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Review

Sustainability assessment, potentials and challenges of 3D printed concrete structures: A systematic review for built environmental applications

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A B S T R A C T

The built environment defines humankind's daily lives, sophistication, efficiency, and effectiveness. Despite this, its primary industry, construction—which transforms the built environment into a reality and an operation—remains in need of more efficient, innovative, and sustainable strategies, technologies, and instruments. The incorporation of digital fabrication into 3D printing (3DP) technology offers an entirely different and expanded freedom of geometry, functionality, materials, savings, efficiency, and effectiveness. For the inherent potential of 3DP technology, its sustainability assessment and potential contributions should be explored systematically to shed light on future applications and further innovations. This study presents a systematic review of the sustainability potential, assessments, and challenges of 3DP concrete for built environment applications. A comprehensive and comparative review of related literature is performed to identify the current trends and research gaps and recommend reducing or eliminating the energy and environmental footprints and the socio-economic impact. The study concludes that, in terms of documented global warming potential (GWP) values, 3DP technology appears to be a promising alternative to conventional construction and concrete use. A life cycle analysis (LCA) is recorded that is meant to be widely used as an assessment tool for environmental and energy assessment in digital fabrication technology, leaving an integrated review, including social and economic aspects, understudied. The 3DP concrete technology has unlimited potential in terms of material flexibility, savings, labour's cost, design flexibility, and operation agility. Besides, researchers intend on introducing unconventional and locally available materials to increase the sustainability of 3DP technology in construction.

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Abbreviations: AM, Additive Manufacturing; BJ, Binder Jetting; BFS, Blast furnace slag; CDW, Construction and Demolishing Waste; CAD, Computer-aided design; CC, Contour crafting; CP, Concrete printing; EP, Extrusion Printing; FDM, Fused-Deposition modelling; FA, Fly ash; LCA, Life cycle assessment; LCC, Life Cycle Costing; GWP, Global Warming Potential; RCA, Recyclable concrete aggregates.

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1. Introduction

The construction industry is responsible for approximately 38% of greenhouse gas release, 40% of solid waste, and 12% of portable water use. Its footprint and impact are expected to increase since the urban population is estimated to represent 68% of the world's total residents by 2050—meaning more built environment projects, more construction, and more concrete use. This will result in immense economic, social, and environmental burdens on the planet, ecological system, and people regarding housing, transportation, and other infrastructure necessities. More efficient, innovative, and sustainable strategies and technologies must be developed and adopted by the construction industry to meet the built environment's needs and social and economic conditions (Gengnagel et al., 2020).

Concrete is one of the most widely used materials by volume in built-environment applications due to higher durability, strength, availability, design flexibility, fire resistance ability, and low cost (Valipour et al., 2014a). It is also one of the most-used materials on earth, implemented as everything from small-to full-scale building components, as it shows incomparable structural strength while at the same time can be cast into almost any kind of shape at relatively competitive cost levels. Concrete is the mixture of cement, fine and coarse aggregates, mineral admixture, and water for hydration. The conventional way of forming standard geometries of concrete is to use wooden or metal formwork, which can be purchased at half the concrete cost (Jipaet al., 2018). However, construction technology has remained notably stagnant when compared to other sectors and industries such as manufacturing. Concrete fabrication has become quite involved with its customized and irregular structures, and it has reached the limits of its initial possibilities (Jipaet al., 2018).

Digital fabrication can be a promising solution to the mass-market requirement of sustainability. The potential for freedom in geometry, less material consumption, more sustainable and eco-friendly material selection, low waste, high recycling rate, and cost-effectiveness are vital features that make three-dimensional printing (3DP) a suitable technology for concrete construction (Panda et al., 2018). Pagna (Pegna, 1997) is considered the pioneer of additive manufacturing technology of cementitious material.

3DP technology for construction is increasing worldwide, with CyBe, Apis Cor, and Winsun already undertaking 3D-printing projects for construction throughout Asia and Europe (Alhumayani et al., 2020). The use of digital structure goes beyond even earth, though, as its application is also considered a future construction material for inhabitants in space (Cesaretti et al., 2014). Apis Cor built the world's largest 3D-printed building for Dubai: 640 m^2 and 9.5 m in height. 3D printing technology was used to fabricate the walls onsite while its slabs and foundation were conventionally constructed.

3DP, also known as Additive Manufacturing (AM), is a one-step process for approaching the demand for more sustainable and resource-efficient concrete construction practices. It provides ways to improve the carbon footprints of buildings by reducing their embodied and operating energy (Ghaffar et al., 2018a). Due to the diverse nature and availability of renewable energy, its integration into the construction sector could further reduce its environmental effect. However, due to massive demand and environmental impact, concrete is a substantial affliction to the living atmosphere.

Although numerous studies have examined improvements to 3DP technology for the construction, the field is still in an early stage of material advancement, scale, and overall project cost (Berman, 2012). Likewise, the environmental impact and life cycle assessment of 3D-printing technology for construction is another aspect that is primarily unexplored in almost every phase, including design, process technology, and material (Dixit, 2019). Several previous reviews of 3DP systems for construction have covered the general technological consideration, potential, and material development (Paul et al., 2018; Sai Sandeep and Muralidhara Rao, 2017; Ma and Wang, 2018; Perrot and Amziane, 2019; Labonnote et al., 2016). However, it is also essential to assess technology's sustainability—energy, environmental footprint and identify potential opportunities—to reduce future challenges.

The ability to satisfy the increasingly intertwined and challenging requirements of the built environment should be the fundamental requirement of such techniques under today's social, economic, and environmental conditions. This study systematically reviews the sustainability potential of and the challenges to concrete's 3D-printing technology for the built environment. The review focuses on the ecological, social, and economic character of 3D-printing technology for concrete construction and identifies its corresponding performance's critical parameters. The study contributes to the literature by presenting guidelines, current trends and challenges, research gaps, and suggesting future research directions within the study's scope. Following are the specific objectives of this paper:

a. Identify the energy, environmental and socio-economic benefits of current 3D-printing technology for concrete construction.
b. Identify the key parameters that affect these benefits.
c. Identify the technical challenges and potential opportunities for enhancing these benefits.
d. Evaluate the tradeoff between the potential gains and an environmental load of 3D-printing technology for concrete construction.

e. Identify the current research gaps.
f. Propose future research direction aimed at more sustainable 3D-printing technology for concrete construction.

2. Methodology

Publication Search: A wide range of scientific literature has been reviewed, using available databases including science direct, Springer Link, ASCE, Wiley online library, PubMed, and Taylor & Francis. The primary searches were carried out using keywords in the title, abstract, or author keywords, taking into account the study's scope. The main keywords were concrete printing, digital concrete, 3D printing for concrete, sustainable concrete, green concrete, sustainable concrete construction, recycled concrete, sustainable 3D construction, Life Cycle Analysis (LCA), Concrete LCA, LCA 3D printing, and a combination of these words. The articles with original research that were peer-reviewed and written in the English language were selected. Peer-reviewed journals are the primary source of research considered in this study; however, other resources, like conference proceedings, book chapters, and academic theses, are also considered to increase the review's quality.

Exclusion Criteria: Further screening was carried out by searching through the main body of the articles, based on the following three principal criteria:

a. Include studies with at least one environmental, social, or economic sustainability assessment.
b. Exclude 3DP technologies used for applications other than construction.
c. Exclude construction materials other than concrete.

The majority of studies focused only on technological development; they are excluded from this review. Also, many studies were found that had performed a sustainability assessment of green concrete only. These include the concrete with high life cycle sustainability or at least one of its components from waste material or have production process with no environmental destruction (Suhendro, 2014). However, such studies were also excluded, as their failure to consider 3D printing renders them only relevant to a subsection of the article. Similarly, many reviews on 3D printing for construction have been filtered out based on the selection criteria for a sustainability assessment defined above. Careful selection has been performed to include the articles with significant output, to reduce the duplication of results.

3. 3D printing technology for concrete construction: an overview

Before proceeding to the sustainability assessment, potential, and challenges of concrete printing in the built environment, it is essential to overview critical aspects of this technology. 3D printing technology's three fundamental features for concrete printing discussed in this section are printing technologies, material, and required parameters.

3.1. 3D printing technologies for concrete structures

The basic principle of 3D printing technology for concrete construction is similar to any 3D printing process. The development of structure in 3D printing consists of three main steps: the computer-aided design (CAD) design of the final product, the slicing and tool path section, and the 3D printing. The CAD model of the final product is moved to the slicing application, where the product is sliced into layers of different heights. The printing path for those layers is converted into a G-code file. A successful printing process requires an excellent combination of printing parameters and the material's printing property (see Fig. 1).

The printing machine used in 3D printing technology for concrete construction is either gantry-based or robotics-based. In a robotics-based system, a printer head is connected to the robot and two peristaltic pumps. The first pump is used to supply the concrete material and the second to supply the accelerator. All three components, the printer head and the two pumps, are controlled with a micro-controller. In a gantry-based printer, a hose from the mixer is connected to the printer head. A four-degree freedom system is used to manage the printer head connected to the vertical arm. A nozzle, commonly made of steel, is attached to the printer head. The size and shape of the nozzle vary depending on the chosen approach. Trowels were added in contour crafting to achieve advanced smoothness, which is the main difference in the concrete printing method.

Three leading 3D printing technologies used for concrete structures are extrusion printing (Khoshnevis, 2004), Powder Jetting method (Lowke et al., 2018), and 3D printed formwork (Hack et al., 2017) methods. In the extrusion printing method (EPM; also called the extrusion-based layer method) and the Binder Jetting method (BJM), the selected material is deposited layer by layer in an incremental manner, determined by commands from the computer-aided design (CAD) tool. The EP technique is predominantly used for onsite construction, while the BJM is used offsite for prefabricated complex shapes that are assembled at the next stage. The third method is a hybrid of 3D printing and moulding and is known as the 3D printed formwork technique; in this method, the initial mould or formwork for the concrete structure is fabricated with 3D printing technology. Concrete material is then added to the formwork or mould to obtain the final concrete structure.

3.1.1. Extrusion printing (EP)

The EP is the core fabrication technique of the concrete printing process. This method resembles the fused-deposition modelling (FDM) technique, where a robot, a crane, or a gantry 3D printer is used for concrete printing. The EP is further divided into contour crafting (CC) and concrete printing (CP). CP is similar to CC; it was developed by a researcher at Loughborough University, UK, using a 5.4 × 4.4 × 5.4 m (L x W x H) gantry printer. Both methods use direct concrete material to print layer by layer to form the final structure. The key feature of contour crafting is the attached trowel guide. The trowel guide is used to guide the material and newly high-surface finish even with a thick printing layer. The trowel can be deflected at different angles to form non-orthogonal shapes. Concrete-printed structures with embedded spaces for plumbing and electricity are successfully printed using CC (Khoshnevis, 2004).

3.1.2. Binder Jetting method (BJM)

This method is encouraged for concrete structures with complex designs containing voids and overhanging features. During the BJM, a binder material is ejected onto a targeted powder bed to form a two-dimensional (2D) layer. The penetration of the binder can control the thickness of the printed layer. The cycle repeats, and these 2D layers are incrementally added to form the final product. The unbound material can be simply removed and recycled in the following printing process. Unlike EP, this method is rarely used for onsite construction due to its sensitivity to weather (Cesaretti et al., 2014). Monolite UK ltd (D shape) and Voxeljet are working with this technology for use in the architecture and construction industries. The BJM provides a higher resolution than and superior surface finish to the EP. A detailed review of the BJM for concrete 3D printing and its future potential was conducted by Lowke et al.


(i) [20]
(ii) [21]
(iii) [22]
(iv) [23]
(v) [24]
(vi) [25]

Fig. 1. Few real-world examples of 3D printing technology for concrete construction exist, from (Al Rashid et al., 2020): (i)3D Housing 05, Milan (ARUP), (ii) 3D-Printed Multi-Story Apartment, Winsun (World's First 3D-Printed Apartment Complex), (iii) Double-Story Administrative Building in Dubai (Dubai Project - Apis Cor.), (iv) First 3D-Printed Office in Dubai (World's First 3D-Printed Office Building Unveiled in Dubai), (v) Europe's First 3D-Printed Building (The BOD) (BOD2), (vi) Woven Concrete Benches (XtreeE)

(Lowke et al., 2018).

3.1.3. *3D printed formwork printing*

Direct 3D printing of complex concrete structures is challenging, as most printing technologies have previously been unable to address architectural components' demanding requirements (Leschok and Dillenburger, 2020). This technique applies to integrating 3D printing technology to fabricate formwork or mesh mould for concrete structures. It relies on the principle of keeping the required printing of concrete inside 3D-printed support.

Two main techniques in this category are the 3D printed formwork and the mesh mould fabrication technique, which act as a hybrid of the 3D printing and casting technique used to fabricate concrete structures. Both methods use extrusion-based technology for their 3D printing formwork, followed by the casting of concrete. In the formwork process, mould is manufactured and used predominantly for prefabricated concrete structures containing irregular and complex concrete structures with fine details and a good surface finish. The mesh mould method produces wireframe work with a specific focus on increasing the strength of the frame while at the same time overcoming the printing difficulties of concrete material.

3.1.3.1. 3D-printed mesh mould technique. The mesh mould is a novel construction technique used for concrete printing where formwork and reinforcement are fabricated as a single element called mesh (Hack et al., 2017). The concrete is then poured, and the surface smoothens manually. A 3D-printed mesh acts as formwork for concrete pouring and as reinforcement in the next stage when the concrete is cured (Hack et al., 2013). Like formwork, in the mesh mould technique, an in situ structure of the material—frequently thermoplastic polymer—is produced by extrusion using a 6-axis robot. This also reduces the time required to create complex designs and is feasible for large-scale fabrication. The mesh acts as a reinforcement and increases the strength of the concrete (Tay et al., 2017). The mesh density can be increased for greater strength, and the structure can be made more complicated, keeping in mind the requirement of strength in specific directions. Both polymer-based and steel-wire-based meshes have been studied for this technique in literature. Fig. 2 represents a prototype of a mesh mould

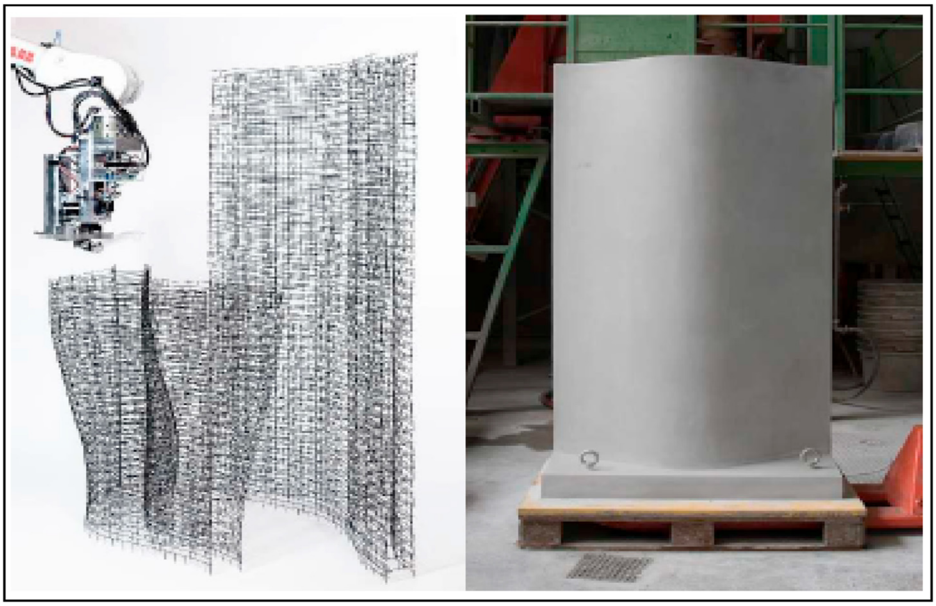

Fig. 2. Mesh mould structure prototype by ETH Zurich, Gramazio Kohler research (Agustí-Juan et al., 2017).

structure. It should be noted that, in the case of standard concrete structures such as straight walls and blocks, the integration of FDM 3D printing technology for formwork cannot compete with the traditional method in terms of speed or cost.

3.1.3.2. 3D printed permeable formwork technique. The conventional way of forming standard geometries of concrete uses wooden or metal formwork, which costs 50% of the cost of concrete (Jipaet al., 2018). However, this process more complicated and reach its limit for more complex and irregular structures. The use of digital fabrication for the fabrication of non-standard geometries of formworks gives full freedom of geometry, functionality and reduce material saving.

Leschok and Dillenburger (Leschok and Dillenburger, 2020) reported PVA based 3D printed dissolvable formwork using FDM technique for casting concrete components. They stated the successful implementation of this technique for full-scale concrete elements with structural complexity and high surface finish. The printed 3D material can be peeled off and recycled or washed away in dissolvable material.

3.2. Concrete material for 3DP technology

3.2.1. Standard concrete material

Concrete is the mixture of cement, fine and coarse aggregates, mineral admixture, and water for hydration (Wangler et al., 2019). The hydration of cement resulted in the formation of viscous paste for bonding of the mixture. Since printable concrete is still in the development phase, there is no standard composition yet available (Panda et al., 2017a). The aggregates used in 3D printing are limited to an adequate small size due to nozzle size and printing resolution, hence also called printable mortar. They are used to provide compressive strength and bulk to concrete. Sand is the most reported material as aggregates in published research. Compared to conventional concrete, 3D printable concrete required a lower water quantity due to the necessary fresh properties of fast setting, lower slump, and high strength (Le et al., 2012). Admixture such as accelerators, retarders and superplasticizers are used to control the workability of printable concrete.

Cement is the most critical part of concrete with the ability to bond the concrete mixture. Portland cement, a mix of clay, limestone, and eventual chemical collector of aluminous, siliceous, and ferrous nature, is the most common cement used in concrete material (Bartolo and Gaspar, 2008; Roussel et al., 2012; Scrivener et al., 2018). The primary research in 3D printing technology for concrete construction focuses on developing cementitious material with appropriate formulation for "printability" and "buildability". The rheological requirement of fresh concrete is its properties that are required for successful printing (Kruger et al., 2020). Nicolas Rousel (Roussel, 2018) reported the rheological condition of printable concrete in terms of elastic modulus, viscosity, structuration rate, yield stress and critical strain. A complete study of fresh concrete's rheological requirement is performed from the deposition process at nozzle up to surface cracking and buckling stability after the printing. The study summarized the rheological requirement as a function of printing parameters for printable concrete.

3.2.2. Toward sustainable concrete materials

The production of concrete has a significant impact on the environment and construction industry and faces a severe environmental problem. Hence, the scientific community is continuously trying to avoid ordinary concrete and replace it with more sustainable concrete with less environmental impacts. For this purpose, natural aggregates are trying to replace by recyclable aggregates (e.g. blast furnace slag, fly ash and marble sludge), Fig. 3. Ordinary cement is switching alkali-activated binders, recycled fibres, and unconventional locally available material are investigated in the concrete mixture. For example, in ordinary concrete material, 60% of the binder content is Portland cement, and this proportion is even higher in 3D printable concrete. Silica fume, fly ash, and lime filler are used as supplementary cementitious materials to replace the Portland cement (Chen et al., 2017). Some of these efforts for sustainable concrete are summarized below:

3.2.2.1. Geopolymer cement concrete. Geopolymer is made of alkali-based chemical for activating amorphous alumino-silicate materials. The common source of amorphous alumino-silicate materials in geopolymer concrete is Fly ash (FA), natural zeolite, and Blast

Fig. 3. Different recycled aggregates for modified concrete.

furnace slag (BFS), which helps the clean environment. While sodium hydroxide is a widely used alkali activator used in Geopolymer production. NaOH and sodium silicate are the major components of Geopolymer reported with high environmental impact (Salas et al., 2018), (Habert et al., 2011), as mentioned in the manuscript. However, the use of geopolymer concrete reduces the stock of wastes and reduces carbon emission by reducing Portland cement demand (Raijiwala and Patil, 2010). In contrast to Portland cement, most geopolymer systems rely on minimally processed natural minerals and industrial byproducts or wastes to provide binding agents, thus enabling palpable energy and CO_2 savings in the construction sector.

For most standard types of geopolymers, the resultant environmental impact is lower than OPC concrete (Panda et al., 2020). Several studies in the literature show that the production of most of the geopolymer concrete has a lower impact on global warming than standard Ordinary Portland Cement (OPC) concrete, including (Habert et al., 2011), (Raijiwala and Patil, 2010), (Sandanayake et al., 2018).

3.2.2.2. Reinforced concrete. The cementitious mixture is generally brittle in nature. Structural stability and ductility are the key requirements of 3D printing concrete. The application of fibers to enhance the ductility and tensile strength of printable concrete has received considerable attention (Ahmed et al., 2020). Several studies have used several fibers materials such as glass (Panda et al., 2017b), (Öz et al., 2019), PP and PVA (Nematollahiet al., 2018), basalt, steel fibers for compressive strength, post-peak, and interface strength behavior. The alignment of fiber is an essential parameter for the final properties; for example, tensile strength results in parallel to fiber alignment. These fibers are used in concrete for 3D printing to achieve structural stability and ductility (Weng et al., 2018), (Zareiyan and Khoshnevis, 2018). Besides, the compatibility of fiber with the printing system is crucial for successful printing.

3.2.2.3. Waste and byproduct concrete. There is increasing interest in waste and byproducts in the concrete industry, due to their socio-economic and environmental advantages. Various waste and byproducts of industrial processes, i.e., fly ash, blast furnace slags, marble sludge, incineration ashes, glass powder, metal slag, and rubber, are used to sustain growth reduce CO_2 footprint (Bovea and Powell, 2016). 30% of the marble goes to scrap during marble rock processing in the industry (Colangelo et al., 2018a). The amount of this scrap is increasing with the increasing demand for marble with time. The addition, some aggregates material like blast furnace slags to concrete also reduces the heat of hydration and increases in strength (Meyer, 2009). The replacement results in reducing CO2 emission and energy consumption since blast furnace slags are already undergone the oxidation transformation of carbonate. This material can use in various other application including road construction and an adsorbent material.

Almeida et al. (Almeida et al., 2007) investigated the feasibility of natural stone processing waste in concrete. The fine aggregates of high-performance aggregates were replaced with the byproduct slurry of natural stone. The substitution of 5% stone slurry resulted in the highest performance enhancement for modulus of elasticity, tensile and compressive strength, and durability. The stone dust also enhanced hydration chemical reaction due to better dispersion of cement particles. The results indicated 16% enhancement in hardened concrete performance for voids volume reduction.

3.2.2.4. Recycled concrete and construction and demolishing waste (CDW). The use of CDW and recycled concrete aggregates (RCA) has emerged with the expectation to address the requirement of raw material in construction and transforming the growing waste into a beneficial resource. Three main advantages of recycled aggregates for concrete material are the reduction in demand for new resources, reducing the landfill with trash, and reducing energy for production. CDW is a significant contributor to the total waste produced in developing and developed countries (Jayasuriya et al., 2020), (Kim et al., 2018). Such waste consists of bricks, concrete, metals, wood, plastic, gypsum, solvents, and asbestos derived from demolishing buildings, roads, and civil infrastructure (Blengini and Garbarino, 2010). These materials are passed through crushing and selection plants for the technical requirement of reuse. The separation and recovery process of CDW is well defined and cost-effective (Colangelo et al., 2015). CDW is generally used for recycled aggregate used in pedestrian routes and pavements of roads and recently in concrete building blocks.

4. Sustainability assessment for 3DP technology for concrete construction

Digital fabrication using 3D printing is an environmentally friendly technique with minimal waste. It reduces the post-processing requirements by giving numerous design and economic feasibility possibilities. It allows the designers to integrate the required details in the fabrication stage, such as adding aesthetic features and embedded circuits to integrate electrical and HVAC facilities, with minimal or no extra cost. Hence, the planning, assessment, and optimization of the architecture are performed during the design phase. LCA and LCC are two widely considered tools in literature for the environmental and economic sustainability of 3D printing technology for concrete construction (Colangelo et al., 2018a), (Raposo et al., 2019), (Illankoon et al., 2018). The authors also suggested ex-ante LCA in some cases for the emerging materials in concrete 3D printing. This approach helps in creating knowledge regarding the potential development of new technology in its early stage. To satisfy the building sector's increasing demand and considering current environmental circumstances, more sustainable, innovative, and efficient techniques must be adopted by the construction industry. This section focus on the sustainability assessment of 3D printing technology for concrete construction.

4.1. Energy and environmental assessment

This section focus on the energy and ecological potential and assessment of 3D printing technology for concrete printing. LCA is the standard methodology used in literature to evaluate 3D printing technology's environmental load for concrete structures. It provides a comprehensive and systematic approach to assess the environmental impacts of construction. The process includes construction materials, waste factors, reworks and damage, temporary construction structures, locally available and natural materials, more sustainable and multi-dimensional materials, transportation, and construction. Gursel et al. (Gursel and Ostertag, 2019) suggested three key factors that need to consider more wisely in current LCA studies; (i) holistic calculation of environmental effects, as most of the studies focused on greenhouse gas and energy use but neglecting other significantly essential factors of heavy metals toxic emissions and a volatile organic compound. (ii) Ignoring critical phase based on assumption or previous literature. (iii) Lack of consideration of regional and technological variation.

The method includes life cycle analysis of 3D printing technology's critical components for concrete construction, from initial embodied energy to demolishing at the End-of-Life phase. While, Fossil depletion, Climate change, Agricultural Land Occupation, Freshwater Eco-toxicity and Eutrophication, Human Toxicity, Marine Eco-toxicity and Eutrophication, Ozone Depletion, Particulate Matter Formation, Photochemical Oxidant Formation, Terrestrial Acidification, Water Depletion, Urban Land Occupation, and Metal Depletion are some of the parameters that are considered for calculating the environmental impact of different 3D printing technologies in the construction sector.

4.1.1. Concrete material

Cement is the leading factor of greenhouse gas emissions in OPC concrete. However, only an optimal percentage is preferred to exchange with other materials for optimum strength and environmental impact. For example, Valipour et al. (Valipour et al., 2014b) observed zeolite's environmental potential to replace ordinary cement in concrete material. The LCA analysis was performed for the optimization of the substituted material for the most effective mixture. The study reported 64.3%, 69.7% and 60.3% reduction in GWP potential for 30%, 20% and 10% replacement of cement with zeolite material, respectively. Similarly, the partial replacement of zeolites, such as 10% and 20%, increased in compressive strength, while its increase to 30% decreased its strength.

The distance between the construction site and material production is also an important variable and significantly reduces the environmental impact. To analyze this variable, Cabello et al. (Ferreiro-Cabello et al., 2017) compared three main variables: materials wasted, distance traveled for the transportation of components, and working hours in the concrete construction process. LCA tool is used to investigate the sensitivity of their environmental impact. The minimal environmental impact is reported for working hours after a comparison of six different scenarios. The transport of construction components is identified as the most sensitive variable. Depending upon the construction site's distance, the structural element's environmental impact can be decreased up to 65.6% or increase by 18.2%. While for material waste, the ecological implications varied between 9.8% and −9.8%. The study emphasized the importance of waste management and transport and the usually controlled factors of materials and working hours. It is worth noting that transport sensitivity can be different for cases where prefabricated elements are not employed.

In a detailed LCA analysis for general 3D printing technology for the construction sector, Saade et al. (Colangelo et al., 2018b) identified different global warming potential (GWP). The study reported that concrete material is the main contributor of GWP, and in the case of the 3D printing process, it is more significant. Since the cement is the most contributing factor for environmental impact in OPC concrete, alternate and more sustainable concrete is widely explored in literature. Many studies have been performed to analyze the ecological potential of ecological concrete and traditional concrete.

4.1.1.1. Environmental impact of geopolymer cement concrete. Both 3D printing technology and sustainable concrete are the concrete industry's innovations to reduce its environmental impacts. Geopolymer concrete results in ecological performance enhancement at the material level. Using waste in geopolymer concrete further increases its potential for more incredible ecological performance (Singh et al., 2015). Yao et al. (Yao et al., 2020) investigated the combined advantage of both 3D printing and geo-polymers for concrete construction. The study aims to analyze the environmental advantage, limitations, and potential for further improvement. The analysis was performed using LCA and compared the existing production system. The result disclosed the potential benefit of 3D printing technology mainly due to reduction in waste material. However, geopolymer concrete's environmental effect is reported to be greater due to raw material production and is highly subjected to the recipe used. Silicate is indicated as the leading component for environmental impact in geopolymer concrete. With the optimization of transportation and production, the Geopolymer resulted in a lower carbon footprint; however, its performance is negative for categories like ozone depletion and depletion of abiotic resources. The study suggested that the ex-ante LCA be performed to explore technology's future by its possible technological innovation and to identify the hotspots for improvement.

Petrillo et al. (Petrillo et al., 2016a) and Turner and Collins (Turner and Collins, 2013) reported alkali activators' production as a key contributor to Geopolymer concrete's environmental impacts. The research was conducted for the comparison of geopolymer concrete and OPC concrete. Both the studies were performed at a lab-scale and then scaled up, to compare with ordinary concrete results. The studies reported a 16% and 9% reduction in carbon footprint for geopolymer concrete. Similar conclusion for geopolymer concrete is stated by Habert et al. (Habert et al., 2011), with maximum environmental impact by sodium silicate production. However, using alkali activator with a more sustainable source such as rice husk ash has been reported with substantial capacity for environmental compatibility (Vieira et al., 2016).

Raw material and production process are essential parameters in the environmental impact of geopolymer concrete production. Salas et al. (Salas et al., 2018) performed a detailed analysis of Geopolymer concrete's ecological impact with the type of electrical energy used and the process of alkali activators production. Natural zeolite, sand, sodium silicate, and sodium hydroxide were observed as raw materials in novel geopolymer concrete previously developed by (Vieira et al., 2016). The energy mix with higher hydroelectricity is reported as more favorable ecological results. In contrast, the production of sodium hydroxide resulted in the most relevant process for environmental impact. Geopolymer concrete is analyzed with superior environmental performance with the potential of 64% reduction in GWP compared to conventional.

4.1.1.2. Environmental impact of waste and byproduct concrete. The environmental impact of waste and byproducts in concrete material is widely analyzed in the literature. Fly ash is used both in Geopolymer to replace the ordinary Portland cement and as an aggregate to replace the natural aggregates. Smith and Durham (Smith and Durham, 2016) performed cradle to grave LCA for novel concrete mixture with fly ash in pavements. The study reported an increase in environmental efficiency by 23% by incorporating 20% fly ash while attaining the required standards.

Similarly, Marble waste performs as a promising replacement of sand and cement with high capability to reduce ecological impacts. A detailed environmental and economic review for marble waste powder is performed in their study by Singh et al. (Singh et al., 2017). Colangelo et al. (Colangelo et al., 2018a) conducted a comparative analysis of marble sludge with three different concrete types. Four different kinds of byproducts aggregates, i.e., marble sludge, construction and demolition waste (CDW), blast furnace slag and incinerator ashes, were used to reduce the environmental and energy impacts of concrete material. The results indicated a positive effect of the addition of recycled aggregates. Blast furnace waste was analyzed as the least impact on the environment.

4.1.1.3. Environmental impact of recycled and CDW concrete. The replacement of natural aggregates in concrete with recycled material from CDW shows a significant gain in decreasing natural resource depletion and waste diminution. Marinkovic et al. (Wangler et al., 2019) analyzed the environmental potential for aggregates' production and transportation to the construction site only. Considering the same lifetime and construction and demolishing phase, hence neglecting their effect in the comparison study. The study revealed the transportation distance and type of transportation as a leading factor for environmental impact in terms of GWP, energy use, photochemical oxidants production, eutrophication and acidification. Besides the reported advantages of a decrease in waste and natural resource depletion, the study emphasizes the importance of concrete recycling near the concrete production site. In a similar study, Farina et al. (Farina et al., 2020) the concrete mixture's environmental and energy potential with different percentages of CDW (10%, 40%, 40% and 100%). The LCA was performed for the production process for 24 different scenarios. The study also analyzed the impact of the transportation distance of 30, 50, 60, and 150 km from the recycling site. The study reported the high environmental potential for recycled CDW for replacing natural aggregates. Shan et al. (Colangelo et al., 2018b) highlighted the importance of transportation in recycled aggregates and recommended local recycled aggregates.

The replacement of recycled aggregates usually results in lower mechanical properties than the natural aggregates used in concrete material. Hence, the reduction in these properties needs to keep above the required limit. Like other CDW aggregates, recycled concrete aggregates (RCA) in new concrete construction have high ecological potential. Guo et al. (Colangelo et al., 2018b) explore the mechanical and environmental potential of incorporating 75% of RCA to new concrete clocks. The RCA included a slightly lower mechanical and durability performance; however, the ecological potential was much higher. Some of the other studies of CDW and RCA are reported in Table 1.

4.1.1.4. LCA of reinforced concrete. Minimal studies are present on the environmental performance of the fiber-reinforced concrete. Similarly, Raposo et al. (Raposo et al., 2019) performed the LCA for concrete with seismic reinforcement along with their life cycle cost (LCC). The leading objective of the study was to optimize the process for the lowest environmental effect and cost. The study analyzed the BIM model of the prefabricated concrete building for the impact categories were Global warming, ozone depletion, acidification, smog formation, and eutrophication. Global warming is reported as the leading environmental effect followed by smog formation. The study reported the lack of ecological results for demolishing the building and lack of material in the LCA study database.

Several other studies on environmental impact analysis of concrete with external material for reinforcement, i.e. textile reinforcement concrete (Laiblováet al., 2019), fibre reinforced (Inman et al., 2017), (Cadenazzi et al., 2019), green hybrid fibre reinforced concrete (Hay and Ostertag, 2018). Portal et al. (Williams Portal et al., 2015) explored the sustainability potential for textile fiber reinforced concrete and compared it with other reinforcement fibres. Textile fibers are reported with higher sustainable potential as compared to carbon, glass, and basalt fibres. Textile fibers are also reported with high mechanical behavior. Basalt fibres have resulted in lower energy demand, while carbon had the least environmental impact. The studies with bar reinforcement concrete, where externally fabricated structures are used to modify the overall concrete structure, are not considered in this review. As they are not directly related to the sustainable concrete material nor 3D printing for concrete construction.

4.1.2. 3DP systems

The environmental effect of different aspects of 3D printing systems such as polymer 3D printing technology (Faludi et al., 2015), the industrialization of 3D printing technology (Ford and Despeisse, 2016), fused deposition modelling (FDM) for the novel material (Esposito Corcione et al., 2018) has been considered in the literature. However, there is a lack of studies examining 3D printing systems' environmental impact in large-scale concrete printing.

4.1.2.1. 3D printing technology for concrete construction. Few studies have extended the analysis to 3D printing technology's environmental impact for concrete construction as a greater system. Juan et al. (Agustí-Juan et al., 2017) investigated the ecological assessment and potential benefits of a robotically fabricated and complex concrete wall. The study aimed to assess the environmental opportunities of digital fabrication when applied to complex shapes. The mesh mould technique was used for the fabrication of a concrete wall with steel-wire-based mesh. LCA were performed to quantify the environmental effect of digital fabrication and compare it with conventional construction. The results proved that concrete materials are the major contributor in the case of a digitally fabricated wall. Environmental benefits of digital fabrication were reported for complex structures. While, conventional fabrication techniques had a less environmental impact for simple and plain walls. For digital fabrication, the additional complexity in the designs was achieved without added ecological impact.

Kuzmenko et al. (Kuzmenko et al., 2020) performed an LCA of 3D printing technology for concrete construction to determine the tradeoff between the environmental benefit of material-saving and the 3D printing system's impact. The assessment was performed with a 6-axis robotic arm with concrete printing and sensitivity study. Special focus was given to the automated system's environmental footprint by considering a detailed life cycle model for the printing cell. The study reported a significant contribution by the robotic printing system, even exceeding the materials in some cases. The environmental impact of the product could be improved by 15% with optimizing the printing process.

However, several variables, including the printing system, process, and material used, other studies reveal different parameters as lead causes of the environmental impact in 3D printing for concrete construction. For example, Alhumayani et al. (Alhumayani et al., 2020) performed the ecological analysis for 3D-printed load-bearing walls of small- or medium-sized houses and compared

Table 1
Modified concrete material for higher environmental sustainability potential, using life cycle assessment.

S. No	Author [ref.]	Analyzed Material	Major Added Components	Major Environmental impacts/outputs
1	McGrath et al. (McGrath et al., 2018)	Geopolymer concrete	Pulverized Fuel Ash (PFA)	. Allocation of mass as an important environmental parameter. . Designation of material as waste or byproduct changed the results.
2	Asadollahfardi et al. (Asadollahfardi et al., 2019)	multiple sustainable concrete	Geopolymer, Ordinary Portland cement, nano-silica, micro-nano bubble concrete, and micro-silica.	. Highest GWP in Geopolymer concrete with 26% reduction as compared to OPC. . Increase in GWP by 56%, 38% and 17% for micro-silica, micro-nano bubble and nano-silica concrete.
3	Petrillo et al. (Petrillo et al., 2016b)	Geopolymer vs OPC	Recycled clay soil, Waste and CDW as raw material in Geopolymer	. The use of CDW and recycled clay soil helps in solving resource conversion into useful byproducts and conservation of waste. . A high potential for carbon footprint reduction. . Transportation is an important variable to consider environmental impact.
4	The et al. (Teh et al., 2017)	*Ordinary and modified cement concrete*	Ordinary Portland Cement (OPC), Standard OPC, blended cement-based and geopolymer cement concrete	. OPC resulted in higher greenhouse gas emissions according to hybrid life-cycle assessment . For geopolymers, the results are sensitive to the method for allocation emissions form fly ash and slag.
5	Colangelo et al. (Colangelo et al., 2018b)	multiple sustainable concrete	CDW concrete, Marble Sludge concrete, Cement Kilin Dust (CKD).	.CDW and CDK mixture resulted in a lower impact. . Thirty-seven possible concrete recovery scenarios were analyzed. . The optimal solution for concrete production is analyzed to minimal emission and production impacts.
6	Zhang et al. (Zhang et al., 2019)	RCA concrete	Recycled Concrete aggregates and natural concrete aggregates	. Transportation distance for aggregates is one of the critical parameters
7	Jiménez et al. (Jiménez et al., 2018)	Recycled aggregates concrete	recycled and crushed virgin limestone aggregates	. Cement is the highest contributor to emissions. . The decrease in emissions with an increase in recycled aggregates.
10	Shi et al. (Shi et al., 2018)	Recycled aggregates concrete	Recycled asphalt as aggregates in OPC concrete	. Reported economic, social and environmental benefits for RAA.
11	Xia et al. (Mah et al., 2018)	Recycled aggregates concrete	Recycled concrete aggregates	.introduce a novel framework for LCA with sustainable design parameters, unified system boundary and indicator function. . 13% and 15% reduction in ADP and GWP for 100% RCA.
12	Kurda et al. (Kurda et al., 2018)	multiple sustainable concrete	Recycle concrete Aggregates (RCA), Fly ash with and without Superplasticizer	. Superplasticizer increased environmental impacts . RCA resulted in no impact on most of the environmental impact categories. . The coarse natural aggregates performed better than RCA.
13	Shi et al. (Shi et al., 2019)	Recycled aggregates	RCA and Ordinary Portland cement with natural aggregates	. RCA based Portland cement concrete are more environmentally and socially sustainable. . Potential of RCA for decreasing environmental impact are higher in-use phase than the production phase.
14	Svetlana Pushkar (Pushkar, 2019)	Byproduct in concrete	Replacement of Sand with Coal Bottom Ash.	. The replacement was environmentally beneficial for mixture with the fixed slump. . Environmentally harmful for mixture with a fixed water/cement ratio.
15	Byproduct	Byproduct in concrete	Byproduct for cement and aggregate replacement	. 40% cement replacement with fly ash results in approximately 43% carbon footprint and 38% embodied energy consumption.
16	Matos et al. (de Matos et al., 2019)	Byproduct in concrete	Replacement of cement with Flyash	. Fly ash replacement enhanced rheological properties . FA grinding resulted in higher stability and compressive strength. 60% replacement resulted in a 30% CO_2 emission.
17	Seto et al. (Seto et al., 2017)	Byproduct in concrete	Replacement of cement with Flyash	. A higher percentage of fly ash resulted in lower ecological impacts. . Allocation is reported as a sensitive variable for overall environmental impact.
18	Raun and Unluer (Ruan and Unluer, 2017)	multiple sustainable concrete	Replacement of fly ash with MgO and ground granulated blast furnace slag (GGBS)	. 50% replacement with fly ash resulted in highest strength. . Fly ash and GGBS both resulted in lower ecological impact by replacement of MgO.
19	Domagoj Nakic (Nakic, 2018)	Waste	sewage sludge ash (SSA) based concrete	. 10% of ordinary cement was replaced with SSA . Same technical performance. . Approx. 9% lower environmental impact for GWP. Potential for reducing GHG and energy conservation.
20	Deschamps et al. (Deschamps et al., 2018)	Waste	Glass powder in concrete	. Transportation is reported as sensitive variable . High environmental potential for glass powder.
21	Yin et al. (Yin et al., 2016)	Recycled material	Recycled polypropylene (PP) fibre in concrete	. Recycled PP fibers were compared with virgin PP and steel mesh . Lower environmental impact is reported for recycled PP.
22	Aysegul Petek Gursel (Gursel and Ostertag, 2019)	Waste material	Copper slag aggregates	. Environmental impact decreases with an increase in Cu slag aggregates . For 40 and 100% replacement, reduction in: GWP 7% and 35%, embodied energy 8% and 40%, particulate matter formation 7% and 35%.
23	Svetlana Pushkar (Pushkar, 2017)	Byproduct in concrete	Blast furnace slag	. Effect of blast furnace slag on compressive strength and the environmental effect is analyzed. . Considering blast furnace slag as byproduct or waste is observed as sensitive terminology for environmental impact analysis.
24	(Mohammad et al., 2020)	role of reinforcement, new light weight material	expanded perlite (EXP) by relpace river sand	. EXP based light weight and high thermal insulated printible concrete material. The study reported decrease in AP, GWP, EP and FFD impact using 3D printing.

that with conventional construction techniques. Two different materials, concrete and Cob (an earth-based sustainable material), were analyzed in this study. The Cob material resulted in lower environmental impacts and GWP for both conventional and 3D printing techniques. While, concrete-based 3D-printed structures resulted in higher environmental impacts in GWP, stratospheric ozone depletion, and fine particulate matter formation. Further material science research and renewable energy practice were recommended.

Weng et al. (Wenget al., 2020) perform a comparative analysis of productivity, environmental impacts, and economic analysis for concrete-based prefabricated and 3D-printed prefabricated bathroom structures. Extrusion-based technology is used for 3D printing. Factors including electricity expenditure, material consumption, installation cost, and labor cost were compared in this study. The results reported an 85.9% reduction in CO_2 emission, a 25.4% reduction in cost, and an 87% reduction in energy consumption for the 3D-printed structure. A 48% improvement was reported for productivity, and a 26% improvement was noted for self-weight reduction. The study reported the feasibility of 3D printing technology for concrete-based prefabricated structures. These studies are summarized in Table 2.

4.2. Economic effect

Due to the construction industry's cost-sensitive nature, the implementation of 3D printing technology is highly dependent on its economic sustainability (Mata-Falcón et al., 2019), (Matoset al., 2018). Many studies have presumed the economic sustainability and high productivity for 3D printing technology in concrete construction (Ma et al., 2020; Kastiukas et al., 2020; Ghaffar et al., 2018b), and several websites and weblogs (e.g. www.3ders.org) have reported reduced construction budgets. For example, WinSub reported a $4800 cost for a 3D-printed house of approximately 200 m^2, significantly lower than the price of the same home constructed conventionally (Wu et al., 2016). However, 3D printing technologies' economic feasibility for concrete construction is still being researched (Siddika et al., 2019).

Life-cycle cost (LCC) is the most-used technique used in literature to investigate the economic advantages and disadvantages of concrete 3D printed structures over a specific study period. It accounts for the owning, working, maintaining, and disposing of raw material cost (Petrillo et al., 2016b). Material is the most-considered aspect of 3D printing technology for concrete structures in terms of economic sustainability. Investigating geopolymer concrete's sustainability, Petrillo et al. (Petrillo et al., 2016a) recommended an increase in industrial waste such as fly ash or blast waste for both economic and environmental sustainability. Illankon et al. (Illankoon et al., 2018) investigated different percentages of silica fume, fly ash, and slag as supplementary cementitious material using the LCC method. The results reported a slight difference in overall results for all three materials. Several other studies have also investigated green concrete's economic sustainability (Srinivas Reddy and BalaMurugan, 2020; Jahanbakhsh et al., 2020; Berg et al., 2006; Younis et al., 2018).

The involvement of 3D printing not only affords the possibility of one-step fabrication for concrete structures with fine details, aesthetic design, or complex geometries, but it also provides more economical solutions in terms of required efforts, energy, and material saving. Buswell et al. (Buswell et al., 2007) reported a high 3D printing technology cost for simple concrete structures due to the involved unique material required for printing. Similarly, Le et al. (Leet al., 2012) reported the possibility of a reduction in both remedial work and construction material resulting from the integration of mechanical and electrical services. However, the cost can be reduced for designs with more complex shapes or added amenities like built-in electrical conducts.

The economic feasibility of 3D printing technology for concrete construction also depends on the choice of method. It is possible, for instance, that the mesh mould technique holds more significant potential for economic sustainability than both the EP and BJM due to the possibility it affords for the exclusion of the complex concrete printing process, high-cost reinforcement replacement, and the time it saves. In their study, de Soto et al. (Esposito Corcione et al., 2018) reported higher productivity for a 3D printing wall using mesh mould technology than for traditional construction. The study reported that no additional cost came with the structure's increased complexity. They also noted the weight reduction of the overall design due to the elimination of manual reinforcement.

As the majority of automatic industries have high capital-cost, and it is essential to include the cost of the 3D printer in the overall construction (Pan et al., 2018). Although the price of 3D printers has been decreasing significantly in recent years, the particular software packages required for the source code to compile and edit for the printing of large houses and architectural models—could add to the overall cost. Apart from these short-term advantages and disadvantages, empirical studies are still required to understand financial performance over a concrete construction project's lifespan.

Although a key factor of automation in any industry is its ability to reduce costs, 3D printing technology's economic feasibility for concrete construction as a whole system has yet to be determined. Contradictory results in literature identify the need for a standard methodology for measuring economic feasibility. Many variables

Table 2
Life Cycle Assessment of 3D printing technology for concrete construction.

S. No	Material	Printing technology	Major Environmental Effects Contributor			Ref.
			1	2	3	
1	*Concrete (Portland cement)*	*EP: Concrete printing, mortar 3D Printing: 6-axis robotic system with a printing head.*	*Concrete material*	*Printing system*	-	Kuzmenko et al. (2020)
2	*Concrete (Portland cement)*	*Mesh mould technique fabricated robotically through steel wires cutting, bending, and welding.*	*Concrete material*	*Reinforced steel production*	*Robot and tool production (digital technology)*	Agustí-Juan et al. (2017)
3	*Geopolymer Concrete*	*Large-scale inkjet 3D printer*	*Fly ash and Slag production (for geopolymer concrete)*	*Silicate (for geopolymer concrete)*	*Transportation*	Yao et al. (2020)
4	*Concrete and Cob*	*EP: Contour crafting*	*Concrete (ordinary cement)*	*Cob*	-	Alhumayani et al. (2020)
5	*concrete*	*EP: Extrusion-based compared to precast method*	*Electricity (precast)*	*Form-work (precast method)*	*Concrete (3D printed extrusion)*	Wenget al. (2020)

are involved, which can cause different effects for the same technology depending on scale, time, or location. The lack of data is one of the reasons for limited exploration. Raposo et al. (Raposo et al., 2019) performed an LCA for concrete with seismic reinforcement along with their life cycle cost (LCC). The LCC accounts for all the expenses from conception up to final discarding. The calculation considered workforce, material, and equipment cost. The inflation rate and other economic indicators were not applied due to difficulty in projection and availability of the data for the involved lifetime, approximately 50 years.

4.3. Social impact

Three-dimensional printing technology is gaining popularity in media as a solution for cost-effective housing worldwide. The technology is encouraged by a small but growing group of enthusiast research groups, industries, and hobbyists for successful implementation in the construction market. However, it is still a construction industry phenomenon that requires more exploration for the current social climate. This section covers the social assessment of 3D printing technology for concrete construction in terms of its effects on society, including the loss or replacement of jobs, the requirement of more skilled workers, the high safety level, and the acceptance of the current technology a replacement for traditional construction.

Three-dimensional printing is a computer-controlled technique. Its application in construction could reduce the required labour force significantly, which will result in the reduction of jobs; approximately 24% of construction jobs in the UK, 26% in Japan, 35% in the US, and 41% in Germany will be automated by 2030 (Garcíade Sotoet al., 2018). Notably, construction is one of the primary sources of income for labour in developing countries. Along with other advantages, the reduction in labour could be a significant consequence. However, due to technology's programmable nature, the required skill is easy to learn, affording fewer chances for error.

Although low-skill occupations could be at risk due to automation in the construction industry, the application of 3D printing technology for construction will also result in the creation of high-quality jobs regarding the manufacturing of the 3D printer, the innovation and preparation of new material, supplies, and the design of new infrastructure. High-skill tasks will be replaced with routine tasks, and the need for medium-qualified jobs will increase (Garcíade Sotoet al., 2018). Due to the possibility of local material and waste, the technology could also decrease imports and help the local job market.

The easy fabrication process of complex concrete structures by formwork-like techniques can increase small industries for prefabricated concrete structures. The waste reduction, resulting from the development of recycled and waste-based concrete and the near-zero waste involved in 3D printing construction techniques, is another social advantage of this technology.

Due to its digital and automatic nature, this technology has the potential to advance human wellbeing through difficult situations, like disaster management, or those who require aid in remote areas that are difficult to access. However, like most new technology, 3D printing in construction is also expected to face social adaptation challenges. For this purpose, good policies will need to be prepared and implemented once the environmental, economic, and social sustainability potentialities have been thoroughly explored.

5. Research gaps and future recommendations

This section summarizes the research issues and gaps identified by the literature and put a prediction forwards for the future direction and needs of 3DP technology for the construction industry through the scope of technical, environmental, and socio-economic sustainability.

1. Since cementitious binders are the major contributor to concrete 3D printing structures' environmental impacts, for building more sustainable and robust constructions, there is a need to develop more durable and environmentally friendly binders to replace OPC.
2. Since complexity does not result in further environmental cost, high-performance and multifaceted design can be easily applied in concrete 3D printing.
3. Lower resolution in 3DP can also be applied to decrease the required time, cost and material. Such strategies can be learned from already developed 3DP applications, i.e., metal and polymer printing.
4. Since high mechanical strength and ductility are crucial structural requirements, the high-performance composite polymer with high mechanical strength and ductility should be investigated for the Mesh Mould technique.
5. Steel provides one of the highest environmental effects in concrete structures; high-performance composite polymer should be examined to replace or decrease the required steel in a concrete formwork in the Mesh Mould technique.
6. Transportation and Ordinary Portland cement (OPC) are the leading factors in 3D printing technology's environmental impact on concrete. The increase in local material, with higher ecological sustainability, needs to be considered to overcome this challenge.
7. High strength and more sustainable material should be synthesized for the Mesh Mould technique due to its potential to replace many of the environmental and technical challenges of direct concrete printing.
8. Because 3DP technology requires more energy than conventional concrete construction, using renewable energy in 3D printing for concrete construction can make the process more sustainable.
9. The overall cost of 3D printing technology in the concrete structure has not been definitively discovered. Apart from the results from short-term benefits and shortcomings, empirical studies must understand the financial performance over a concrete construction project's entire lifespan.
10. An integrated sustainability assessment tool is needed to systematically assess the environmental, economic, and social aspects of concrete 3D printing technology.

6. Conclusion

Considering the current environmental circumstances and increasing demands from the building sector, techniques like 3DP that are more sustainable, innovative, and efficient must be adopted by the construction industry. This study investigated the sustainability of 3D printing technologies for concrete construction in the built environment. The extrusion printing, powder-bed, and 3-D printed permeable technique methods are three leading 3D printing technologies used for concrete structures. The LCA and LCI are widely used techniques for examining the environmental and economic feasibility of the technology. The primary outcomes of the study can be summarized as:

- Three-dimensional printing is an environmentally friendly technique with minimal waste. The potential benefit of digital fabrication increases proportionally with the level of complexity in a design.

- An integrated sustainability assessment tool is needed for environmental, economic, and social aspects to assess concrete 3D printing sustainability in construction systematically.
- Portland cement is a leading component in the environmental impact of concrete material due to its energy-intensive process and the chemical reaction involved in its production.
- The scientific community continuously attempts to avoid ordinary concrete and modify it with more sustainable materials such as blast furnace slag, fly ash, marble sludge, recycled concrete, and CDW.
- The majority of recycled aggregates studied have identified the transportation distance for sums as a variable sensitive to environmental impacts. The onsite or nearby production of recycled aggregates is environmentally preferred.
- An interconnection between advanced material design and digital fabrication is highly recommended.
- The potential benefit of digital fabrication increases proportionally with the level of complexity in a design. However, the 3D printing process's environmental impact does not grow with the architectural form's uniqueness and complexity.
- Since the 3D printing process is energy-intensive, the application of renewable energy sources to 3D printing in concrete construction can make the process more sustainable both environmentally and economically.
- The introduction of 3D printing technology into concrete construction can reduce human power's overall cost and reduce remedial work and material. However, technology's economic feasibility as a whole system has yet to be determined.
- Apart from these short-term advantages and disadvantages, empirical studies are still required to understand financial performance over a concrete construction project's lifespan.
- Its application could affect the labour's job market. However, there is also a possibility of creating high-quality jobs related to the manufacturing of the 3D printer and the innovation and preparation of new material, supplies, and new infrastructure design.

Declaration of competing interest

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

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