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REVIEW

A comprehensive review of 3D printing in construction: technology, materials, and digital workflow

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Abstract

The rapid evolution of 3D printing technologies is redefining the construction industry by enabling faster, cost-effective, and sustainable building solutions. This paper presents a comprehensive review of additive manufacturing techniques applied in construction, emphasizing material extrusion, powder bed fusion, and hybrid systems. It discusses advancements in 3D printable materials such as cementitious composites, geopolymer concretes, fiber-reinforced mixes, and soil-based alternatives, highlighting their rheological behavior, printability, and structural performance. The study also examines the integration of digital workflows—comprising parametric modelling, BIM, and slicing software—that streamline design-to-production processes. Real-world case studies from India, including the 3D-printed G+1 villa by Godrej Properties and Tvasta Engineering, L&T's reinforced concrete building, and the Bengaluru 3D-printed post office, demonstrate the practical viability and scalability of this technology. The review identifies current challenges in large-scale implementation, cost optimization, and workforce training while emphasizing future directions involving AI-driven automation, sustainable materials, and multi-material printing. The findings underscore 3D printing's transformative potential in achieving resilient, eco-efficient, and customized construction.

Keywords 3D printing in construction · Additive manufacturing · Construction technology · Digital workflow · Sustainable material

Introduction

The construction industry has long relied on labour-intensive methods, resulting in high costs, prolonged project timelines, and significant material wastage. With the growing demand for sustainable and cost-effective housing solutions, researchers and engineers are exploring innovative alternatives. 3D printing, also known as additive manufacturing (AM), has emerged as a transformative technology, introducing automation and efficiency to the construction sector. By enabling rapid prototyping and direct fabrication of complex structures, 3D printing reduces reliance on manual labour, minimizes waste, and enhances architectural flexibility [1].

Unlike conventional construction techniques, which generate substantial waste through on-site cutting and assembly, 3D printing offers precise material deposition, significantly reducing waste. It also supports the use of eco-friendly materials, such as recycled plastics and biodegradable composites, lowering the industry's carbon footprint. Advancements in material science, robotics, and computational design are key drivers of this technology's adoption. 3D concrete printing (3DCP), for instance, can reduce labour costs by 50–80% [2] and address labour shortages in countries like the USA, UAE, Qatar, Malaysia, and Singapore, where construction heavily depends on migrant workers. Additionally, 3D printing accelerates construction timelines by 33–42% when printing components for assembly and by 61–72% when printing directly on-site.

Digital workflows are critical to optimizing 3D-printed construction projects. BIM is a developing approach for digitally modelling the physical and functional attributes of a building or facility [3]. Technologies like Building

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(i) (ii)

Fig. 1 (i) World's highest 3D-Printed Military Bunker, Ladakh (*Source* Simpliforge Creations Construction n.d.) (ii) largest Win sun building [8]

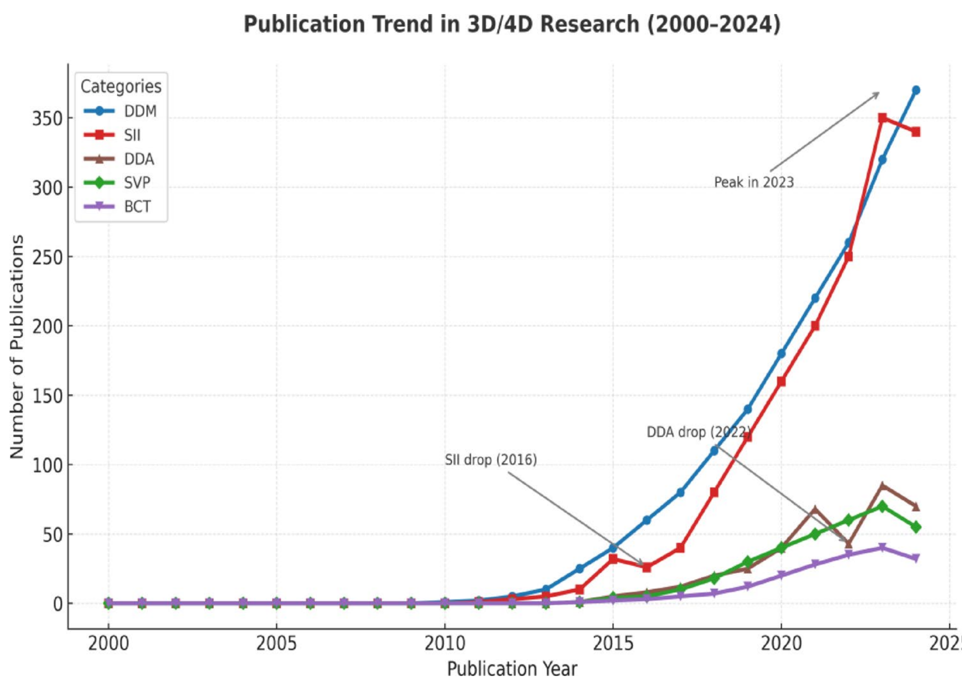


Fig. 2 Publication trends over time 2000–2024 [9]

Information Modelling (BIM), computational design, and slicing software facilitate the translation of digital models into physical structures [4]. BIM, a collaborative digital process, creates data-rich representations of a building's physical and functional characteristics, enabling seamless integration with 3D printing [5, 6]. As the industry evolves, the integration of 3D printing with hybrid construction techniques, artificial intelligence (AI), and sustainable materials is poised to further revolutionize the sector (Fig. 1).

This review examines the technologies, materials, and digital tools shaping the future of 3D printing in construction. It also addresses the challenges and limitations of adopting this technology and explores emerging trends that could drive its widespread implementation. A notable example of 3D printing's potential is the world's highest on-site 3D-printed military bunker, constructed at 11,000 feet in Leh, Ladakh, by Simpliforge Creations in collaboration with IIT Hyderabad and the Indian Army under Project PRABAL [7]. Between 2014 and 2015, WinSun fabricated a multi-story apartment building by 3D printing its components in a factory. They used an enormous 3D printer, measuring 20 feet high, 33 feet wide, and 132 feet long, which leveraged recycled construction materials and proprietary technology. Once printed, these sections were transported to the site and assembled to construct the complete building [8]. From 2000 to 2024 in Fig. 2, publications on 3D/4D research show a steady upward trend, especially in DDM, SVP, and BCT categories. Temporary declines occurred for SII in 2016 and DDA in 2022, followed by recovery. The year 2023 marked the peak in publications, reflecting heightened research interest, while the apparent drop in 2024 is due to data being collected only until February, with further growth expected later in the year [9] .

Overview of major additive manufacturing processes

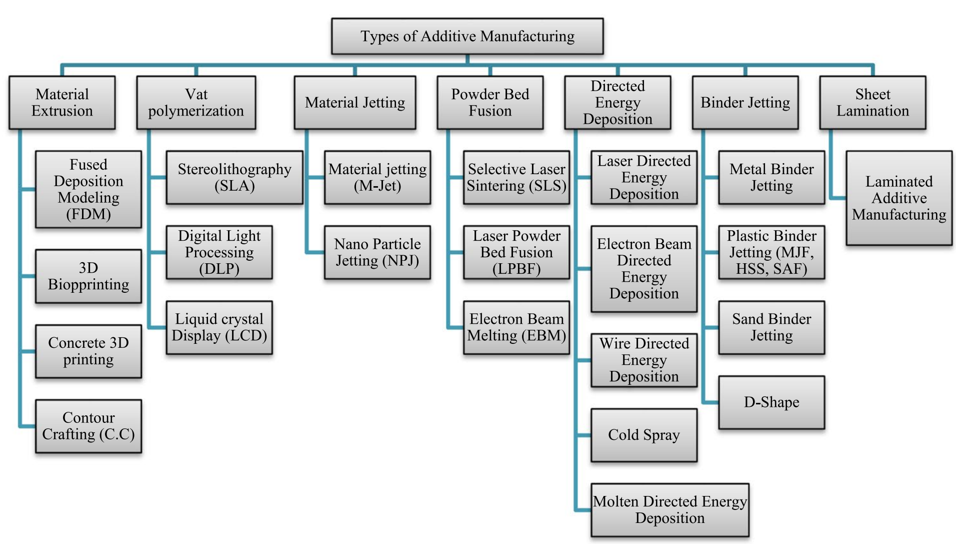
Additive manufacturing (AM), commonly known as 3D printing is a cutting-edge technology recently adopted in the construction industry, playing a pivotal role in advancing the sector's digital transformation. Additive manufacturing (AM) is the process of creating objects by building up materials layer by layer based on 3D model data, as defined by the American Society for Testing and Materials [10]. The types of additive manufacturing could be divided by what they produce or which type of material they use, but to apply structure to the technology worldwide, the International Standards Organization (ISO) divided them into seven general types (Fig. 3):

Material extrusion

Material Extrusion (MEX) is a foundational additive manufacturing process involving the precise deposition of material, layer-by-layer, through a heated nozzle. Renowned for its cost-effectiveness and broad material compatibility, MEX handles polymers, metals, ceramics, composites, bio-inks, and even concrete. While versatile, it typically presents limitations in mechanical strength and dimensional accuracy (often cited as ± 0.5% or ± 0.5 mm)(All3DP Pro n.d.) compared to other AM methods. Common applications range widely from rapid prototyping and creating manufacturing aids like jigs and fixtures to producing end-use parts and large-scale structures.

Key MEX sub-techniques include Fused Deposition Modelling (FDM), which primarily processes thermoplastic filaments or pellets by heating and extruding them based on digital designs; metal FDM is an advancing area requiring post-processing. 3D Bio-printing utilizes MEX principles with specialized bio-inks containing living cells and supportive scaffolds to fabricate complex tissue-like structures for medical research, drug testing, and regenerative medicine. 3D bio-printing technologies, such as extrusion bio-printing, utilize automated bioink deposition via computer-controlled processes, but still include manual steps that may compromise the instruments' usability and precision [11]. Furthermore, large-scale Concrete 3D printing employs gantry or robotic systems to extrude concrete or other materials, enabling the automated construction of buildings and infrastructure with potential benefits in cost, speed, and waste reduction. Collectively, these evolving MEX technologies demonstrate significant impact across diverse sectors. The material is usually a mortar with high cement content, featuring a maximum particle size of about 2–3 mm, though larger aggregates are sometimes used [12]. Contour Crafting technology offers innovative solutions for the architecture, engineering, and construction industries. It facilitates the efficient building of diverse projects, from detailed models to large-scale constructions [13]. A key benefit is its ability to realize intricate designs that push beyond the limits of conventional building techniques, potentially resulting in more robust structures. Simulation studies suggest that CC enhances construction quality while dramatically shortening project timelines, potentially completing work three times faster than usual methods (Fig. 4).

Fig. 3 Types of major additive manufacturing



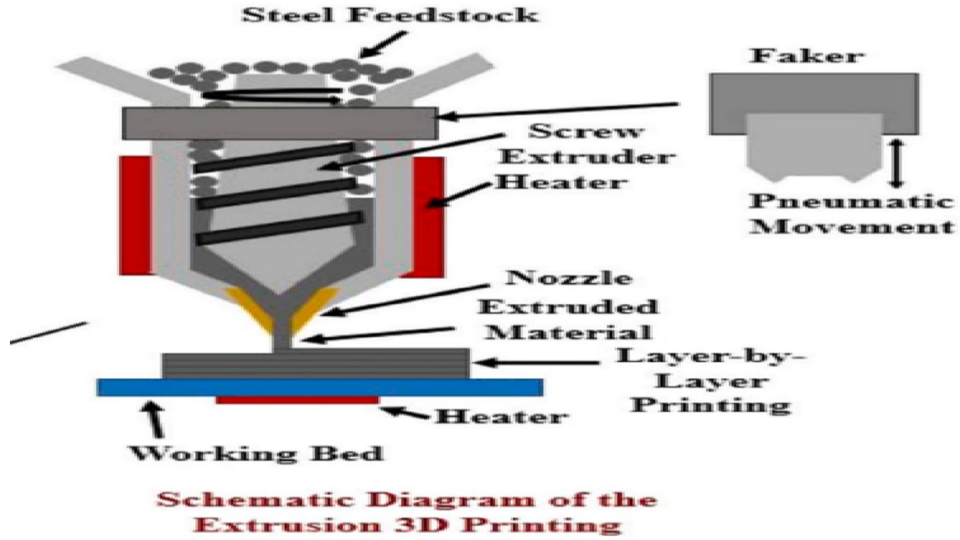


Fig. 4 schematic figure material extrusion 3D printing [14]

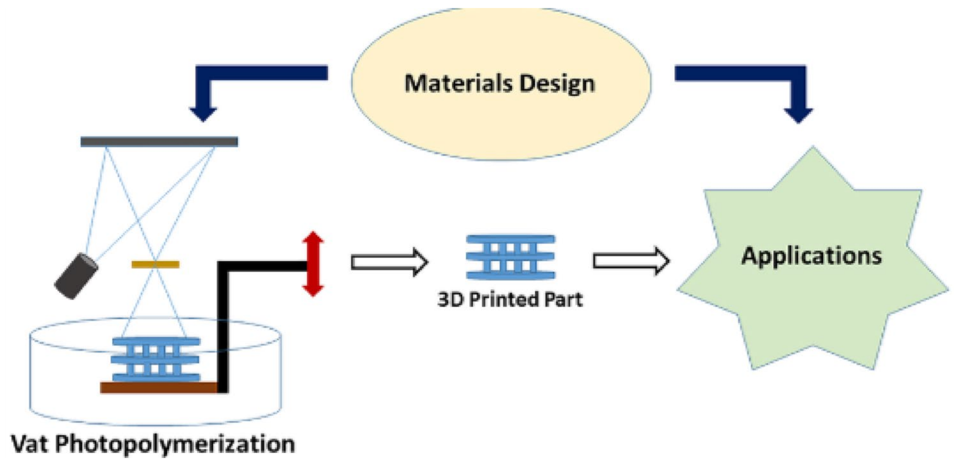


Fig. 5 schematic figure Vat polymerization 3D printing [18]

Vat polymerization

Involves a liquid photopolymer resin in a shallow vat, where ultraviolet mask projection selectively triggers photo-initiated cross linking to create solid geometries and features, built layer by layer [15]. The SL process, pioneered by 3D Systems Inc., was the first commercial additive manufacturing technique, utilizing UV light to polymerize photosensitive resin layer by layer. MSL, an additive 3D micro manufacturing method, was initially developed by Ikuta and Hirowatari [16] with the integrated hardened (IH) polymer SL, later enhanced by the super IH process [17]; (Digital Light Processing DLP), employing projectors for rapid, full-layer curing(All3DP Pro n.d.); and Liquid Crystal Display (LCD) or Masked SLA (MSLA), offering a cost-effective, fast alternative with LCD masks. These methods process various materials, including standard, biocompatible, and filled resins. Renowned for high dimensional accuracy, smooth surface finishes, and fine feature detail, vat polymerization is widely adopted in jewellery, dental, and industrial sectors. Unique manufacturer variations further expand its capabilities(All3DP Pro n.d.) (Fig. 5).

2.3 Material Jetting (M-Jet)

Is an advanced additive manufacturing technology that enables high-precision, multi-material, and full-colour 3D printing by depositing and curing photopolymer or wax droplets layer by layer [19]. This process offers exceptional dimensional accuracy ($\pm$0.1 mm), smooth surface finishes, and the ability to produce complex geometries using dissolvable support structures. The literature suggests that MJ technology offers higher resolution than FDM, potentially leading to visible, rough weld lines between consecutive layers in FDM printing [20]. Compared to other resin-based methods, M-Jet provides faster printing speeds and eliminates the need for post-curing, making it ideal for industries such as automotive, healthcare, and product design [19]. Additionally, Nano Particle Jetting (NPJ), a specialized form of material jetting, extends the technology's capabilities to

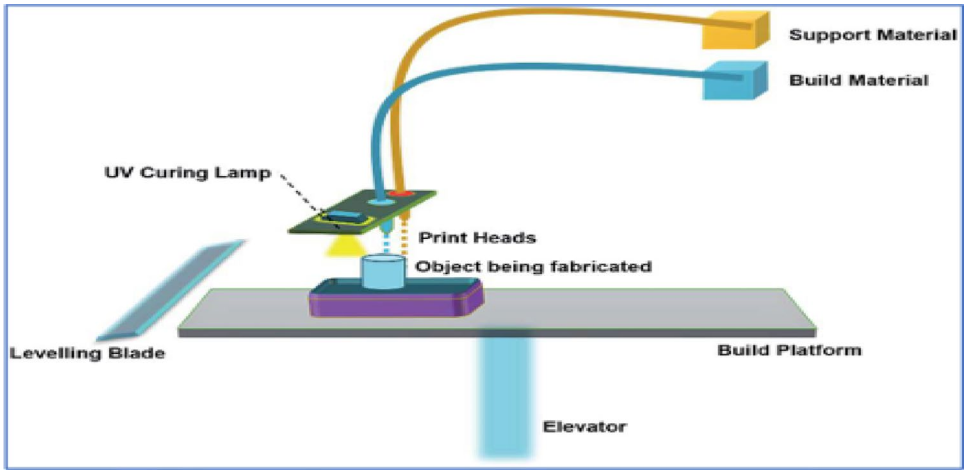


Fig. 6 schematic figure material jetting [21]

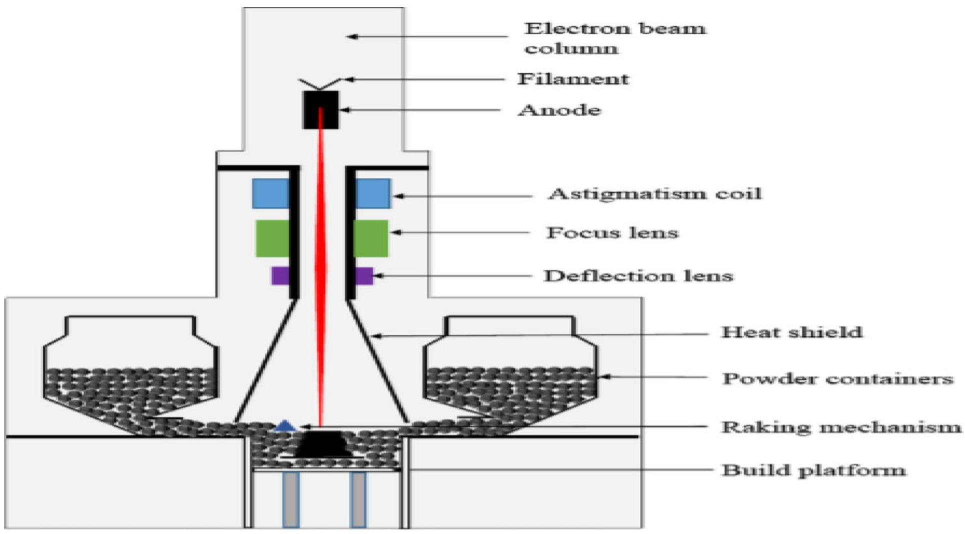


Fig. 7 schematic figure powder bed fusion [26]

metal and ceramic materials by utilizing ultrafine nano particle suspensions and sintering-based post-processing [14]. Despite its advantages, material jetting faces limitations in material strength and higher costs compared to alternative 3D printing methods. This paper explores the principles, applications, benefits, and challenges of M-Jet and NPJ, highlighting their role in industrial prototyping and functional part production (Fig. 6).

Powder bed fusion (PBF)

Is a widely used additive manufacturing technology that employs a laser or electron beam to selectively fuse powdered materials—polymers, metals, or ceramics—into high-strength, complex parts [22]. Powder bed fusion (PBF) is a set of additive manufacturing (AM) techniques that employ an energy source to selectively fuse or melt powder particles, constructing parts layer by layer to achieve the desired shape [23]. Key PBF methods include Selective Laser Sintering (SLS) for polymers SLS is utilized in Additive Manufacturing (AM), a key component of the next industrial revolution [24], Laser Powder Bed Fusion (LPBF/DMLS/SLM) for metals, and Electron Beam Melting (EBM) is highly effective for constructing circular or intricate shapes with thin walls [25]. These processes enable intricate geometries without extensive support structures, though post-processing (e.g., heat treatment, surface finishing) is often required. Its applications span aerospace, medical, and industrial sectors, with ongoing advancements improving material diversity and process efficiency (Fig. 7).

Directed energy deposition (DED)

Is an additive manufacturing technology that deposits and fuses metal material using energy sources such as lasers, electron beams, or electric arcs [27]. It is widely used for repairing and enhancing metal parts, often combined with CNC machining for improved precision. DED processes enable the creation of complex shapes on both flat and irregular surfaces by depositing metallic material layer by layer,

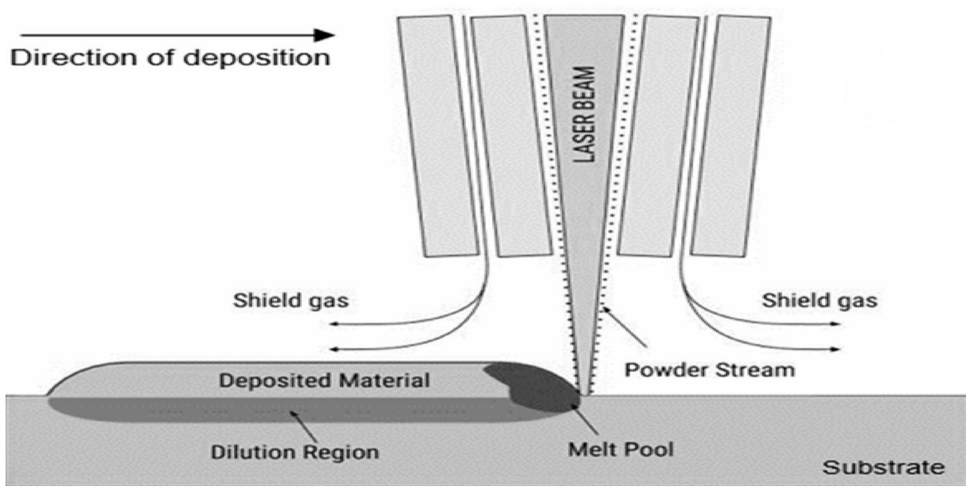


Fig. 8 schematic figure directed energy deposition with powder [29]

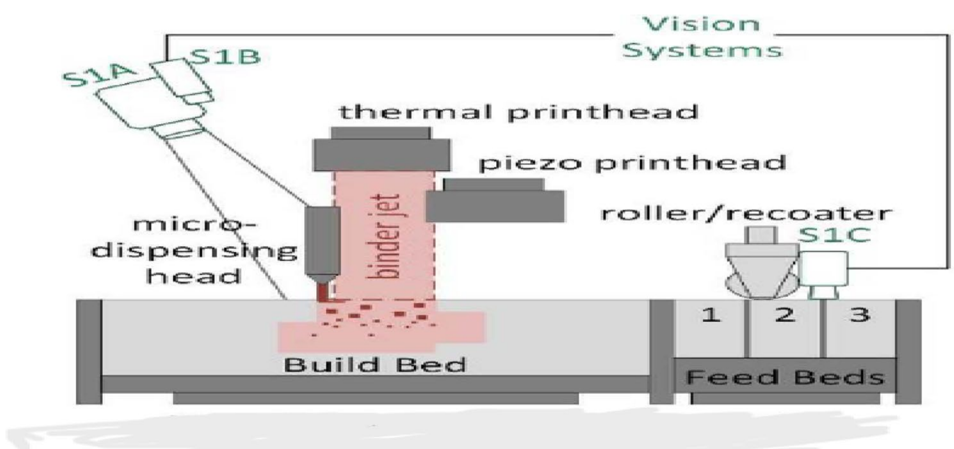


Fig. 9 schematic figure of binder jetting [33]

in contrast to PBF processes [28]. DED supports both powder and wire feedstock, with wire being more cost-effective. While it excels in high deposition rates and industrial applications like aerospace and power generation, it faces challenges with complex geometries and surface finish. Key variants include Laser DED (high-speed but lower accuracy), Electron Beam DED (vacuum-based, ideal for reactive metals), Wire Arc Additive Manufacturing (WAAM, cost-efficient), Cold Spray (solid-state deposition), and Molten DED (liquid metal deposition). Each method offers unique advantages in material compatibility, speed, and post-processing requirements (Fig. 8).

Binder jetting

Is an additive manufacturing process that uses a liquid binder to selectively bond powdered materials, such as metal, plastic, ceramic, or sand, layer by layer [30]. The process involves spreading thin powder layers and depositing binder via inkjet print heads, with unused powder being recycled. Binder Jetting (BJ) was developed in 1993 at MIT [31]. Post-processing varies by material, including sintering for metals, curing for plastics, and direct use for sand moulds. Metal Binder Jetting produces high-strength, complex parts with smooth surfaces, suitable for medical and industrial applications [32]. Plastic Binder Jetting employs polymer powders, sometimes with heat fusion, for enhanced part strength. Sand Binder Jetting rapidly creates intricate casting moulds at low cost, benefiting foundries with complex geometries. The technology enables efficient, scalable production across diverse industries (Fig. 9).

Sheet lamination

Is an additive manufacturing technique that builds 3D objects by stacking and bonding thin material sheets, such as paper, polymers, or metals, using heat or ultrasonic waves [34]. The layered sheets are precisely cut into shape using lasers, knives, or CNC routers. While this method enables rapid, low-cost production of prototypes and composite parts, it generates significant waste compared to other 3D printing technologies. Common variants include Laminated Object Manufacturing (LOM) and Ultrasonic Consolidation (UC). LOM is recognized as a recent technological advancement,

Table 1 Benefits, limitations, and uses of 3D printing technologies

Technology category	Advantages	Challenges	Applications
Material extrusion (MEX)	Most cost-effective method & its Wide range of materials (plastics, metals, food, concrete, bio-inks), Reduced labour costs & waste (Construction)	Lower strength compared to other methods, Lower accuracy (±0.5% or ±0.5 mm), Post-processing needed for metal FDM	Prototypes, jigs, fixtures, Hobbyist to industrial parts (FDM), Houses, infrastructure (Construction),Tissue engineering, drug testing, medical research (Bio-printing)
Vat polymerization	High dimensional accuracy (up to ±0.5%),Smooth surface finishes, Fine feature details, Faster than SLA (DLP/LCD) Affordable options (LCD)	Requires cleaning and post-curing, Limited to photopolymer resins (though variants exist)	Jewellery, Dental applications (moulds, guides), Industrial prototypes, Highly detailed models
Material jetting (M-Jet)	Multi-material & full-colour capability, High dimensional accuracy (±0.1 mm),Smooth surface finish, No post-curing (M-Jet sub-type), Dissolvable supports allow complex geometries, High precision (NPJ)	Limited material strength (photopolymers/wax), Costlier than other resin methods Requires sintering (NPJ)	Detailed, realistic prototypes, Medical models, Accurate prototyping (automotive, healthcare), High-precision metal/ceramic parts (NPJ)
Powder bed fusion (PBF)	High-strength, durable parts, Excellent mechanical properties, Creates complex geometries (powder supports part, No mandatory post-processing (SLS), Good for conductive/reactive metals (EBM)	High machine and material costs, Slower build rates, Requires post-processing (LPBF, EBM), Requires controlled environments (LPBF, EBM)	Functional components, Low-run production parts, Aerospace, medical, industrial parts (LPBF), Ducting, Parts from Nylon, TPU (SLS)
Directed energy deposition (DED)	Repair or enhance existing metal parts, High build-up rates, Cost-efficient (especially wire-based like WAAM, Good for large structures, Uses powder or wire, Minimal thermal stress (Cold Spray)	Struggles with complex geometries, Lower accuracy & surface finish quality, Often requires post-machining, Requires vacuum/inert gas (some types)	Repairing/adding features to metal parts, Aerospace components (airframes), Power generation (turbine blades), Offshore industry applications, Large-scale metal printing
Binder jetting	Works with various powders (metal, sand, ceramic, plastic),Relatively fast, Lower cost (especially sand), Good for complex geometries, Scalable for volume production (Metal BJ)	Parts are initially fragile ('green state'), Requires significant post-processing (sintering, infiltration, curing), Potential porosity (metal)	Sand casting moulds and cores (foundries), Complex, lightweight metal parts (volume production, medical), Plastic functional parts, Ceramic components
Sheet lamination	Fast production speed, Cost-effective (for certain uses), Multi-material capability (layered), Uses sheet materials (paper, plastic, metal)	Generates significant waste, Lower accuracy, Requires post-processing (excess removal), Less common/often superseded, Primarily for non-functional parts	Non-functional prototypes, Visual models, Composite items (layered materials)

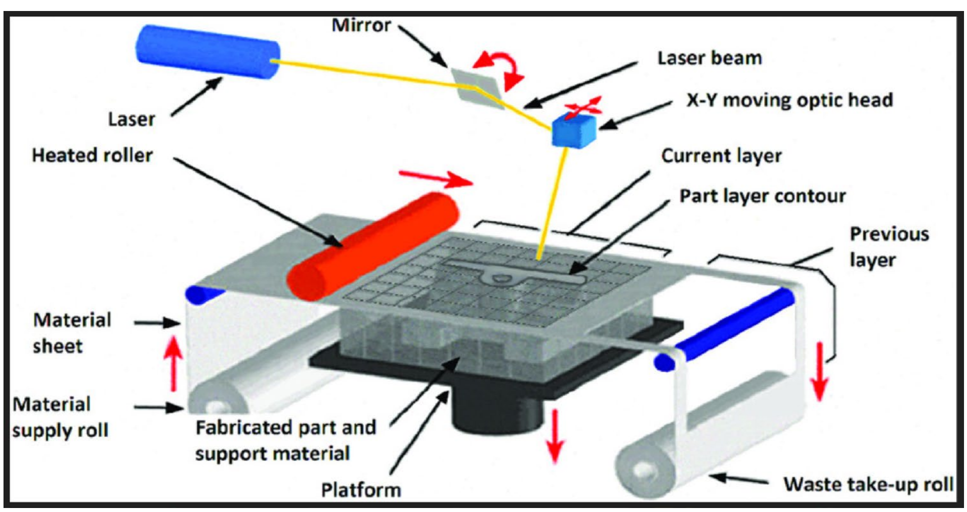


Fig. 10 Schematic figure sheet lamination 3D printing [35]

often referred to as the "Fourth Industrial Revolution" (Industry 4.0) [32]. Despite advantages like multi-material compatibility and quick production, sheet lamination suffers from lower accuracy and often requires post-processing. Due to advancements in alternative 3D printing methods, it has become less prevalent today. Nonetheless, it remains relevant for specific applications requiring simplicity and cost-efficiency (Table 1; Fig. 10).

Large-scale 3D printing used in construction Industry.

In recent years, large-scale additive manufacturing (AM) has advanced to meet the demands of architecture and construction. These printing processes, varying in deposition techniques and construction methods, primarily encompass three types that enable automated construction.

Contour crafting (cc)

Contour Crafting, a 3D printing technology for construction, is under development by Behrokh Khoshnevis at the University of Southern California's Information Science Institute. In 2010, Khoshnevis noted that NASA was exploring its potential for building bases on the Moon and Mars [36]. In 2013, NASA provided funding for a small study at the university to advance the Contour Crafting technique. Contour Crafting is an additive manufacturing technique that leverages computer-controlled towelling to produce precise, smooth planar and free-form surfaces [37].It is a large-scale, computer-controlled construction technique that utilizes trowelling to produce smooth, precise planar and freeform surfaces. It provides enhanced surface quality, faster construction speeds, and a broader selection of usable materials [38] (Fig. 11).

D- shape

It is a process similar to the inkjet powder bed technique, where a binder is precisely applied to the printing material [5]. Initially, D-Shape technology focused on the factory production of intricate structural components. Current studies are investigating the feasibility of using this technology directly on-site, employing materials found locally, such as sand, along with necessary binding agents [40]. After the printing process finishes, the object is extracted from the loose powder bed [10]. The "Organic Villa" concept by D-Shape envisions a future where advanced additive manufacturing creates complex, sustainable, and unique homes. This is epitomized by Andrea Morgante's Radiolaria urban temple in Pontedera, Pisa, which blends ancient ribbed stone vaulting with 3D printing to form an organic, open-cell structure. More than an architectural feat, Radiolaria functions as a vibrant social hub, reinventing temple architecture as a dynamic communal space [41] (Fig. 12).

Concrete printing

3D concrete printing, encompassing extrusion-based methods like Contour Crafting, uses robotic arms to layer cementitious materials, pioneered by Joseph Pegna in 1997. It offers up to 80% cost savings, 40% less material use, and enables complex, sustainable designs. This printing method eliminates the need for labour-intensive formwork and can

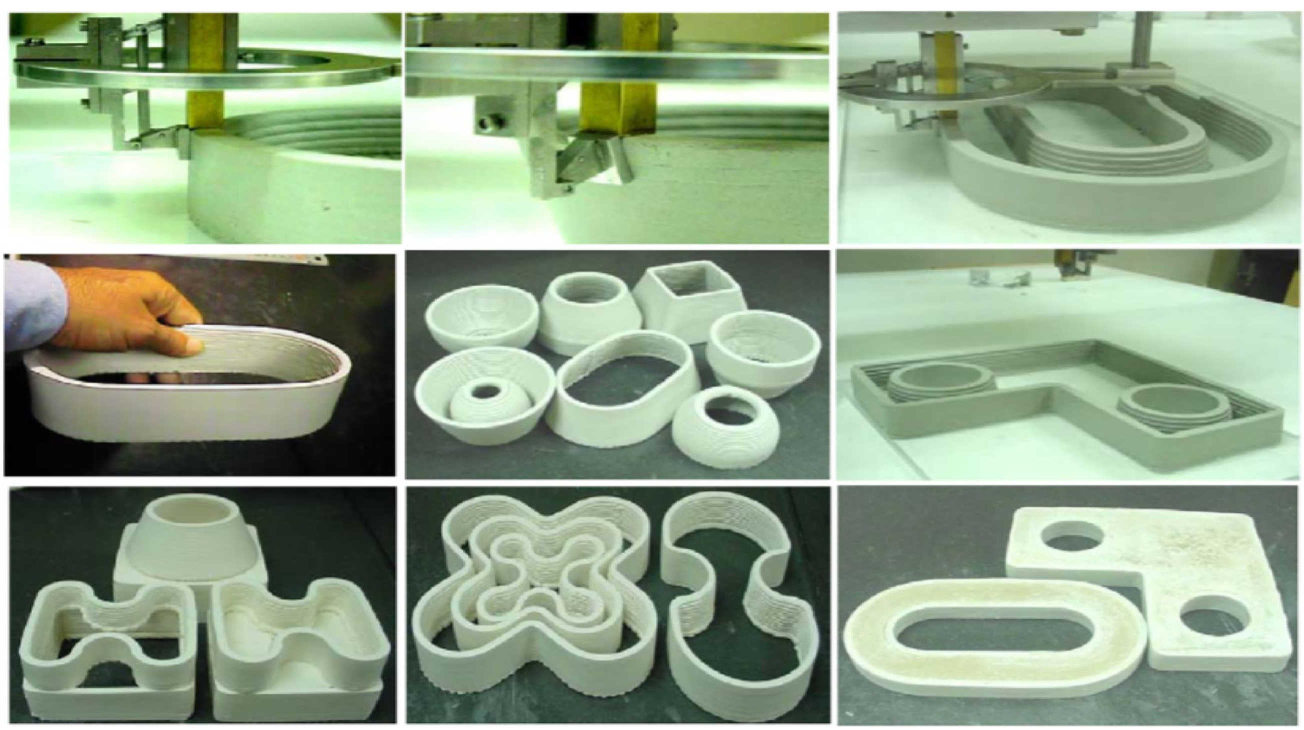


Fig. 11 Techniques of contour crafting [39]

Fig. 12 D- Shape construction (i). the radiolaria pavilion [42] (ii). Organic villa [43]

(i) (ii)

Table 2 Aspects of contour crafting, D-Shape and concrete 3D printing

Aspect	Contour crafting	D-Shape	Concrete 3D printing (General)
Technology	Extrusion-based, layered concrete deposition	Powder-bed, binder-jetting	Primarily extrusion-based, varies by system
Materials	Quick-setting concrete, advanced mixes	Sand, magnesium oxide, binders	Specialized concrete mixes, some with additives
Speed	Very fast (e.g., house in 20 h)	Slower, factory-based	Varies (e.g., 24 h for small houses)
Geometric Freedom	High, but limited by nozzle and layer stacking	Very high, supports overhangs	High, depends on printer and nozzle design
Applications	Housing, disaster relief, lunar bases	Sculptures, prototypes, lunar infrastructure	Housing, infrastructure, decorative elements
Commercial status	Active, with partnerships (e.g., QUIKRETE)	Inactive since ~ 2015	Growing, with multiple active companies
Portability	Highly portable (e.g., D-Crafter)	Factory-based, less portable	Varies (mobile printers like Apis Cor exist)

Fig. 13 3D Concrete printing [45]

integrate functional voids directly into the structure [10]. Applications include precast components, bridges, and full buildings, like ICON's Texas community. Challenges include material clogging due to premature setting or poor fluidity [12]. However, the process was developed without using the trowels typical in contour crafting, thereby requiring a finer deposition resolution to achieve higher levels of three-dimensional flexibility.This finer print resolution has enabled improved control over both internal and external geometries [44] (Table 2; Figs. 13, 14).

Different types of 3D printing in construction

Gantry-based 3D printers offer high precision and large build volumes for construction and industrial parts but are bulky and less mobile. Cable-driven printers provide scalability and portability for large workspaces, with moderate accuracy and complex control. Robotic printers excel in flexibility for complex, non-planar designs but face precision challenges at scale and require advanced programming. Each system suits different needs: gantry for precision, cable-driven for portability, and robotic for versatility (Fig. 15).

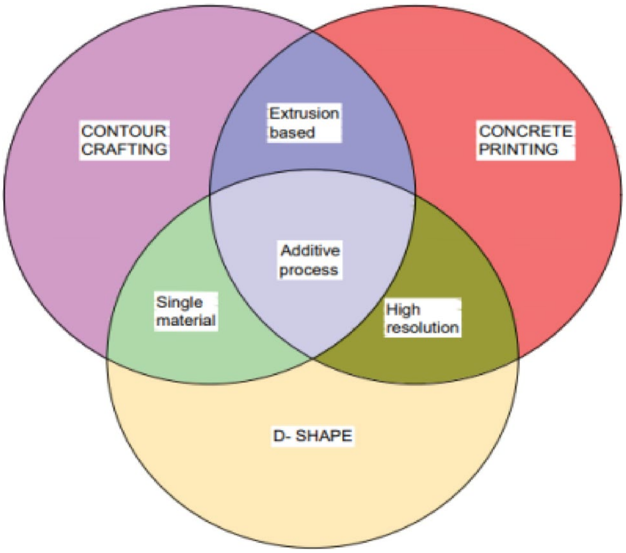


Fig. 14 3DP processes [10]

Gantry-based 3D printing systems

Employ various motion control configurations, each with distinct advantages and limitations. The *Cartesian-XY-Head* system offers simplicity and precision but suffers from vibration at high speeds. They offer extra roll, pitch, and yaw controls for the end effectors (print nozzle), enabling more precise and complex print designs, like printing with the tangential continuity technique [46]. The *Ultimaker-style* crossed gantry enhances stability with synchronized motion but requires complex calibration [47]. *Core-XY* reduces moving mass for higher acceleration but demands precise belt tensioning. The *i3-style Cartesian-XZ-Head* is cost-effective for hobbyists but struggles with stiffness and bed levelling. Meanwhile, the H-bot system enables high-speed printing with reduced inertia but is maintenance-intensive. While designs like V-rails and linear rails improve precision, trade-offs exist in speed, complexity, and calibration. Selecting the optimal gantry system depends on balancing performance, ease of use, and application requirements (Table 3).

Robotic arm-based 3D

Printing offers versatile solutions for construction, ranging from mobile to large-scale stationary systems. Compared to gantry printers, the robotic arm system is a newer technology that enables more precise and detailed object printing through the tangential continuity method [48]. The CyBe RC (Robot Crawler) is a mobile 3D printer with hydraulic feet for stability, enabling on-site and precast concrete printing on uneven terrain. The CyBe RT (Robot Track) is a track-based system for prefab home production, scalable with extendable tracks for larger prints. The CyBe RT is a stationary, cost-effective printer for research, prototyping, and small-scale manufacturing. For industrial-scale modular construction, the CyBe GR (Gantry Robot) utilizes PPVC methods to produce fully finished 3D modules, cutting costs by up to 50%. These systems enhance precision, efficiency, and flexibility in concrete 3D printing for diverse applications (Table 4).

Cables driven parallel 3D printing

The CDPP utilizes FDM technology, with the print head possessing translational movement along the X, Y, and Z axes. These three degrees of freedom are essential for 3D printing. CDPRs combine the high speed and load capacity of parallel mechanisms with the benefits of cable-driven systems, including reduced weight, easy reconfiguration [49], and excellent repeatability and motion resolution [50].

Fig. 15 Classification of different types of 3D printing used in construction industry

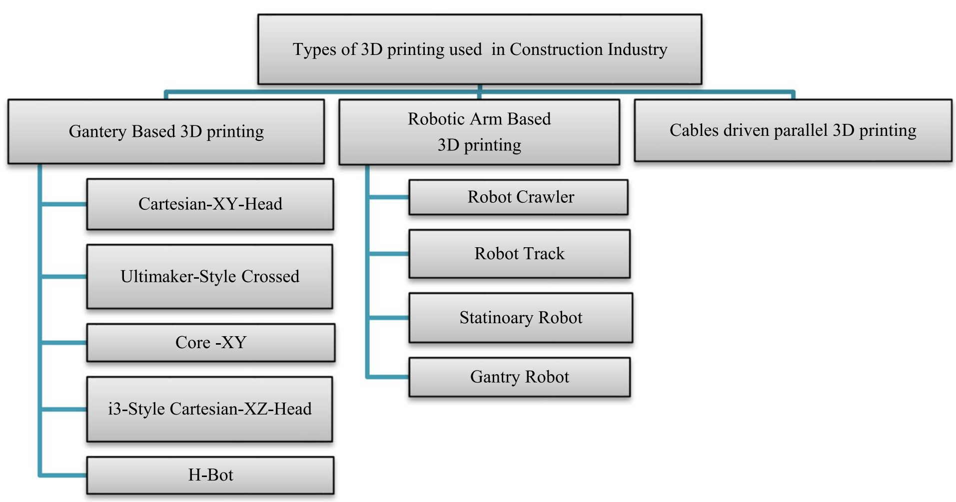


Table 3 Advantages, applications/suitability, and challenges of gantry system

Gantry system	Advantages	Applications/Suitability	Challenges
Cartesian-XY-Head	Good precision, Good repeatability, Simple to construct, Simple to operate, Fixed print bed	General purpose, where simplicity is valued	Vibration issues at high acceleration (due to moving gantry mass), Limitations in speed, Limitations in acceleration, Limitations in stiffness
Ultimaker-Style Crossed	Stability (parallel gantries, fixed bed), Smooth movement, Improved print quality, Precision, Reduced sudden directional changes	Applications requiring high stability and print quality	Complex design, Requires careful calibration, Requires careful alignment, Limited print bed access during printing
CoreXY	Reduced moving mass, Higher acceleration, Precise movements, Improved print quality, Faster motion, Stationary motors	Popular among advanced users; applications where speed and precision are key	Requires careful belt tensioning, Requires careful calibration, More complex to set up
i3-Style Cartesian-XZ-Head	Simple design, Cost-effective, Good accuracy (especially for smaller prints)	Ideal for hobbyists; suitable for smaller prints	Low stiffness, High inertia (limits speed/acceleration, Challenges in bed levelling, Challenges in consistent layer thickness, Moving bed can impact tall prints
H-Bot	Increased stability, Reduced inertia, Higher accelerations, Better print quality, Stationary motors, Capable of high-speed, high-quality prints (when maintained)	High-speed, high-quality printing (requires user commitment to maintenance)	Complex to set up, Challenging to calibrate, Requires frequent maintenance (belt slack), Belt slack issues can affect precision

Table 4 Advantages and applications of robotic type

Robot type	Advantages	Application
CyBe RC (Crawler)	Mobile, Stable (hydraulic feet), Extended range (hydraulic feet), Creates intricate shapes/textures (rotating nozzle), Suitable for complex tasks	On-site printing, Factory precast printing, Complex concrete printing tasks
CyBe RT (Track)	Stationary & Stable (track-based), Extendable track (for larger elements), Creates larger elements in fewer pieces	Precast factories (producing prefab homes) Institutes/Companies (sequential printing, design testing)
CyBe R (Stationary)	Stationary & Stable, Economical entry-level option, Supports innovation & unique designs	Off-site, facility-based printing, Research, Testing, Prototyping, Precast production, Small-scale manufacturing
CyBe GR (Gantry)	Large-scale, Precise Uses PPVC method, Produces complete 3D modules (with internal finishes), Reduces construction costs (up to 50%)	Factory setting modular apartment construction (using PPVC method)

Materials used in 3D construction printing

3D construction printing uses specialized materials designed to work seamlessly with printing technology. These materials are essential for ensuring structural integrity, durability, and high construction quality. Their composition and properties are tailored to meet the unique demands of the printing process. Commonly used materials include various types of concrete, mortar, and composite mixes. Each material offers specific advantages depending on the project requirements, contributing to the efficiency and sustainability of 3D-printed structures.

Metals and metal alloy

Metal 3D printing, or additive manufacturing (AM), is no longer just for research and prototypes; it's now used for advanced applications like smart bridges. These methods typically use high heat sources like electron beams or lasers to melt metal powders or wires. While Directed Energy Deposition (DED) and Powder Bed Fusion (PBF) are common, newer techniques like friction stir welding and binder jetting are also emerging. Popular metals include stainless steel, aluminium, and titanium, with specialized uses like nickel-base alloys in aerospace due to their extreme heat and corrosion resistance. Notably, PBF-printed metal parts often boast superior resolution and enhanced properties compared to traditionally made components [51, 52].

3D Printable concrete

3D printable concrete is a specialized material designed for construction 3D printing. It typically includes cement, aggregates like sand or gravel, water, and various additives. Engineered for optimal viscosity, flow ability, and setting time, it ensures smooth extrusion through the printer's nozzle. Once cured, it provides strong and durable structural properties, The printability of 3D-printed concrete relies heavily on its workability and mechanical properties, which can be enhanced through careful material selection (e.g., different fibres, admixtures, and high-quality sand) and optimization of printing parameters (e.g., rest time, nozzle speed, and nozzle standoff distance) [53]. Printing parameters like speed, nozzle size, standoff distance, and temperature must be precisely defined and controlled, as they influence the rheology and post-print performance of concrete elements [54].

Fibre-reinforced concrete

The incorporation of fibre reinforcement in printed concrete elements is increasingly recognized for enhancing ductility, tensile strength, deflection resistance, and fracture energy [55]. Various fibers are employed in 3D-printed concrete (3DPC) construction, including polyethylene microfibers [56], polypropylene fibers, polyvinyl alcohol fibers, carbon, glass, and basalt fibers, and steel fibers. Fibre-reinforced concrete incorporates steel or synthetic fibres to enhance strength and crack resistance. This results in improved tensile strength and ductility, making it ideal for structural elements under bending or tensile forces. Incorporating fibres into the concrete mix prior to printing ensures a more uniform distribution. This pre-mixing method improves the concrete's mechanical properties, including tensile strength, toughness, and crack resistance.

Geo-polymer concrete

In 1978, French Professor Davidovits coined the term "geopolymer" to describe a wide range of materials defined by their inorganic molecular networks [57]. Geo-polymer concrete is an eco-friendly alternative to traditional Portland cement-based concrete, using alkali-activated materials like fly ash or slag as binders. Using geo-polymer binders, such as fly ash and slag, instead of Portland cement in 3D printed concrete can greatly enhance sustainability by reducing carbon dioxide emissions. This approach can lower embodied carbon by 58.97–80.65% compared to certain printable cementitious mixtures [58]. Its sustainability and durability make it a suitable choice for 3D construction printing, contributing to greener and more resilient structures.

Ceramic

Ceramic 3D printing is highly sought after in biomaterial fabrication and tissue engineering, particularly for creating scaffolds for repairing teeth and bones. These materials are valued for their strength, durability, and heat resistance, along with their ability to be shaped effectively. Despite challenges like lower printing resolution and the need for costly post-processing, research shows that optimizing ceramic properties allows for printing complex, high-performance structures like honeycombs with improved accuracy and crack control [59].

Advanced additives and admixtures

Chemical additives and admixtures are often added to construction materials to enhance workability, adjust setting time, and improve overall properties. These additives can modify the material's Rheology, reduce water content, and strengthen the bonding between layers. Additionally, they optimize curing processes, ensuring the concrete's durability and structural integrity. Their application allows for precise control over 3D printable concrete's performance, leading to reliable and efficient construction.

Soil-based material

The future of construction is increasingly focused on economic viability and environmental sustainability, making material choices critical. Among these, earth or soil-based materials stand out as the most sustainable and eco-friendly option. These materials have a rich history, used for thousands of years with many ancient soil structures still standing globally. Recent decades have seen the development of various building codes for earth-based construction, facilitating large-scale 3D printed adobe structures using local clayey soil and sand blends, exemplifying their natural consistency [60]. The "Beacon" project is a prime example of successful 3D printed soil construction (Fig. 16).

Other specialized materials

Specialized materials like polymer-based or composite materials are often used in 3D construction printing based on project needs. These materials provide unique properties such as lightweight structures and enhanced insulation. Their application enables greater customization and promotes innovation in construction, offering tailored solutions for specific requirements (Table 5).

Material rheology and printing process parameters in 3D concrete printing

Rheological characteristics in 3d concrete printing (3dcp)

The key rheological parameters influencing 3D Concrete Printing (3DCP) materials are yield stress, viscosity, and thixotropy.

Yield stress (τ_0) represents the minimum shear stress required for the material to begin flowing. When the applied

Fig. 16 The Beacon is a structure crafted from 3D printed clay [61]

Table 5 Function of materials used in 3D printing [62]

Material categories	What it's made of	How it is printed	What is it used for
Metals & Metal alloys	Metal powders or wires like steel, titanium, platinum, silver, and aluminium	Melting/fusing techniques such as Selective Laser Melting (SLM), Laser Beam Melting (LBM), and Directed Energy Deposition (DED); also extrusion and binder jetting	Creating strong, durable parts for aerospace (like satellite brackets), medical implants (surgical implants, dental crowns), jewellry, bridges, machine parts, and prototypes
Polymers & Composites	Various forms of plastics and reinforced materials: powders, liquids, sheets, filaments, tapes, or pellets (e.g., ABS, PLA, carbon fiber)	Common methods include extruding melted plastic (FDM), solidifying liquid resins with light (SLA), material jetting, powder bed fusion (SLS), and sheet lamination	Widely used for prototypes, educational tools, automotive parts, specialized clothing, and medical devices like hearing aids and low-cost prosthetics
Ceramics	Silicon carbide, porcelain, silica, glass, and ceramic fibers	Techniques like photo polymerization, binder jetting, extrusion, and direct ink writing, often followed by high-temperature sintering	Making medical implants (artificial bones/teeth), craft items, electrical components (conductors/insulators), car parts, and lightweight armour
3D printable concrete	A mix of cement, aggregates, plasticizer, and water	Primarily extrusion (contour crafting) and selective binder jetting	Used in construction for quickly building prototypes, tiny homes, apartments, and bridges
Soil-based materials	Earth-based substances such as red clay with straw, or stabilized soil	Extrusion and binder jetting, sometimes with hydro gel stabilizers	Ideal for constructing low-cost houses, adobe structures, and for repairing degraded soil

stress is below this threshold, the material behaves like a solid; once the yield stress is exceeded, it transitions into a flowing state.

Viscosity (η) refers to the internal resistance between adjacent fluid layers moving relative to one another. In simple terms, higher viscosity indicates greater resistance to flow, resulting in reduced material flowability.

Concrete, being a heterogeneous composite consisting of cement, water, admixtures, and aggregates, undergoes complex physical and chemical interactions. Over time, cement particles tend to flocculate (cluster together) when the material is at rest, forming a structural network. Consequently, both yield stress and viscosity increase with time. The structural build-up rate quantifies this time-dependent rise in yield stress. Conversely, when shear or mixing is applied, deflocculation occurs, dispersing cement particles and lowering the yield stress and viscosity. This reversible, time-dependent change in flow behavior is known as thixotropy [63–65].

These three rheological properties—yield stress, viscosity, and thixotropy—are crucial in determining the pumpability, extrudability, and buildability of 3DCP mixtures. Depending on the specific stage of the printing process, one or more of these parameters may dominate, making it essential to identify which parameter most significantly influences each phase.

Extrusion and pumping

In the initial phase of 3D Concrete Printing (3DCP), the freshly mixed material is transported through hoses or pipelines directly to the nozzle or an intermediate mixing unit [65]. During this pumping stage, it is essential that the material flows smoothly without clogging the pump or pipeline system. Among various devices, progressive cavity pumps are most commonly employed for transferring material in 3DCP. Research indicates that viscosity is the most critical parameter influencing pumpability [66, 67]. However, for mixes with high yield stress, the yield stress-to-viscosity ratio becomes an important governing factor. In conventional or self-compacting concretes, the formation of a lubrication layer (LL) along the inner surface of pipes or hoses enhances pumpability and reduces pumping pressure [68]. Two primary flow regimes are generally observed in concrete pumping (1) Slip flow with an unsheared bulk core, and (2) Combined shear and slip flow, where partial shearing occurs in conjunction with slip flow [69].

Therefore, it is vital to evaluate the viscosity and yield stress both in the lubrication layer and in the bulk material. When viscosity or yield stress is too high, the material's pumpability decreases. To improve flow, these parameters should be minimized; however, they cannot be reduced excessively in 3DCP because the printed material must still retain sufficient buildability to support subsequent layers. Thus, selecting optimal rheological parameters is crucial to balance pumpability, extrudability, and structural stability during layer-by-layer construction. In practice, highly thixotropic materials are often used in 3DCP (particularly when accelerators are not introduced near the nozzle). During pumping and extrusion, the material experiences high shear rates due to increased pumping pressures, flow velocities, and the rotational motion of pump screws or extruder devices. Under these conditions, viscosity temporarily decreases, allowing smooth flow. Once extruded, the material becomes nearly static—shear rates drop, viscosity rises, and yield stress increases due to structural build-up, resulting in enhanced early-age strength of deposited layers. Moreover, the structural build-up rate significantly influences the process. Studies have shown that even short interruptions (around 20 minutes) in pumping can cause blockages if the thixotropic build-up rate is about 0.3 Pa s^{-1} [70]. Hence, monitoring this parameter is crucial to define acceptable pause durations during pumping and extrusion. The extrusion process requires similar rheological characteristics as pumping but is also affected by nozzle diameter, geometry, extrusion speed, and type of extruder [71]. Generally, larger nozzles improve extrudability by reducing aggregate blocking, while longer die lengths tend to reduce flow efficiency [72]. In this context, the focus remains on rheological and material parameters, as detailed analysis of geometrical factors is beyond the scope of this discussion.

Buildability

After pumping and extrusion, 3D Concrete Printing (3DCP) proceeds with layer-by-layer construction, where each layer must have sufficient strength and stiffness to support the subsequent ones. Two major failure types can occur Strength-Based Failure—Happens when stresses from the upper layers exceed the material's strength. Various models, such as the Drucker–Prager [73], rheology-based, and Mohr–Coulomb criteria, have been used to predict this. Studies show that Mohr–Coulomb models provide more accurate predictions since they account for frictional effects, while rheology-based models often underestimate failure height. Stability (Buckling) Failure—Common in tall, slender printed structures due to geometric imperfections or eccentric layer placement. Finite element and parametric models have been developed (e.g., by Wolfs and Suiker) [74] to predict buckling, considering time-dependent material properties and print conditions. The critical transition height (H_t) marks the point between strength-dominated and buckling-dominated failure [75]. Below this height, plastic collapse occurs; above it, buckling prevails. Because 3D printable concretes exhibit highly time-dependent rheological behavior, accurately determining their rheological and elastic parameters is vital for ensuring pumpability, extrudability, and buildability. Therefore, appropriate rheological models and testing methods must be selected for reliable material characterization.

Rheological modelling and time-dependent flow behaviour in 3d concrete printing

The flow behaviour of concrete, particularly in 3D Concrete Printing (3DCP), is primarily described using rheological models that define the relationship between shear stress and shear rate, with the Bingham model ($\tau=\tau_0+\mu\dot{\gamma}$) being the simplest, characterized by a yield stress (τ_0) and plastic viscosity (μ). However, because concrete is typically a shear-thinning fluid (viscosity decreases with shear rate), the Herschel–Bulkley model [76] ($\tau=\tau_0+K\dot{\gamma}n$, with $n<1$) is more commonly used to accurately capture this non-Newtonian behaviour. In 3DCP applications, the time-dependent evolution of these properties is crucial; specifically, the yield stress increases with age, a process modelled either linearly (Roussel Model) [77] or with a transition from linear to exponential increase (Perrot Model). While viscosity is also time-dependent (e.g., Papo model), this change is often ignored in practical 3DCP measurements since the most critical material behaviour occurs within the first few minutes, before significant viscosity changes take place.

Discussion on the effect of printing parameters

Printing factors including layer deposition time, nozzle size, and print speed have a significant impact on the performance of 3D-printed concrete structures, including interlayer adhesion and structural stability. Optimization of these parameters is critical for maintaining print quality and structural dependability, as evidenced by experimental and computational investigations [78, 79].

Figure 15 depicts the correlations between essential printing settings, intermediate interfacial effects, and final structural performance. This conceptual diagram depicts the exterior ring displays critical process parameters, such as layer deposition time, print speed, nozzle size, height, and layer thickness. These factors impact key processes, including interlayer bonding strength, compaction, adhesion, and interface porosity, affecting the structural integrity and mechanical performance of printed concrete.

The gap between subsequent layers, or layer deposition time, has a major influence on interlayer bond strength. Prolonged intervals can weaken interlayer adhesion and bonding strength, causing structural weakness at layer interfaces. Optimized deposition intervals can improve mechanical integrity and reduce anisotropic behaviour in printed structures [80].

Print speed impacts the quality and structural performance of printed structures. High printing rates can weaken interlayer bonding due to insufficient compaction and adhesion between layers, resulting in decreased structural integrity. Printing at modest rates improves rheological control, interfacial bonding, stability, and geometric precision [81].

The nozzle diameter plays a crucial role in determining the filament geometry and the interlayer bonding area. Using a larger nozzle typically improves buildability by producing wider and thicker filaments, which enhances the overall structural stability [82]. In contrast, smaller nozzle diameters promote better fiber alignment in fiber-reinforced concrete, leading to improved tensile and flexural strength due to more effective fiber orientation along the printing path. Hence, choosing an appropriate nozzle size requires a careful balance between achieving sufficient buildability and optimizing mechanical performance.

The standoff distance, or nozzle height, is another crucial parameter influencing interlayer adhesion. When the standoff distance is too large, the compaction pressure from the nozzle decreases, leading to weak interlayer bonding and higher porosity at the interfaces. In contrast, maintaining a suitably reduced nozzle height promotes better filament interpenetration and densification at the interface, thereby enhancing overall structural integrity and minimizing interfacial defects [83].

Recent advancements in nozzle design—such as the inclusion of interface-shaping features and side trowels—further improve interlayer bonding by optimizing the filament geometry and reducing defects [84]. These innovative nozzles help minimize stress concentrations caused by notches and increase interlayer shear strength (Tables 6, 7).

Overall, parameters such as nozzle height, filament geometry, and compaction pressure collectively influence interfacial bonding and global structural performance. As

Table 6 Significance of printing process parameters

Category	Parameter	Significance
Printing setup Parameters	Nozzle size	Diameter of the nozzle opening; affects extrusion rate, print precision, and filament overlap
	Nozzle height	Vertical distance between the nozzle tip and the previous layer; crucial for interlayer bonding and surface smoothness
	Layer thickness	Height of each deposited layer; influences print resolution, build time, and overall structural quality
Process parameters	Print speed	Movement speed of the nozzle during extrusion; affects material flow consistency and dimensional accuracy
	Layer deposition time	Time required to complete a single layer; impacts layer bonding, curing, and temperature gradients
Material interaction parameters	Compaction	Degree of material densification during deposition; influences strength and void reduction
	Adhesion	Bonding strength between adjacent layers; determines mechanical integrity and durability of the printed structure
	Interface porosity	Presence of voids or gaps between layers; affects overall density, permeability, and structural performance

Table 7 Printing setup parameters in 3dpc [85]

Study/Research	Nozzle geometry	Nozzle dimension (mm)	Extrusion/ Flow rate	Printing speed (mm/s)	Layer thickness (mm)	Key findings
Rahul et al. [86]	Rectangular	30 × 20	1.6 L/min	44	20	Utilized a rectangular nozzle for improved print stability and interlayer bonding
Paul et al. [87]	Rectangular	10 × 20	3 L/min	150	–	Achieved higher deposition rates through increased printing speed and flow rate
Panda et al. [88]	Circular	10	0.5 L/min	80	–	Demonstrated uniform filament extrusion suitable for small-scale structures
Le et al. [1]	Circular	9	–	–	6	Focused on layer bonding performance with fine nozzle control
Asprone et al. [89]	Circular	25	–	20	20	Used a larger circular nozzle for printing structural-scale elements
Kazemian et al. [90]	Slice-type	–	–	60	25.4–38.1	Examined wide-layer deposition using variable nozzle heights
Dong et al. [85]	Circular	10–40	–	15–45	–	Investigated fiber alignment in UHPC under varying nozzle diameters and print speeds
Nan Zhang et al. [91]	Conical/ Customized Circular	Variable (cone angle and length modified)	96–288 mm/s (internal flow rate)	50–200	5–40	Analyzed how nozzle geometry influences flow resistance and print quality
Mazhoud et al. [92]	Circular	55	–	16	10	Optimized nozzle structure and speed for underwater extrusion conditions

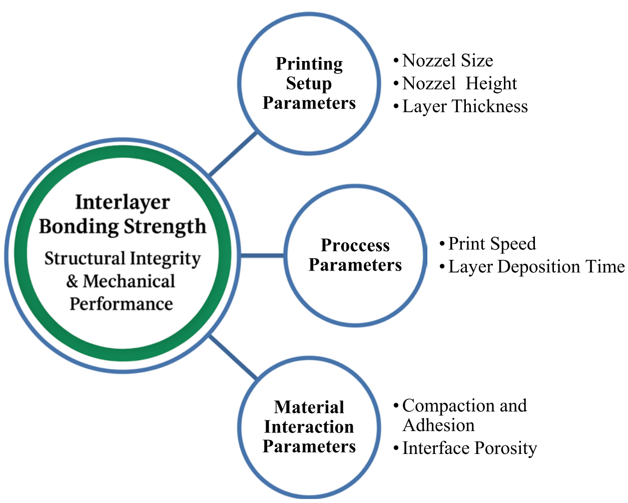


Fig. 17 Influence of critical 3D printing process parameters on structural performance [93]

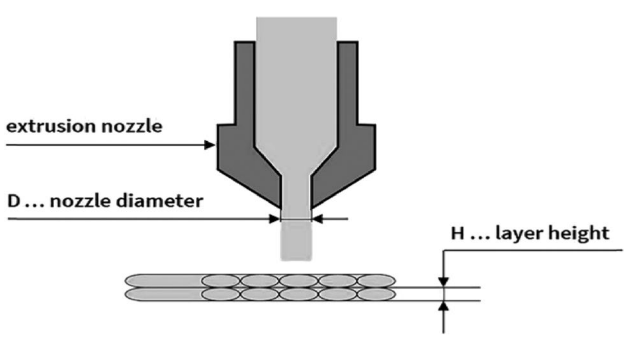


Fig. 18 Printing setup parameters [94]

depicted in Fig. 15, the coordinated control of these printing parameters is essential for achieving uniform interface quality, high structural integrity, and consistent mechanical performance in 3D-printed concrete. Therefore, systematic optimization through rheological and mechanical assessments is fundamental to ensuring reliable printing and superior build quality (Figs. 17, 18).

Software's used in 3D printing

Several key software tools integral to the modern 3D design, modelling, and printing workflow. It covers a spectrum of Computer-Aided Design (CAD) platforms [8], ranging from professional-grade solutions like Autodesk's Fusion 360 (a cloud-based, integrated CAD/CAE/CAM platform), Dassault Systèmes' SOLIDWORKS (a long-established, parametric, feature-based tool strong in solid modelling and PDM), and On-shape (a fully cloud-based CAD system emphasizing real-time collaboration) to the versatile SIMPLY 3D (offering comprehensive modelling, advanced rendering, and simulation capabilities) [95]. For beginners and educators, Autodesk's Tinker CAD offers a user-friendly, web-based introduction to 3D modelling with simplified tools.

Beyond initial design, the document details essential software for the 3D printing process itself. Slic3r, a widely adopted open-source slicing software, is highlighted for its role in converting digital 3D models into printable G-code instructions, offering extensive customization and efficient

Table 8 Software for designing or making 3D models [95]

Software name	Function	Advantages	Disadvantages
Free CAD	Creating and modifying 3D models	Free to use; can import models from other design software; has a large database; user-friendly interface	Requires knowledge of Python programming
Autodesk AutoCAD	Building precise 3D models with design visualization	Includes a built-in module for printing; supports 3D models, raster, and vector graphics; enables teamwork; offers visualization	It is a paid software package
Autodesk fusion 360	Parametric modelling, designing assemblies, 3D print ready	Offers modelling and analysis tools; integrates diverse tools and workflows into one platform; cloud-based for easy team collaboration and data sharing	The interface and features can be difficult to master; needs a powerful computer to run well
Paint 3D	Standard Windows 10 tool for creating basic 3D models	Simple to use; quick to learn; easy to operate; readily available	It is limited to basic shapes and lacks advanced tools, making it unsuitable for professional or complex 3D modelling tasks
Z-Brush	Primarily used for artistic modelling of 3D objects	A strong foundation for making 3D models with accurate visualization	Highly specialized; complex to use and learn
COMPASS-3D	Versatile software for 3D models, objects, and 2D drawings	Allows for quick Computer-Aided (CA) design; easy to operate and learn; has a user-friendly interface	Resulting models have a somewhat low level of detail
Slicers			
Cura	A straightforward and intuitive slicer	Estimates printing time and material weight; shows a layer-by-layer print preview; can create custom support designs	–
Kisslicer	A slicer that works on multiple operating systems	Capable of generating complex and dependable support structures	Consumes a significant amount of material for supports
Slic3r	Included with Repetier Host software; features advanced 3D cellular infill	Receives frequent updates and offers many configuration options	Difficult to learn

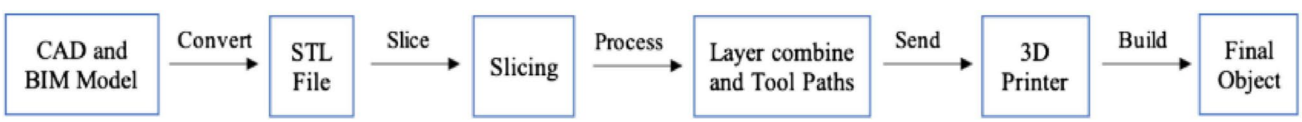


Fig. 19 Stages involved in 3DP [96]

algorithms. Finally, Repetier-Host, another open-source tool, is described as a comprehensive solution for managing and controlling 3D printers, featuring multi-printer support, model previewing, and customizable print settings. Together, these software packages represent a diverse ecosystem catering to users from hobbyists to industry professionals, enabling the entire process from conceptualization to physical production (Table 8; Fig. 19).

Case studies on 3D printed construction in india

Case study 1: India's first 3D-printed G + 1 reinforced concrete building by L&T construction

At its Kancheepuram plant in Tamil Nadu, Larsen & Toubro (L&T) Construction successfully 3D printed India's first G+1 (ground-plus-one) reinforced concrete building, marking a significant milestone. Using an indigenously developed 3D printable concrete mix made of ordinary building materials rather than commercially available ready-mix mortars, the 700 square foot structure was finished in 106 hours [97]. L&T's mix included coarse aggregates, which improved mechanical performance, durability, and cost effectiveness in contrast to mortars with smaller particle sizes and less strength.

The structure's horizontal welded mesh and vertical reinforcement bars were prime examples of a hybrid construction method that combines conventional reinforcement methods with additive manufacturing. The project showed adherence to structural norms and made use of COBOD's 3D printing technology. Henrik Lund-Nielsen, the founder of COBOD, claims that by demonstrating the possibilities of actual concrete, this project marks a significant advancement for 3D concrete printing worldwide. All things considered, the project demonstrates India's increasing proficiency in automated, scalable, and sustainable construction technologies, opening the door for the development of infrastructure and reasonably priced mass housing (Fig. 20).

Fig. 20 3D-printed G + 1 Reinforced concrete building by L&T construction [98]

Fig. 21 3D-Printed post office [100]

Case study 2: India's first 3D-printed post office in Bengaluru

In Bengaluru's Cambridge Layout, Larsen & Toubro (L&T) Construction and the Indian Institute of Technology Madras (IIT Madras) successfully created the country's first 3D-printed post office [99]. The 1021 square foot construction was finished in 43 days, two days earlier than expected, proving the effectiveness and speed of 3D concrete printing. Specialized rapid-setting concrete was used to print the building layer by layer, creating a continuous structure free of vertical joints. Its design demonstrated architectural flexibility beyond conventional techniques by enabling continuous concrete footings, reinforced three-layer walls, and curved surfaces.

The project was completed at a cost of ₹23 lakh (≈$27,840)—nearly 30–40% cheaper than conventional construction. According to L&T officials, robotic automation and pre-embedded design integration drastically reduced labour time and errors. The initiative highlights the potential of 3D printing for sustainable, cost-effective, and rapid infrastructure development. The Department of Posts now plans to replicate this technology across 400 future sites in Karnataka, marking a major step toward affordable and customizable construction solutions in India (Fig. 21).

Case study 3: India's first 3D-printed G + 1 villa

India's first 3D-printed G + 1 villa was unveiled at Godrej Eden Estate in Pune by Godrej Properties and Tvasta Engineering, a start up from IIT Madras [101]. The 2200-square-foot mansion was built in four months utilizing additive manufacturing technology, showcasing the effectiveness, speed, and accuracy of 3D concrete printing. A specialized concrete printer was used to build the structure layer by layer, ensuring durability while reducing construction time, labour, and material waste.

Fig. 22 3D-Printed villa [102]

In order to reduce its impact on the environment, the project incorporates recycled materials from a variety of industries, emphasizing sustainability. The villa's 3D-printed walls offer excellent insulation, which contributes to energy efficiency, and its organic, algorithm-driven design improves both structural strength and aesthetic appeal. Curved shapes, sculptural staircases, and natural lighting are examples of architectural elements that produce a contemporary and environmentally friendly living area. With its demonstration of how robots, automation, and sustainable materials can revolutionize residential building and serve the goal of intelligent, environmentally friendly urban dwelling, this project represents a significant advancement in India's construction industry (Fig. 22).

Obstacles in 3D printing for construction

Ensuring strength, longevity, and large-scale production

A key hurdle is guaranteeing that 3D-printed construction parts are strong and durable enough. The method of printing layer by layer can create weak spots or unevenness in the material. More research is needed to improve the overall quality and performance. Furthermore, using 3D printing for large building projects presents difficulties with how fast printing can occur, how consistently materials are delivered during printing, and managing the overall process. Addressing these issues is vital for 3D printing to become a practical option in construction.

Affordability and worker expertise

Even with its potential benefits, 3D printing can be expensive, particularly for smaller projects. It's important to find ways to make it more economical and use materials efficiently. Additionally, the construction industry needs workers who know how to use and look after 3D printing equipment. Training workers and closing this skills gap is essential for successfully adopting this technology.

Equipment and technology costs

Challenge: The procurement of 3D printing systems, specialized software, and compatible construction materials involves substantial upfront investment. The high capital cost of large-scale printers, along with expenses for calibration, transportation, and setup, can create significant financial barriers. Moreover, continuous technological upgrades and proprietary material requirements further increase operational costs, making it difficult for small and medium-sized construction firms to afford the technology [103]. Limitation: These cost-related challenges restrict the widespread adoption of 3D construction printing, particularly in developing regions or among smaller enterprises with limited budgets. Consequently, the technology remains concentrated within large corporations or research-based projects, slowing global scalability and practical implementation.

Scaling-up

Challenge: Expanding 3D construction printing to accommodate large and complex structures—such as multi-story buildings, bridges, or skyscrapers—introduces significant technical and logistical challenges. The limitations of printer size, material delivery systems, curing times, and precision control become more pronounced as project scale increases. Additionally, ensuring structural integrity and uniform material properties across larger builds requires advanced real-time monitoring, robust robotics, and reliable automation systems.

Limitation

Current 3D printing technologies may not yet be fully optimized for large-scale or high-rise construction applications. The inability to efficiently scale up restricts the technology's use to low-rise or modular structures, thereby limiting its broader potential within the global construction industry.

Workforce training

Challenge: The integration of 3D printing into construction necessitates a workforce proficient in both digital and practical construction domains. Engineers, architects, and site operators must be trained in CAD modeling, printer calibration, robotic control, and digital workflow management. The transition from conventional to automated construction methods requires a new skill set, combining computational design with on-site troubleshooting and quality assurance. Limitation: A shortage of trained personnel and insufficient training programs can create a significant gap between technological potential and real-world execution. Without adequate human expertise, the efficiency and accuracy of 3D printed construction projects can be compromised, leading to reduced productivity and slower adoption rates.

Future directions for 3D printing in construction

Combining with artificial intelligence and automation

Merging 3D printing with AI and automated systems could transform construction. This could lead to building processes that are self-governing and can adjust as needed.

Personalized and large-scale custom designs

3D printing offers the exciting prospect of mass customization. This means buildings could be uniquely designed to meet specific needs without losing efficiency or becoming too expensive. Investigating how customization can be applied in different areas is a key area for future study.

Eco-friendly building materials

Future efforts should concentrate on creating sustainable and environmentally friendly materials for 3D printing. Using recycled or plant-based materials could greatly lessen the environmental footprint of 3D-printed buildings.

Printing with multiple materials

Progress in 3D printing that uses several different materials at once could lead to new types of complex structures. These structures could combine materials with unique characteristics to serve multiple functions.

Conclusion

3D printing in construction has emerged as a disruptive innovation capable of transforming the global building industry through automation, precision, and sustainability. The technology enables reduced material waste, accelerated timelines, and enhanced design flexibility, addressing key challenges of cost, labour dependency, and environmental impact. Case studies such as L&T's reinforced G + 1 structure, the Bengaluru 3D-printed post office, and Tvasta's villa with Godrej Properties demonstrate the successful integration of digital design, robotics, and concrete printing at varying scales. Despite the evident advantages, challenges persist in material standardization, scalability, and skill development. Future research should focus on optimizing mix rheology, implementing real-time monitoring systems, and advancing multi-material and AI-assisted printing for complex, load-bearing structures. With continued innovation and interdisciplinary collaboration, 3D printing is poised to become a cornerstone of sustainable and intelligent construction, paving the way toward a new era of digital and hybrid building systems.

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Declarations

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

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