications, cost efficiency significantly applies through material savings. The precision of additive manufacturing reduces material consumption, leading to cost savings of up to 25% compared to traditional methods. The avoidance of formwork in 3D printing also cuts labor and material costs significantly [87]. Energy-efficient 3D-printed structures contribute to lower operational costs over their lifecycle. Buildings with optimized thermal properties report up to a 30% reduction in energy expenses for heating and cooling [52]. However, high initial costs for 3D printing equipment remain a barrier. However, the scalability of the technology and reductions in construction time promise high returns on investment in the long term [79] (Table 6).

As the research critique on energy demands, although 3D printing reduces waste, certain printing technologies like laser sintering are highly energy intensive. Utilizing renewable energy sources for operations can mitigate this challenge [16]. Hence, the limited availability of scalable, cost-effective, and sustainable materials for 3D printing poses a significant barrier. Greater research into locally sourced materials and waste-derived composites is necessary [5]. Localized sourcing and transporting materials to construction sites contributes to emissions. Strategies such as on-site printing facilities or localized material production can effectively reduce this footprint [20].

6.7.3 Architectural flexibility

The potential of 3D printing to enable intricate and personalized patterns that are difficult or impossible to achieve with traditional construction methods exemplifies its architectural flexibility. This capability unlocks new possibilities for building design, allowing architects and designers to experiment with complex and innovative structures. Architectural flexibility evaluates the extent to which 3D printing can transcend the limitations of conventional building techniques, fostering both esthetic and functional advancements in construction [74] (Table 7).

Studies have shown that robotic arm-type 3D printing excels in creating intricate curves and custom shapes, as demonstrated in projects such as *multipurpose pavilion* [63], and the construction of the Pavilion of the Future in Dubai [4]. This project utilized selective laser sintering (SLS) technology for precision and material efficiency. FDM techniques have been employed to produce modular housing units tailored to specific client requirements. For example, the TECLA project in Italy utilized 3D-printed clay to create eco-friendly, customizable homes. Focusing on innovative design exploration, 3D printing enables the integration of functional and esthetic elements into architectural projects. For instance, selective binding techniques were used in the Gaia Project to create sustainable designs integrating advanced insulation properties and organic forms [52].

Considering the sustainability aspects of the architectural flexibility, advanced material deposition methods ensure minimal waste. In the Gaia Project, the use of recycled aggregates and bio-based materials reduced embodied carbon by 35% compared to traditional methods [15]. Structures printed using FDM and SLA technologies demonstrated superior insulation capabilities, reducing operational energy use for heating and cooling [86]. Studies emphasize the role of 3D printing in facilitating the reuse of construction materials, aligning with circular economy principles. This approach minimizes landfill waste and promotes resource conservation [1] (Table 7).

In addition to the technological perspective toward architectural flexibility, one of the critical developments in architectural 3D printing is the integration of Design for Manufacturing and Assembly (DfMA) principles—originally from lean manufacturing contexts—into additive and digital fabrication. DfMA emphasizes designing components for efficient manufacturing, transport, and on-site assembly, reducing complexity, waste, and costs while improving performance and constructability [66, 89]. Recent scholarship exemplifies this integration. For instance, Tuvayanond and Prasittisopin [83] systematically reviewed 171 publications to define DfMA procedures—spanning digital fabrication, AM toolpath design, BIM integration, and emerging machine learning—to enhance efficiency and sustainability in construction projects. Their work highlights current research gaps in structural performance analysis, BIM coupling, and automation-ready design frameworks. Similarly, Kim et al. [39] developed parametric models for prefabricated bridges, explicitly designed for additive manufacturing and on-site assembly. They combined structural optimization with module-level manufacturability for efficient fabrication and logistics. Additionally, newer studies [49] use bibliometric and thematic analysis to position DfMA as essential

Table 7 Technologies supporting architectural flexibility

3D printing technology	Applications	Advantages
Robotic arm-type	Complex geometries, unique facades	High precision and adaptability
Fused deposition modeling (FDM)	Modular units, eco-homes	Customization, material efficiency
Selective laser sintering (SLS)	Sculptural elements, innovative designs	Precision, reduced waste
Powder-based printing	Organic forms, sustainable designs	Versatility in material use
Hybrid systems	Mixed-material facades, integrated functions	Combines esthetics and functionality

for off-site, modular construction. These works advocate a holistic DfMA methodology that integrates design, fabrication, transportation, and assembly phases within digital ecosystems.

DfMA for 3D-printed architecture includes the following implications:

- Modularization via DfMA enables repeatable, scalable additive manufacturing processes, improving logistics and on-site workflows.
- Parametric design and toolpath planning ensure that printed geometries are optimized for both printing performance and assembly compatibility.
- Digital integration—such as linking BIM with slicing and AM control—allows early-stage constructability checks [69], fabrication cost prediction, and integration of embedded services (e.g., mechanical, electrical, plumbing).
- Structural alignment: Designing modules with additive processes in mind facilitates efficient reinforcement strategies, improved bonding, and sustainable material usage.

6.7.4 Labor efficiency

Labor efficiency is a crucial consideration in the integration of 3D printing within the construction industry. While 3D printing automates many construction tasks, its effectiveness is contingent upon skilled personnel capable of operating, maintaining, and optimizing advanced equipment [35]. This section explores the multifaceted impacts of 3D printing on labor dynamics, emphasizing workforce adaptability, the reduction of manual labor, job reallocation, and enhanced project efficiency. The analysis underscores the necessity of organizational changes and targeted training initiatives to maximize the benefits of this technological shift [15, 86]. The key dimensions of the 3D printing labor efficiency include the following:

(1) Workforce adaptability and upskilling

The transition to 3D printing technologies demands comprehensive training programs. Workers must acquire skills in digital modeling, machine programming, and equipment maintenance to ensure the seamless adoption of these technologies [52]. Programs such as the “Digital Workforce Training” initiative in the European construction sector have successfully bridged skill gaps, enhancing workforce readiness for digital fabrication [5]. Workers with digital modeling and 3D printing skills will be able to provide more productivity through increased ability to solve workplace problems. 3D printing can provide additional and more flexible solutions to the conventional construction process (Fig. 4) through rapid mold development, rapid scaffolding, and rapid aids for quality control [32]. Thus, a lack of accessible training programs poses a significant barrier, with surveys indicating that 60% of construction firms cite workforce skills as a critical limitation to implementing 3D printing [50].

(2) Reduction in manual labor

Automated layer deposition during concrete printing significantly reduces the need for manual labor. This streamlining eliminates repetitive, labor-intensive tasks such as formwork assembly and on-site material handling [58]. As a successful case of this discussion, in Eindhoven, the Netherlands, a 3D-printed residential community reduced the number of required on-site workers by 70%, showcasing the transformative potential of automation in labor optimization [18].

(3) Job reallocation

Automation is leading to the emergence of new roles and reallocation of labor, with growing demand for roles in machine programming, digital fabrication (Dfab) management, and robotics maintenance. These roles require specialized expertise, creating opportunities for skilled laborers [35]. While automation reduces reliance on unskilled labor, it necessitates a workforce transition, emphasizing the importance of vocational programs tailored to emerging job requirements [15].

(4) Efficiency in project execution

The automation of complex construction tasks accelerates project execution, particularly for intricate designs or tight schedules. Studies report that 3D printing reduces construction timelines by 30–50% compared to conventional methods [18]. Faster project delivery lowers labor costs and enhances profitability. For instance, commercial buildings constructed using 3D printing in Dubai saw a 35% reduction in overall labor costs due to streamlined workflows [79]. Therefore, the transition to 3D printing necessitates a reorganization of traditional construction workflows, emphasizing integrated roles and specialized management. The shift is summarized in Table 8.

In a conventional workflow, design and construction occur in distinct phases, requiring separate teams and processes. Conversely, a 3D printing workflow integrates these phases through digital modeling, overseen by a Dfab Manager. This streamlined process reduces redundancy, improves coordination, and enhances overall project efficiency [35]. Despite the significant advancements and potential benefits of 3D printing in construction, several limitations hinder its widespread adoption, particularly in the context of labor efficiency and workforce dynamics. These challenges reveal the complexities of integrating such a transformative technology into a traditional manual and labor-intensive industry. The construction industry has long been characterized by its reliance on conventional methods and its cautious approach to technological innovations. This resistance to change stems from uncertainty regarding the upfront costs and long-term benefits of 3D printing. Many stakeholders remain skeptical about its feasibility, fearing that the transition may disrupt established workflows and require substantial reorganization. This hesitation is further compounded by a lack of demonstrable case studies that can convincingly illustrate the tangible advantages of 3D printing over traditional construction techniques.

6.8 Case studies and functional applications

The adoption of 3D printing in construction has revolutionized functional applications across diverse sectors. Its ability to deliver high precision, reduce material waste, and enable innovative designs is unlocking new opportunities for sustainable and efficient construction. Key applications and global case studies highlight the versatility and transformative potential of this technology (Fig. 13).

(1) **Residential structures:** 3D concrete printing has significantly reshaped residential construction by offering faster project completion, reduced labor costs, and enhanced architectural flexibility. Tailored housing solutions are realized through customized designs, allowing developers to meet specific client needs while minimizing material waste. Notably, geopolymer concrete, as a preferred material for 3D printing, has demonstrated a 40% reduction in embodied carbon emissions compared to traditional concrete [20, 50]. ICON, a Texas-based firm, has successfully implemented 3D printing to construct affordable housing in underdeveloped regions, reducing construction timelines by 50% while minimizing waste [92] (Fig. 13a).

(2) **Infrastructure:** The precision and material efficiency of 3D printing technologies are advancing large-scale infrastructure projects, including bridges, tunnels, and highways. The ability to achieve intricate designs with high structural integrity has made 3D printing a cost-effective solution for complex infrastructure needs [18]. As a case study, a pedestrian bridge in Madrid, Spain, constructed using additive manufacturing, demonstrated a 50% reduction in waste compared to traditional methods. The design optimized material usage through computational algorithms, aligning with circular economy principles [61, 5] (Fig. 13b).

(3) **Public spaces and landscape design**: The flexibility and adaptability of 3D printing have found application in the development of urban spaces [62], parks, and public installations. Projects such as 3D-printed pavilions in Milan highlight the potential of using recycled materials to construct esthetically appealing and environmentally friendly structures (Fig. 13c) [52]. To indicate the functional application, 3D-printed bus stops and benches were developed in Dubai using sand-based materials, reflecting both material and design innovation while reducing embodied carbon [79].

(4) **Disaster relief**: 3D printing technology plays a critical role in rapid response scenarios, particularly in regions affected by natural disasters. Temporary housing units and essential infrastructure can be deployed within hours using gantry and robotic arm systems. For instance, WASP, an Italian firm, designed 3D-printed shelters using clay-based materials for earthquake-affected regions in Italy, offering a cost-effective and sustainable solution [35, 91]. This presents the resource optimization in which the use of local and biodegradable materials in 3D printing for disaster relief minimizes transportation needs and environmental disruption (Fig. 13d).

Table 9 expands on the global use of 3D printing for sustainable construction, emphasizing diverse technologies and their corresponding sustainability impacts.

6.9 Lifecycle flow of sustainable 3D printing

The lifecycle flow model of 3D printing in construction, adapted from [2, 14, 23, 50], integrates resources, waste, savings, strategies, inputs, outputs, impacts, and outcomes (Fig. 14). It represents a closed-loop system emphasizing

Table 8 organizational changes derived through 3D printing application in construction

Workflow comparison	Conventional workflow	3D printing workflow
Design process	Sequential design and construction phases	Integrated design and construction via digital models
Roles	General and specialized labor under multiple managers	Digital Fabrication (Dfab) Manager oversees entire process
Efficiency	Redundant steps, slower project timelines	Streamlined workflows with automation
Training requirements	Limited to conventional skills	Requires specialized training in digital modeling and operation

Fig. 13 Global 3D printing case studies: **a** ICON residential housing development in Texas, **b** pedestrian bridge in Madrid, **c** public space pavilion in Milan, **d** WASP shelters in Italy

carbon offsetting and energy efficiency strategies. The diagram identifies critical phases in the lifecycle of 3D printing in construction, guided by LCA principles. The blue boxes reflect a specific stage, impacts and outcomes are in eclipse forms, while the cylindrical shapes represent the outputs (Fig. 14):

- Material extraction represents the sourcing of raw materials, including aggregates, polymers, and cementitious binders. This phase accounts for up to 60% of total resource consumption, involves processing materials into usable components, contributing significantly to energy use and waste generation.
- Construction delivers the assembly of 3D-printed structures, leveraging modular and prefabricated techniques to optimize material efficiency and minimize on-site waste.
- Operation indicates the operational energy and resource demands during the lifecycle of constructed assets, often comprising up to 15% of total lifecycle energy consumption.
- Recycling demonstrates material recovery in reducing landfill waste and mitigating carbon emissions.
- Economic impact encompasses costs associated with production and operational savings, as well as revenue from carbon credits.

Table 9 Evidence of global applications of 3D printing in sustainable construction

References	Technology used	Sustainability aspect	Applications
Wu et al. [91]	Robotic arm type	Customized design, resource efficiency	Residential structures, eco- homes, disaster relief
Chen et al. [18]	Gantry type, robotic arm	Material efficiency, adaptability	Infrastructure, residential, public spaces
Sun et al. [77]	Robotic arm type	Sustainable material optimization	Commercial structures, public amenities
Sakin and Kiroglu [68]	Robotic arm type	Time and cost efficiency	Residential, commercial buildings
Pons-Valladares et al. [61]	Robotic arm type	Material efficiency, design optimization	Motor bridges, large-scale infrastructure
Yao et al. [95]	Binder jetting	Circular economy integration	Infrastructure, esthetic urban installations

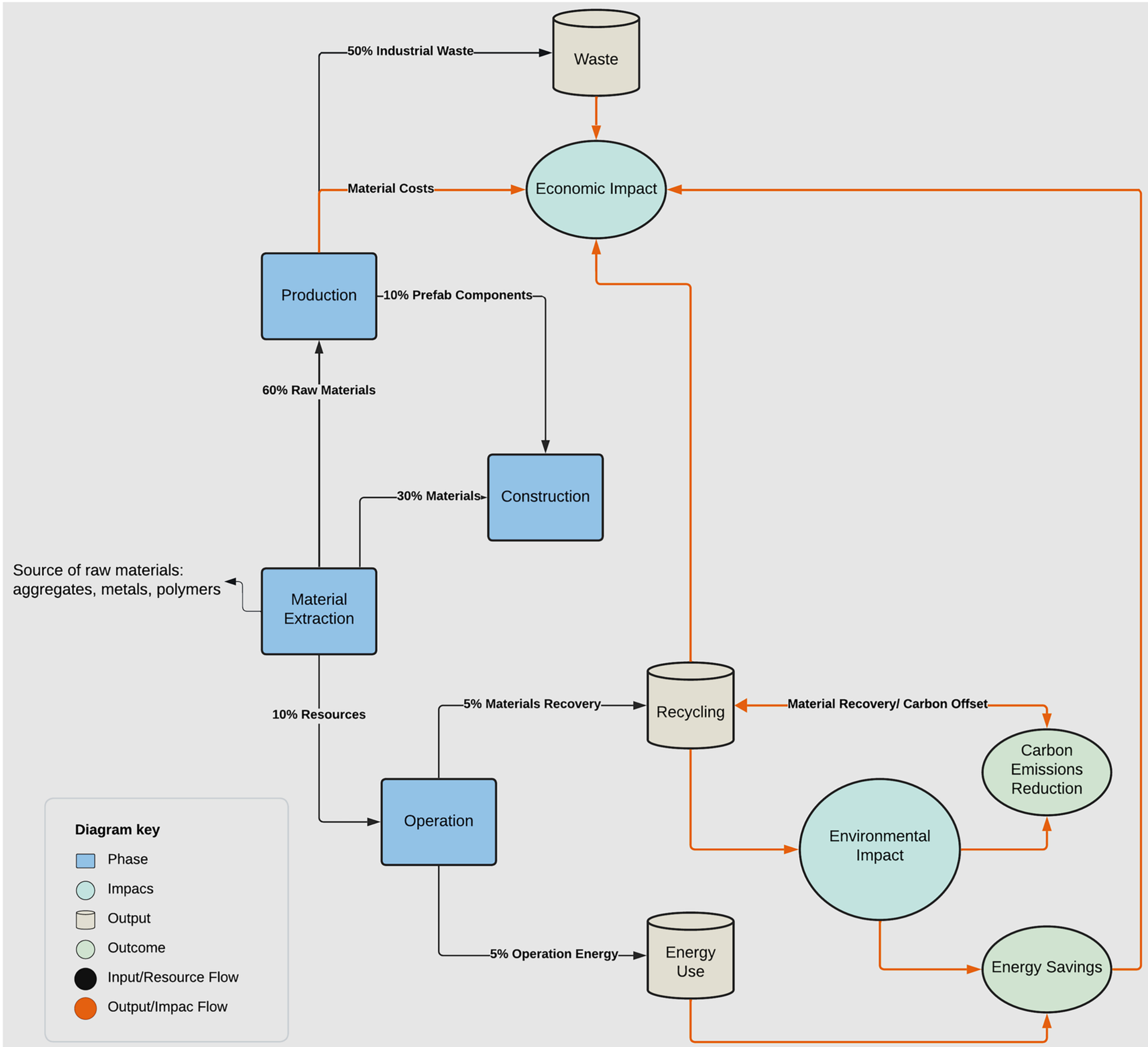

Fig. 14 Lifecycle flow model for sustainable 3D printing in construction. Adapted from [2, 14, 23, 50]

- Environmental impact includes emissions savings, and contributions to a circular economy.

6.9.1 Components and flows of the model

(1) Material extraction

- Material extraction → production (60%): Raw materials such as aggregates, polymers, and cementitious binders are sourced to support additive manufacturing, representing 60% of resource allocation in the lifecycle. This highlights the material-intensive nature of 3D printing processes.
- Material extraction → construction (30%): Raw materials are directly used in modular and prefabricated construction, demonstrating resource efficiency by reducing processing requirements.
- Material extraction → operation (10%): A smaller portion of resources is allocated for maintenance and operational needs during the lifecycle.

(2) Production

- Production → waste (50%): Manufacturing inefficiencies, such as over-deposition and component errors, contribute to significant waste generation during 3D printing.
- Production → construction (10%): Processed materials, including prefabricated components, are allocated for direct use in construction.
- Production → economic impact: Material costs during production significantly affect the economic profile, highlighting the need for efficiency.

(3) Construction

- Construction → recycling: Residual materials and offcuts from the construction phase are recovered and directed to recycling streams, reducing waste and supporting circularity.

(4) Operation

- Operation → energy use (5%): Operational energy requirements, including lighting, heating, and cooling, contribute to 5% of the total lifecycle energy demand.
- Operation → recycling (5%): Operational waste, such as replaced components or failures, is redirected to recycling facilities.

(5) Recycling

- Recycling → environmental impact: Recycling mitigates raw material extraction and landfill waste, contributing to a 20% reduction in lifecycle carbon emissions.
- Recycling → economic impact: By recovering materials and reducing landfill costs, recycling generates significant economic benefits.

(6) Energy use

- Energy use → environmental impact: Integrating renewable energy sources reduces emissions, with renewables potentially contributing up to 40% of lifecycle energy.
- Energy use → energy savings: Improved energy efficiency reduces operational demands by 15%, underscoring the role of sustainability in lifecycle management.

(7) Environmental impact

- Environmental impact → carbon emissions: Remaining emissions, after recycling and energy savings, are assessed for further offsetting strategies.
- Environmental impact → energy savings: Sustainability initiatives that improve energy efficiency directly contribute to reduced emissions.

(8) Carbon emissions

- Carbon emissions → recycling: Recycling incorporates carbon capture technologies, offsetting emissions associated with cement-based materials.
- Carbon emissions → economic impact: Carbon credits incentivize sustainable practices, enhancing economic performance.

(9) Energy savings

- Energy savings → economic impact: Operational savings from energy efficiency directly reduce costs and improve financial sustainability (Fig. 14).

6.9.2 Resources and waste

The lifecycle of 3D printing in construction is fundamentally driven by resource efficiency and strategic waste management. At its core, this process relies on the effective utilization of raw materials, energy inputs, and innovative waste reduction practices to enhance sustainability. Key resources such as aggregates, cement, and polymers form the backbone of 3D printing materials, while energy inputs, including both fossil fuels and renewables, sustain the operational and manufacturing processes. The lifecycle also generates various waste streams, with manufacturing waste accounting for up to 50% of production outputs and construction offcuts and operational waste contributing an additional 5% each. To address these challenges, reduction strategies like recycling and material reuse are employed, significantly reducing landfill contributions by up to 30%.

6.9.3 Savings and strategies

Energy efficiency and carbon offsetting are central to achieving sustainability in 3D printing. Renewable energy integration plays a significant role, reducing emissions by 15% through the incorporation of cleaner energy sources into the lifecycle. Furthermore, lifecycle savings stem from the improved thermal performance of 3D-printed structures, which enhances energy efficiency during operation. These advancements underscore the importance of adopting innovative energy strategies to minimize environmental impacts. Carbon offsetting further amplifies these efforts by targeting emissions associated with material production and processing. Recycling practices offset up to 20% of emissions by reducing the dependency on virgin materials and diverting waste from landfills. In addition, carbon capture technologies embedded within recycling processes specifically address emissions linked to cement production, a critical component of additive manufacturing. Together, these strategies provide a dual approach to environmental and economic sustainability, showcasing the potential for transformative impacts in construction.

6.9.4 Impacts and outputs

The impacts and outputs of 3D printing in construction highlight the dual benefits of economic savings and environmental sustainability. From an economic perspective, cost savings are achieved through enhanced energy efficiency, which reduces operational demands by 5%, and through recycling practices that lower raw material costs and landfill expenses. Additionally, the generation of revenue via carbon credit provides financial incentives for adopting sustainable practices. These credits not only offset emissions but also create opportunities for businesses to align profitability with environmental goals. On the environmental front, the lifecycle demonstrates significant reductions in emissions and waste. Recycling contributes to a 20% decrease in lifecycle carbon emissions by minimizing the need for virgin material extraction and diverting waste from landfills. Concurrently, landfill waste is reduced by 30%, aligning with the principles of the circular economy (Fig. 14).

The lifecycle flow diagram integrates resource flows, energy optimization, and environmental impacts, demonstrating a closed-loop approach aligned with global sustainability goals. This model supports actionable insights into material efficiency, energy savings, and carbon offsetting, as the flowing key highlights:

- Circular flow: The connection between recycling, environmental impact, and economic impact demonstrates the circular economy in action and cost efficiency.
- Integrated impacts: Flows linking energy savings and carbon emissions to economic impact highlight the financial benefits of sustainable practices.
- Waste minimization: Material recovery through recycling significantly reduces landfill contributions, aligning with global sustainability goals.

7 Discussion

The research demonstrates that 3D printing technology possesses transformative potential for the construction sector by directly addressing resource inefficiencies, environmental impacts, and sustainability challenges. This section delves deeper into the technical, economic, and societal aspects of 3D printing, integrating specific examples and literature to provide a robust evaluation.

7.1 Technical sustainability metrics

3D printing achieves notable reductions in material waste through precision layering and on- demand manufacturing processes. Compared to traditional methods, additive manufacturing reduces material wastage by up to 60% [18]. This efficiency is achieved through extrusion techniques such as cementitious material printing and selective binding, which ensure that only the required volume of material is utilized.

To further quantify sustainability impacts, Key Performance Indicators (KPIs) such as energy consumption per cubic meter of printed material, water usage, and thermal performance offer deeper insights. For example, 3D printing technologies have been shown to consume 30% less energy per cubic meter compared to traditional methods [80]. Similarly, water usage is reduced by approximately 25%, while enhanced thermal performance of printed materials contributes to long-term energy efficiency in buildings.

Lifecycle assessments suggest that 3D printing can lower embodied carbon emissions by 20–40%, particularly when utilizing geopolymer concrete or recycled polymers [20]. Emerging innovations in materials such as biopolymer-based composites—including hemp-based and lignin-based binders—expand the range of eco-friendly options [51]. Additionally, the use of recycled aggregates and fibers not only improves the mechanical properties of printed elements but also significantly reduces their carbon footprint.

Comparative lifecycle data reinforce these findings. For instance, ISO 14040/44-aligned assessments demonstrate that 3D printing frameworks achieve up to 50% reductions in carbon emissions over conventional methods when applied to residential and infrastructure projects [76]. These results underscore the need for continued research and the integration of renewable energy systems to address the energy demands of processes such as sintering or laser-based printing.

7.2 Advantages for construction projects

3D printing offers unparalleled advantages in flexibility, cost, speed, and environmental implications (Fig. 15). For instance, gantry-based systems have been deployed in constructing affordable housing projects, reducing costs by 25% and construction timelines by 50%, as demonstrated in projects such as Winsun's 3D-printed houses in China [90]. These cost and time reductions stem from the elimination of extensive formwork and manual labor, coupled with precision material deposition [15].

Moreover, robotic arm systems enable the production of intricate designs and custom architectural components, which are challenging to achieve with traditional methods. Structural testing results from pioneering projects, such as *multipurpose pavilion* [63] and the Pavilion of the Future, highlight how innovative geometries contribute to both structural integrity and esthetic value [17]. Finally, 3D printing offers a new way to consider on-site construction assembly. It provides a flexible way of handling variation in the assembly process, where jigs and fixtures can be changed in real time [14].

Integration with digital workflows further enhances the efficacy of 3D printing. BIM and parametric modeling seamlessly feed into 3D printing processes, enabling precision in material estimation and design optimization [68]. Real-time monitoring tools, such as sensors for layer deposition quality, ensure consistent construction output while reducing errors and waste. Case studies like the TECLA eco-home [81] in Italy showcase the synergy of sustainable materials with cutting-edge design possibilities, reinforcing the viability of 3D printing as a cornerstone of modern construction.

Despite these advantages, upfront investment in 3D printing equipment and the scalability of production for large-scale projects remain critical barriers. Addressing these issues through modular printer configurations, increased adoption of multi-material capabilities, and further cost optimization could unlock broader applications across the sector.

7.3 Critiques and challenges

A primary critique of 3D printing in construction lies in its limited scalability and material availability. For example, the required volumes of specialized binders, extended curing times, and constraints in printhead throughput make mass adoption challenging [27]. While advancements have been made in geopolymer and composite materials, these often require post-processing steps, increasing time and costs. Additionally, the mechanical properties and long-term durability of 3D-printed structures under varying environmental conditions remain underexplored, necessitating further

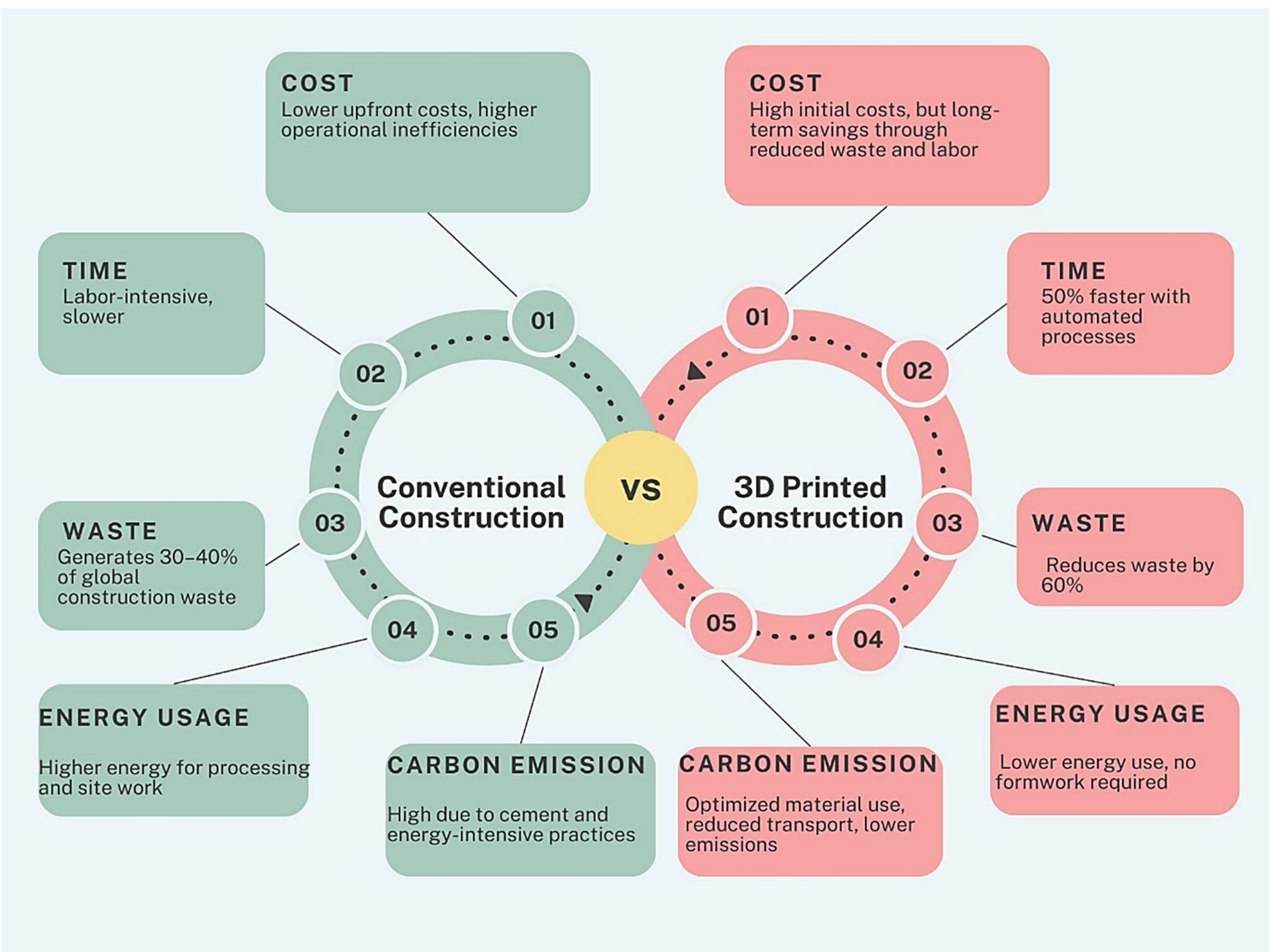

Fig. 15 3D printed versus conventional construction

empirical validation through pilot projects and real-world monitoring [38].

The absence of standardized regulations also complicates the integration of 3D printing into conventional practices. For instance, emerging standards by committees such as RILEM and ASTM (e.g., ASTM F42 for additive manufacturing) are working toward addressing challenges in large-scale concrete printing. Aligning 3D printing technologies with existing structural design codes, such as Eurocode and ACI standards, is critical for ensuring industry-wide acceptance [47].

Long-term durability studies remain crucial for validating the resilience of 3D-printed structures [69]. Ongoing investigations, such as those monitoring 3D-printed elements under real-world environmental conditions, provide valuable insights into lifecycle performance and the potential for broader adoption [38]. Addressing these challenges will require collaboration among industry stakeholders, policymakers, and researchers to drive innovation in sustainable 3D printing practices.

7.4 Future research directions

(1) Standardization and regulatory frameworks: Establishing international standards for material properties, structural integrity, and environmental compliance is crucial to promoting the global adoption of 3D printing technologies. Specific tasks include developing uniform testing parameters for compressive and flexural strength, standardizing rheological properties of fresh printing mixtures, and aligning with Environmental Product Declarations (EPDs) to assess environmental performance.

(2) Durability and longevity studies: Long-term monitoring of 3D-printed structures under diverse environmental conditions can provide valuable insights into their resilience and lifecycle performance. This should encompass studies on microstructural changes, such as shrinkage and interlayer bonding, as well as chemical durability factors, including the corrosion of reinforcements embedded in printed layers.

(3) Economic and social impacts: Investigations into how 3D printing affects job markets, housing affordability, and community acceptance will provide a more comprehensive understanding of its broader implications. Pilot programs assessing community reception, labor reskilling initiatives, and stakeholder perception surveys (e.g., [54]) can offer critical insights into societal impacts.

(4) Energy efficiency improvements: Integrating renewable energy sources into the manufacturing process and optimizing energy-intensive steps, such as sintering, will further enhance 3D printing's environmental performance. Research into energy-efficient nozzles, extruders, and binder compositions, coupled with lifecycle energy models that include supply chain emissions, will fortify the argument for sustainable integration.

(5) Integration with digital design tools: Enhanced integration of BIM and parametric design tools can streamline workflows, improve material estimation, and ensure sustainability benchmarks are met. Real-time sensor feedback loops, generative design algorithms, and advanced robotics can further enhance precision. Emphasizing the synergy of parametric design, structural optimization, and additive manufacturing can unlock dynamic adjustments in print speeds or material densities, ensuring efficiency and quality (Fig. 16).

7.5 Practical applications and implications

Innovations such as hybrid 3D printing systems and AI-driven optimization tools have significantly improved material efficiency and adaptability. By incorporating multi-material capabilities, these technologies can cater to diverse construction needs, ranging from affordable housing to bespoke architectural designs. Additionally, projects like the Pavilion of the Future in Dubai demonstrate the feasibility of applying 3D printing to large-scale infrastructure, combining esthetics with functionality.

Policy and funding channels: Accelerating the adoption of 3D printing in construction requires robust policy incentives and the fostering of public–private partnerships. Examples such as Singapore's Building and Construction Authority (BCA) funding programs and Dubai's "Dubai 3D Printing Strategy" [3] illustrate how government initiatives can drive technological expansion. Subsidies for pilot projects, tax benefits for adopting sustainable technologies, and grants for research and development represent effective pathways to encourage innovation.

Intersection with circular economy: Linking 3D printing with broader circular economy principles enhances its sustainability impact. This includes closed-loop material cycles, design for deconstruction, and cradle-to-cradle manufacturing [60]. For instance, the layer-by-layer approach of 3D printing can facilitate easier disassembly and material reuse at the end of a structure's lifecycle, reducing waste and promoting resource efficiency.

Interdisciplinary collaboration: Future breakthroughs in 3D printing demand collaboration across engineering, materials science, architecture, and policy-making. Such partnerships can yield standardized practices, expedite regulatory acceptance, and facilitate knowledge sharing among diverse stakeholder groups.

Fig. 16 Future research and application direction for 3D printing in sustainable construction

7.6 Potential research impact

The potential research impact spider chart (Fig. 17) is ultimately presented to visually illustrate the relative importance and potential contribution of key research focus areas in advancing 3D printing technology within the construction sector. The spider chart presents several key research impacts of 3D printing in construction:

1. Energy efficiency: Additive manufacturing processes like FDM and SLA consume less energy than conventional methods by eliminating formwork and using automated precision layering. Research suggests that operational energy savings can reach up to 30% in 3D-printed structures due to enhanced thermal properties.
2. Material durability: Innovations in geopolymer concrete, bio-based composites, and fiber-reinforced materials improve the long-term performance of 3D-printed components. Studies indicate that advanced materials enhance resistance to environmental stressors, fire resisting performance [78], ensuring longevity and reduced maintenance.
3. Cost reduction: Precise material deposition minimizes waste, significantly reducing costs. For example, ICON's housing projects demonstrate cost savings of up to 25% compared to conventional methods. The elimination of labor-intensive processes further contributes to economic feasibility.
4. Scalability: Although 3D printing excels in small- to medium-scale projects, scaling up for large infrastructure remains challenging due to printhead throughput and curing times. Research in modular printing and multi-material systems holds promises for addressing scalability issues.
5. Environmental impacts: 3D printing's ability to use recycled and biodegradable materials aligns with circular economy principles, reducing embodied carbon emissions by 20–40%. Lifecycle assessments show significant reductions in construction waste, further enhancing its environmental credentials.
6. Regulatory compliance: The lack of international standards for 3D printing remains a bottleneck. Developing uniform testing protocols and material certifications will facilitate broader adoption. Efforts by ASTM (e.g., ASTM F42 for additive manufacturing) and other standardization bodies are critical to overcoming this challenge.

The chart also highlights areas where focused research can drive significant advancements:

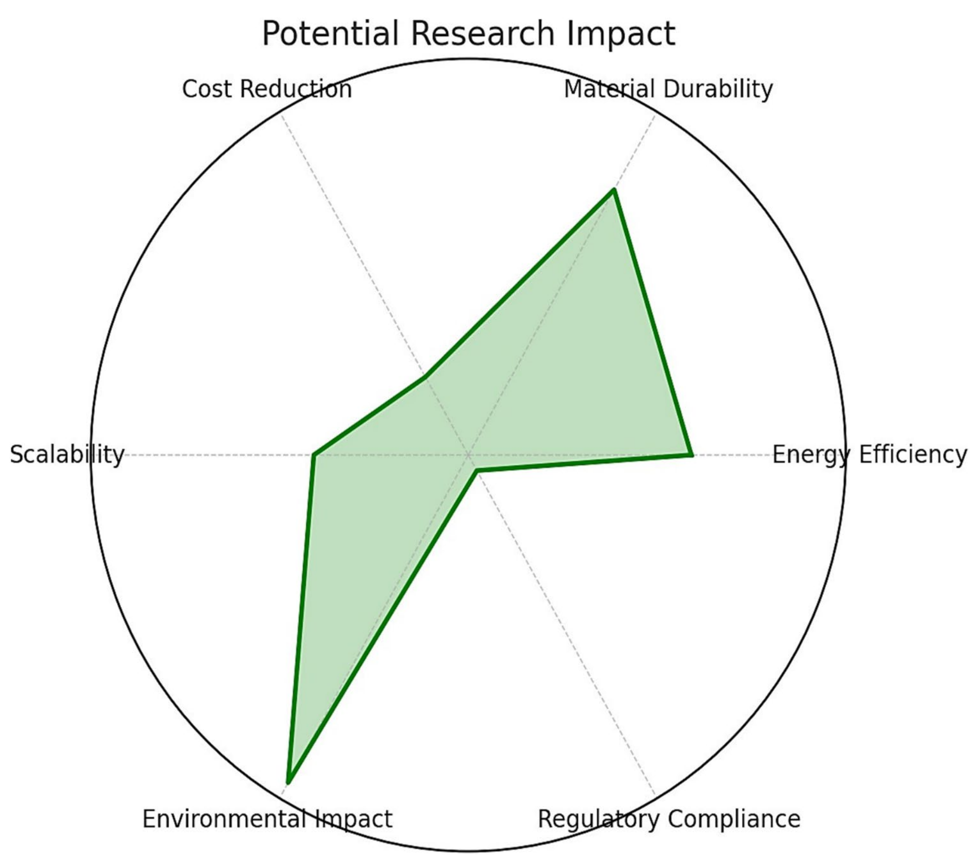

Fig. 17 Potential research impacts to shape the 3D printing role in sustainable construction

- Material science innovations via developing low-carbon, durable, and scalable materials for broader applications.
- Integration with renewable energy by addressing energy-intensive aspects of 3D printing, such as laser sintering, using green energy sources.
- Regulatory framework development by aligning with structural codes like Eurocode and ACI standards to ensure industry-wide compliance and acceptance.
- Lifecycle optimization by incorporating lifecycle assessments into design workflows for better environmental and economic outcomes.

The spider chart (Fig. 17) serves as a strategic tool to prioritize research and development efforts in 3D printing. By focusing on areas with the highest potential impact, such as material durability and environmental sustainability, the construction industry can accelerate its transition toward greener, more cost-effective practices. Bridging gaps in scalability and regulatory frameworks will further solidify 3D printing's role as a cornerstone of sustainable construction.

8 Conclusion

The adoption of 3D printing technology in construction represents a transformative shift toward addressing critical sustainability challenges, including excessive material waste, high carbon emissions, and resource inefficiency. This study systematically evaluated the intersection of 3D printing and sustainable construction through a robust methodological approach, which included a structured literature review using the PRISMA framework, the integration of interdisciplinary insights from material science and environmental engineering, and the synthesis of practical applications to validate theoretical findings. The findings underscore the potential of this technology to redefine modern construction paradigms, aligning them with global sustainability goals and addressing critical industry limitations, including excessive resource waste, high carbon emissions, and the inefficiency of conventional construction workflows.

The thematic analysis highlighted key trends in the adoption of 3D printing for sustainable construction, including the integration of circular economy principles, innovations in material efficiency, and the role of advanced digital tools. Emerging themes emphasized the importance of environmental sustainability, economic feasibility, and the need for regulatory frameworks. Additionally, the thematic analysis identified a growing emphasis on workforce transformation, including the need for upskilling and the creation of specialized roles in digital fabrication.

Content analysis provided a detailed breakdown of the advancements in 3D printing technologies, such as extrusion-based concrete printing and robotic arm systems. It revealed significant progress in material utilization, energy efficiency, and design flexibility. Specific advancements included the use of AI-driven design tools and hybrid printing systems that integrate multiple materials for enhanced performance. Moreover, the analysis identified barriers to widespread adoption, including high initial costs, scalability issues, and a lack of standardization. Key examples from case studies, such as 3D-printed residential and infrastructure projects, underscored the practical applications and potential for innovation within the construction sector. Further findings highlighted the potential of 3D printing to reduce operational energy demands and its alignment with sustainability certifications.

The key findings of the study can be presented through material efficiency and waste reduction, enhanced construction speed and design flexibility, environmental sustainability and economic and social implications. 3D printing enables precise material deposition, reducing waste by up to 60% compared to traditional methods. Techniques such as extrusion-based concrete printing and selective binding ensure optimal resource utilization. The integration of recycled and biodegradable materials, such as geopolymer concrete and bio-based polymers, contributes significantly to reducing embodied carbon emissions by 20–40%. Layer-by-layer additive manufacturing accelerates project timelines, achieving construction speed improvements of 30–50%, particularly in residential and infrastructure projects. The architectural flexibility of 3D printing supports innovative designs and complex geometries, unlocking opportunities for customized, sustainable structures.

3D printing demonstrates superior energy efficiency, with lifecycle assessments revealing up to a 30% reduction in operational energy demands for heating and cooling. Its alignment with circular economy principles, including closed-loop material cycles and cradle-to-cradle manufacturing, positions it as a pivotal technology for reducing waste and promoting resource conservation. Despite high initial costs, 3D printing offers long-term cost savings through reduced material usage, streamlined labor requirements, and shorter construction timelines. The technology presents new labor dynamics, necessitating workforce upskilling and the emergence of specialized roles in digital modeling and robotics management.

The key gaps can be identified in three main groups of material and technological limitations, regulatory and structural challenges and economic barriers. Limited scalability of 3D printing technology for large-scale projects is due to constraints in printhead throughput and curing times. A lack of standardized materials and testing protocols, such as uniform rheological properties and durability assessments, hinders broader adoption. The absence of comprehensive regulatory frameworks and international standards complicates the integration of 3D printing with existing building codes. Limited empirical data on the long-term durability and lifecycle performance of 3D-printed structures occur under diverse environmental conditions, leading to high initial investment costs for 3D printing equipment and technology adoption, particularly for small and medium enterprises. Limited financial incentives and subsidies put the roadblock to support innovation and early adoption in the construction industry.

In response, the key future research can be directed toward research and development, standardization and regulation, integration with digital technologies and policy and funding initiatives. It is imperative to develop advanced, cost-effective, and scalable materials, including locally sourced and waste-derived composites. Moreover, long-term monitoring of 3D-printed structures paves the way to evaluate durability, lifecycle performance, and environmental impacts under real-world conditions. Establishment of international standards for material properties, structural integrity, and environmental compliance and alignment of 3D printing technologies with structural codes, such as Eurocode and ACI standards facilitate industry-wide acceptance and ensure safety and reliability.

Enhanced collaboration between BIM, parametric design tools, and 3D printing workflows optimize resource estimation and project management. This can lead to the exploration of AI-driven optimization for material deposition, quality control, and predictive maintenance. Government-led incentives, such as grants, tax benefits, and public–private partnerships drive adoption and innovation in sustainable construction. Implementation of training programs and vocational initiatives upskill the workforce and bridge knowledge gaps.

This study positions 3D printing as a cornerstone of sustainable construction, demonstrating its ability to harmonize ecological, economic, and social dimensions. By addressing critical knowledge gaps and proposing actionable pathways, the research contributes to the broader discourse on digital and sustainable innovation in the construction sector. The findings highlight 3D printing's transformative potential to mitigate environmental impacts through material efficiency and waste reduction, accelerate the adoption of innovative, eco-friendly building practices, and foster resilience and adaptability in urban infrastructure development. Ultimately, the integration of 3D printing into mainstream construction practices holds the promise of achieving a resilient, efficient, and eco-conscious built environment. By embracing this transformative technology, the construction industry can redefine its role in shaping a sustainable future.

Acknowledgements Declaration of generative AI and AI-assisted technologies in the writing process: In preparing this article, the authors employed ChatGPT to enhance the language and readability of the text, and Gamma AI for visualization of Figs. 6, 8, 11, and 12. Subsequently, the authors conducted a comprehensive review and revision of the content as required, taking full responsibility for the publication's accuracy and integrity.

Author contributions S.B. and B.R. wrote the main manuscript text; M.S. prepared illustrations; A.A. and H.B. reviewed and edited the article. All authors reviewed the manuscript.

Funding Open Access funding enabled and organized by CAUL and its Member Institutions.

Data availability No datasets were generated or analyzed during the current study.

Declarations

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

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