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Review

3D Concrete Printing: Recent Progress, Applications, Challenges, and Role in Achieving Sustainable Development Goals

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Abstract: This work explores the role of 3D concrete printing (3DCP) in achieving the relevant sustainable development goals (SDGs) that were set out by the United Nations. The study focuses on the recent progress and limitations of the three dominant types of cementitious mixtures, ordinary Portland cement (OPC), recycled aggregate-based cement, and geopolymers, and real-world applications for 3DCP. The study reveals that 3DCP has a significant advantage in terms of cost, with a potential to save around 78% and 60% of the costs associated with conventional construction methods and labor, respectively. Moreover, 3DCP consumes less water than conventional construction methods, with a water usage reduction of 20%. Additionally, it was found that 3DCP is on track to reduce the global energy utilization by 5% by the year 2025. Even though 3DCP bears a lower climate change impact, there is still work to be done to improve its sustainability.

Keywords: 3D printing; cement; applications; challenges and barriers; sustainable development goals

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Citation: Alami, A.H.; Olabi, A.G.; Ayoub, M.; Aljaghoub, H.; Alasad, S.; Abdelkareem, M.A. 3D Concrete Printing: Recent Progress, Applications, Challenges, and Role in Achieving Sustainable Development Goals. *Buildings* **2023**, *13*, 924. https://doi.org/10.3390/buildings13040924

Academic Editor: Łukasz Sadowski

Received: 8 March 2023
Revised: 21 March 2023
Accepted: 29 March 2023
Published: 31 March 2023

1. Introduction

With the rapid population growth and the acceleration of urbanization, existing construction methods are bound to become obsolete [1]. Conventional construction methods lack considerations regarding waste repurposing and environmental protection [2,3], as well as their notorious economic deficiencies, making it difficult for developing countries and low-income communities to provide or sustain affordable housing [4]. Concrete is a conventional mixture used in construction that is composed of various key components such as aggregates, a binding cementitious material, and water. Moreover, 3D concrete printing (3DCP) offers a viable alternative to streamline conventional construction methods [5] and attenuate their everlasting challenges in order to increase the efficiency and reduce the overall cost of construction, all while having a lower environmental impact [6].

Research and development in 3DCP focus on fabricating sustainable materials for a futuristic utilization of this technology [7]. The result is a wide arsenal of materials such as ordinary Portland cement (OPC), recycled aggregate [8], and geopolymer-based cementitious binders [9]. OPC is a type of cement that is used in conventional construction and 3D printing applications. OPC hardens and sets when it is mixed with water, providing desired rheological properties, such as the ability to withstand high pressures, tensile forces, facilitating its resistance to external harsh conditions, as well as fire, rust, and rot resistance, and flexibility in molding and shaping [10]. Aggregates are considered main components in concrete that add volume and bulkiness to the mixture, as well as dictate its overall mechanical properties [11]. On a similar note, recent research is concerned with replacing conventional aggregates with recycled alternatives, to attenuate negative environmental effects and reduce the cost of 3DCP, as well as repurposing waste feedstock. Finally, geopolymers utilize industrial waste, such as fly ash (FA), silica fume (SF), and slag [12], with alkaline activators to produce a cementitious-like mixture, with competitive properties and lower environmental impacts. Through automated robotic arms, these materials are activated (using water) and are printed with a high accuracy and efficiency to build targeted structures that can bear flexible complex designs.

Moreover, 3DCP has the ability to effectively lay the groundwork for achieving some of the 17 sustainable development goals (SDGs) set out by the United Nations [13]. The SDGs are a set of 17 goals that were established to address global issues and challenges, such as poverty, climate change, and inequality [14]. For example, 3DCP is a sought-out technology to tackle goals targeting poverty (SDG1), global health and well-being (SDG3), clean water and sanitation (SDG 6), and climate action (SDG13). This is a result of the diversity of sectors that are affected by the conventional construction industry, with a greener alternative being the salvation from many obstacles. The impact of 3DCP on the SDGs is shown in Figure 1. Figure 2 represents the keyword analysis obtained from the VOSviewer software. Each node in the figure represents a keyword. The size of the node indicates the number of times it has been mentioned in research papers. In this keyword analysis, the most trending topic of 3D printing is 3D concrete printing.

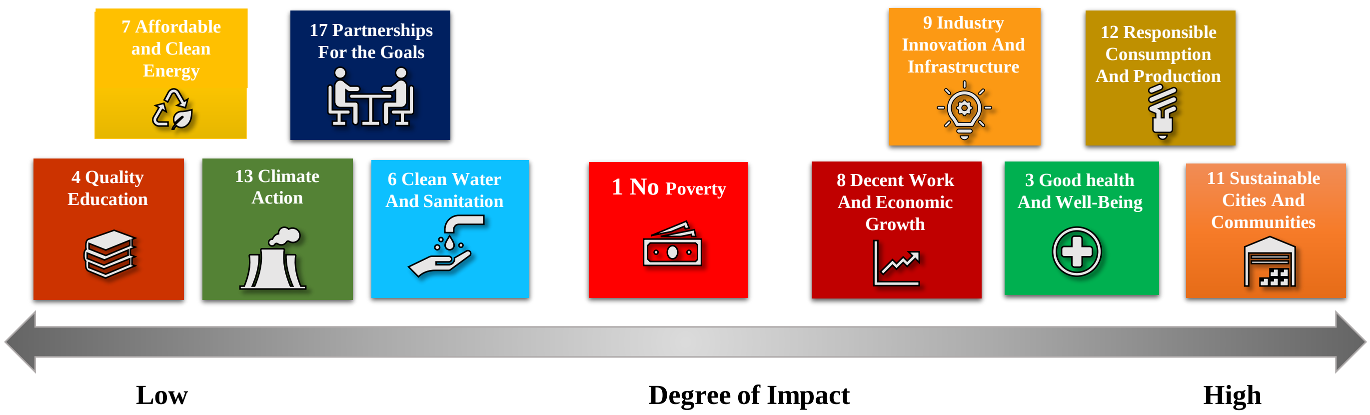

Figure 1. Impact of 3DCP on the SDGs.

This study aims to provide an analysis of the current state of 3DCP, specifically in relation to 3D printing across various materials. The purpose of this analysis is to establish a foundation for predicting the future of this industry, by examining both its recent advancements and its present limitations. In addition, the study delves into the impact of 3DCP on the global community, with respect to its ability to contribute towards the achievement of the United Nations Sustainable Development Goals (SDGs). To accomplish this, the study explores the relevance of 3DCP to each of the SDGs and evaluates its potential to make a significant positive impact on each. The findings of this study are expected to provide valuable insights into the present and future state of the 3D printing industry, as well as its potential to contribute to the greater good of humanity. Through a thorough examination of 3DCP advancements and limitations, this study aims to facilitate a better understanding of the possibilities and challenges facing this growing industry.

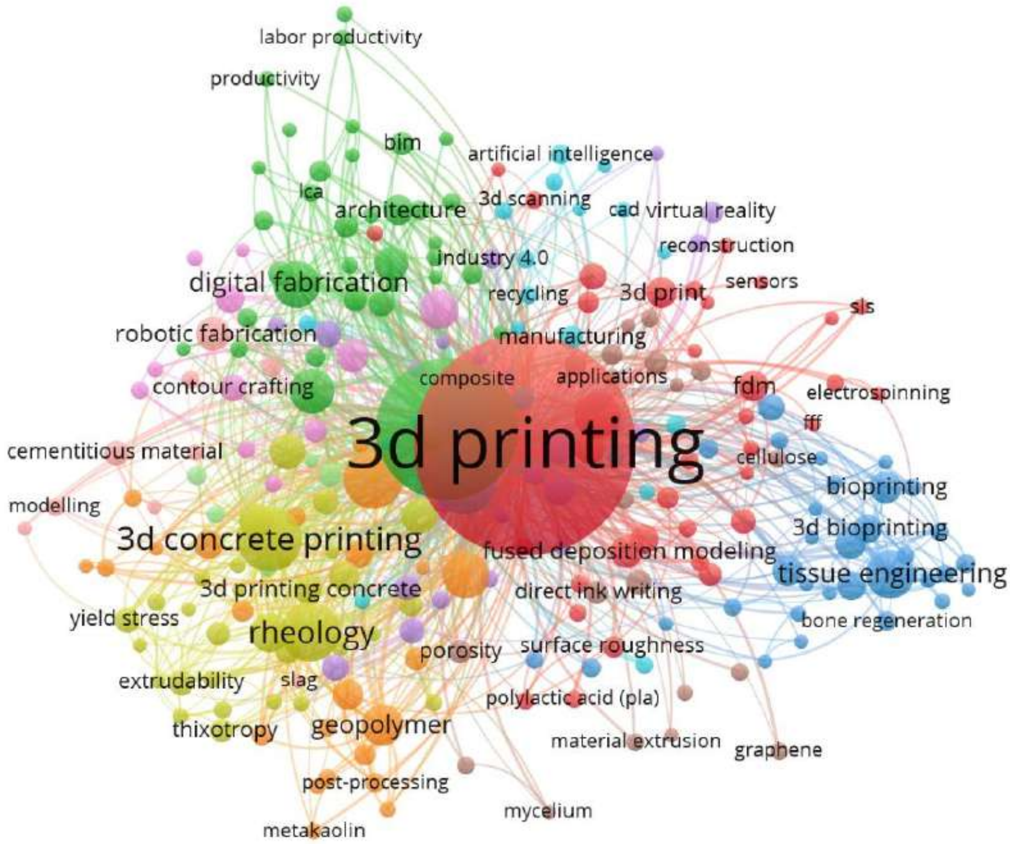

Figure 2. A demonstration of the keyword analysis conducted via VOSviewer software.

2. 3D Concrete Printing

3D concrete printing (3DCP) is an increasingly engaging topic in the context of the future of sustainability, given the combined precision and speed of the 3D printing process, with competitive advantages in terms of durability and strength. 3DCP has the potential to revolutionize the construction industry and facilitate the emergence of large-scale complex structures, with a lucrative building efficiency and low overall costs. Moreover, this industry has a wide potential in repurposing industrial waste through the different building mixtures that are currently under research and development. For instance, Portland cement is the most commonly used cement mixture in construction worldwide. Current research is directed towards decreasing the environmental impact of Portland cement by replacing some of the components in cement mixtures with cheaper and more abundant materials in order to optimize the 3DCP process, which is where alternatives that use recycled aggregates, as well as geopolymers, come into play. In this section the concept and recent progress of ordinary Portland cement, recycled aggregate-based concrete, and geopolymers-based 3DCP are discussed.

2.1. Ordinary Portland Cement (OPC) 3D Printing

For 3D printing applications specifically, OPC is mixed with other additives to allow for a printable material that can be extruded. A 3D-ready OPC is fed through a nozzle into the printer and is layered onto the desired area to construct the end structure. Moreover, 3D printing allows the construction of complex shapes that would otherwise be difficult to achieve via conventional techniques. However, there are challenges to be overcome in terms of 3DCP due to the high abrasive nature of the printed material.

There are three main parameters to be considered when dealing with 3DCP materials which are the workability, printability, and buildability. The workability of a cement 3D printing mixtures is determined by the open time available when the cement is in contact with water. The printability is the ability of the material to pass through a printing nozzle with minimal adverse effects on the printing mechanism and the properties of the material. Finally, the buildability of a material is limited by the ability of layering the material over a base, or the material itself. The current research is focused on different additives that are utilized to fine-tune these parameters for an optimized 3D printing process.

Souza et al. [15] demonstrated the effects of adding setting retarders (sucrose $C_{12}H_{22}O_{11}$), accelerators (calcium nitrate-based, and calcium chloride dihydrate), and superplasticizers (third-generation polycarboxylate ether-based) in the process of 3DCP. The setting retarders and superplasticizers showed an enhancement in the open time for the cement mixture, while the accelerators increased the structuration rate of the cement mixtures. Moreover, the need for additives such as the previously utilized accelerators is emphasized by studies, such as the one conducted by Reales et al. [16], where nanosilica particles were used to study the effect of the fresh state properties of OPC paste, and compared them to those of conventional microparticles such as microsilica, metakaolin, and nanoclay. The nanosilica addition was observed to have enhanced the initial yield stress and the thixotropic build up rate of the paste (the degree of viscosity under the effect of stirring); however, a limitation constrained by the maximum and minimum printing velocities arose and could be attenuated with the use of accelerator additives. Additionally, binder/water mixing ratios are also essential in determining the operation of 3DCP as well as curing time. Chaiyotha et al. [17] determined an optimum binder/water mixing ratio of 0.35 (which is a common ratio even with other cementitious pastes) and a limewater-based curing process for a period of 7, 14, and 28 days, with a 12.36 MPa strength achieved.

2.2. Recycled Aggregates in Conventional Concrete

Aggregates can be defined as inert geological materials, such as gravel, sand, and rocks, that are added to a concrete mixture in order to add bulkiness and volume (making up 60% to 75% of its volume [18]) and enhance its mechanical properties. Furthermore, strength is an important aspect of any concrete mixture and is heavily influenced by its aggregate content, as it helps to evenly distribute any load or stress applied on its final form. Additionally, the more aggregate content added to a concrete mixture, the less it costs to produce it, given how easily obtainable aggregates are. Moreover, the coarse structure of the utilized grains impacts the end texture of the concrete mixture, which can be altered to obtain specific finishes. Although it is worth noting that the coarse nature of a concrete mixture dictates the processing and the 3D printing applicability, given that different printing techniques adhere to specific coarse aggregates requirements [19].

Recycled aggregates, such as recycled concrete, glass, sand, and fine aggregates harbor the previously discussed merits with the addition of providing numerous environmental benefits which are manifested in the reduction of raw conventional aggregate production such as gravel, given that in some geographic locations gravel has been deemed scarce, which means that turning to artificially produced or recycled aggregates is economically and socially more feasible. Moreover, recycled aggregates repurpose waste materials thus reducing potential greenhouse gas emissions that are associated with virgin aggregate production. Additionally, recycled aggregates can be used to achieve various sustainable development goals, such as SDGs 7, 12, and 13, set out by the United Nations given their high environmental sustainability.

Ding et al. [20] investigated the addition of recycled sand sourced from old, crushed concrete, in concrete mixtures for 3D printing purposes. Recycled sand is a conventional byproduct of construction and demolition waste, which means that employing recycled sand will improve the sustainability of the 3D printed concrete structures. Their study reported the effects on the parameters such as the curing age, nozzle height for 3D printing, tensile splitting strength, and flexural strength. The utilized sand particles were up to 0.90 mm, which were obtained from 100% waste concrete and used as the fine aggregate. It was noted that the water requirement for the concrete mixture increased with increasing the recycled sand content. Moreover, the compressive strength decreased by increasing the recycled sand content with reduction percentages reaching

31%. A similar behavior was witnessed for the tensile splitting strength. However, the flexural strength increased up to a recycled sand content of 25% and decreased above that threshold. Having this property, concrete with recycled sand can be used for applications that require materials that withstand high loads, given how they can counter bending and deformation.

Liu et al. [21] investigated the addition of recycled coarse aggregate (RCA) which, similar to recycled sand, comes from demolition and construction waste, in concrete mixtures for 3D printing. Their recycled coarse aggregate was similar to a baseline natural coarse aggregate (NCA), which was sourced from natural gravel, in terms of density at an apparent density of ~2500–2700 kg/m^3 for RCA and NCA, respectively. However, the water absorption for RCA was higher at 7.29 vs. 1.1 for NCA, which led to an increase in the total amount of cement relative to the water content. Moreover, the increased surface roughness of RCA increases its bonding with the existing mortar matrix. Finally, given these two factors, the mechanical strength of the 3D-printed RCA-containing concrete to have favorable mechanical strength properties, not far from those containing NCA, while bearing less effects on the environment and being more economically feasible.

Heidi et al. [22] utilized recycled brick aggregate (RBA) by replacing 64% of the natural aggregate present in an existing 3D printable concrete mixture. Incorporating RBA into the concrete mixture increased the water requirements due to the porous nature of the utilized bricks and their high-water absorption ability, which can negatively impact SDG 6 (clean water and sanitation). Moreover, optimizing the %RBA in the mix can potentially aid in reaching a desired packing density. Although the resulting concrete mixture had low compressive cube strength, and low interlayer and low 3D printed compressive strength, it showed good printability and high repeatability.

Zou et al. [23] studied the addition of recycled fine aggregate (RFA) in 3D printing mixtures with RFA contents of 0%, 50%, and 100% in place of conventional concrete aggregate. It was noted that increasing the RFA content increased the water requirement given the increased water absorption in comparison to the initial aggregate source. The shear stress and viscosity increased over time with increasing RFA%. Moreover, Hao et al. [24] utilized RFA as a support material for a parafilm wax phase change material (PCM) to alter the thermal conductivity of 3D-printed concrete; it was found that the thermal conductivity of PCM-impregnated RFA cement was close to 31% lower than that of mold-casted concrete which can affect the number of printing layers, path, and extrusion rate. Table 1 shows a comparison of different recycled aggregates that were utilized in concrete mixtures with their advantages and disadvantages.

Table 1. Recycled Aggregates Comparison.

Recycled Aggregate	Advantages	Disadvantages	Ref.
Recycled Sand Aggregate (RSA)	Increased the flexural strength with 25% content.	Decreases compressive and tensile splitting strength	[20]
Recycled Coarse Aggregate (RCA)	Increase in the total amount of cement relative to the water content	Unfavorable mechanical strength relative to that of natural coarse aggregates	[21]
Recycled Brick Aggregate (RBA)	Can reach specific packing densities. Good printability and repeatability.	Porous—requires more water Low mechanical strength	[22]
Recycled Fine Aggregate (RFA)	Has a mutual hardening and printing rate, allowing for continuous printing of material. Can be the host matrix for PCM to alter the thermal conductivity of the printed concrete mixture.	Requires a feeding system with a high rate and continuous shearing	[23,24]

2.3. Geopolymers

Geopolymers are a type of material that have been recently implemented and grasped a great deal of attention in 3DCP applications. To put it in simple terms, geopolymers are created by mixing industrial waste such as fly ash (FA), slag, and silica fume (SF), known as aluminosilicate precursors, with an alkaline activator to make up a cementitious material. The first step is the preparation of the aluminosilicate precursor, which is done by grinding the precursor to achieve a workable particle size, which is then subsequently dried to remove any residual moisture. Then, the alkaline activator, which is usually a mixture between an alkali metal silicate, such as sodium silicate or potassium silicate, and an alkali metal hydroxide, such as sodium hydroxide or potassium hydroxide. The geopolymer paste is finally formed after mixing in the dried aluminosilicate precursor with the alkaline activator. The geopolymer paste can then be used in an arsenal of applications such as casting, molding, or in this specific case, 3D printing.

The grand motive behind transitioning into geopolymers in 3D printing is the reduced environmental impact of the end buildings, contrary to traditional ones. Geopolymers repurpose industrial waste into workable cement-like pastes for 3D printing, and thus reducing the amount of waste that goes into landfills. Furthermore, geopolymers utilize less energy during their manufacturing process, leading to an overall reduced carbon footprint for buildings that are based off their derived materials. Additionally, geopolymers are flexible and can be tuned in order to achieve specific requirements for different applications. Finally, geopolymers can revolutionize the construction industry, given how feasible geopolymers are in comparison to conventional ordinary Portland cement OPC. In addition, geopolymers and OPC share similar characteristics, such as high compressive strength, fire resistance, and chemical, mechanical, and thermal stabilities.

Fly ash (FA) is a waste product of coal power plants, that is essentially a fine powder with a propensity to become airborne and cause respiratory health issues. However, combining FA with an alkaline activator can aid in remedying this, by producing a workable paste for 3DCP. Moreover, silica fume (microsilica) is a fine powder that harbors a lot of silicon dioxide, which makes for a good aluminosilicate precursor component. Slag is used as a supplementary cementitious material (SCM) instead of conventional aggregate and is employed in geopolymers to fine tune its mechanical properties. Finally, metakaolin is a good precursor for geopolymer production due to the ease of the Si/Al content tuning; however, it is rather rare and expensive, which gives the other alternatives an edge over it.

Markzyk et al. [12] investigated geopolymers comprising of fly ash (FA) and metakaolin (MK) KM60. The FA was collected from the combined heat and power plant in Skawina, Poland. The aluminosilicate precursors were mixed in with sand at a 1:1 ratio and activated with 10M NaOH, where the ratio of NaOH to water was fixed at 1:2.5. It was noted that the increased Si-O-Si bonds within FA promoted better mechanical properties, such as compressive and flexural strength, after 28 days of curing, due to the residual silica acting as reinforcement. Moreover, Guo et al. [25] investigated the addition of slag and silica powder as additives to an FA-based geopolymer. The utilized FA comprised mostly silica at 53% and Al_2O_3 at 28%, while the slag powder mostly consisted of CaO and silica. It was found that the most suitable content of slag powder and silica fume was 10%, where the rheological properties hit a threshold. It was noted that the gel formation at the center of the print was better than the surface, according to SEM observations. Panda et al. [26] studied a relatively similar 3D printing mix, fly ash with ground granulated blast furnace slag (GGBS) (binder), with the addition of sand where the weight ratio (sand/binder) was varied from 1.1 to 1.9. It was noted that the mixture with a sand/binder ratio of 1.5 showed a yield stress in the range of 0.6–1 kPa and a smooth extrusion process. Moreover, the same type of mixture showed a favorable shape orientation (SRF) which is the ability of the cured mixture to retain its shape under its own weight. Additionally, Panda et al. [27] conducted a similar study where they utilized FA, OPC with FA replacements ranging from 50 to 80%, and SF with a fixed water/binder ratio of 0.45 and a sand/binder ratio of 1.35. It was found that further addition of FA after the 50% mark reduced the yield stress and viscosity, which was attributed to the spherical shape of the FA that prevented the friction force between the OPC particles. Moreover, SF addition up to 5% showed an enhancement of the yield stress properties.

3. Applications

The implementation of 3DCP in the construction sector has proven to be a viable option for infrastructure, façade elements, modular building support, stairs, outdoor furniture, and complicated wall design applications [28], which can have a significant impact on the different SDGs, especially SDG 11, as will be discussed in the following sections. There are various elements that make up a usable 3DCP system, which the previously mentioned printing materials take up a small part in. A 3DCP setup consists of a concrete mixer, that is connected via pipes to a pump that supplies the material to a printing nozzle, which essentially carries out the operation until the final form of the 3D printed structure is reached. The process is shown in Figure 3.

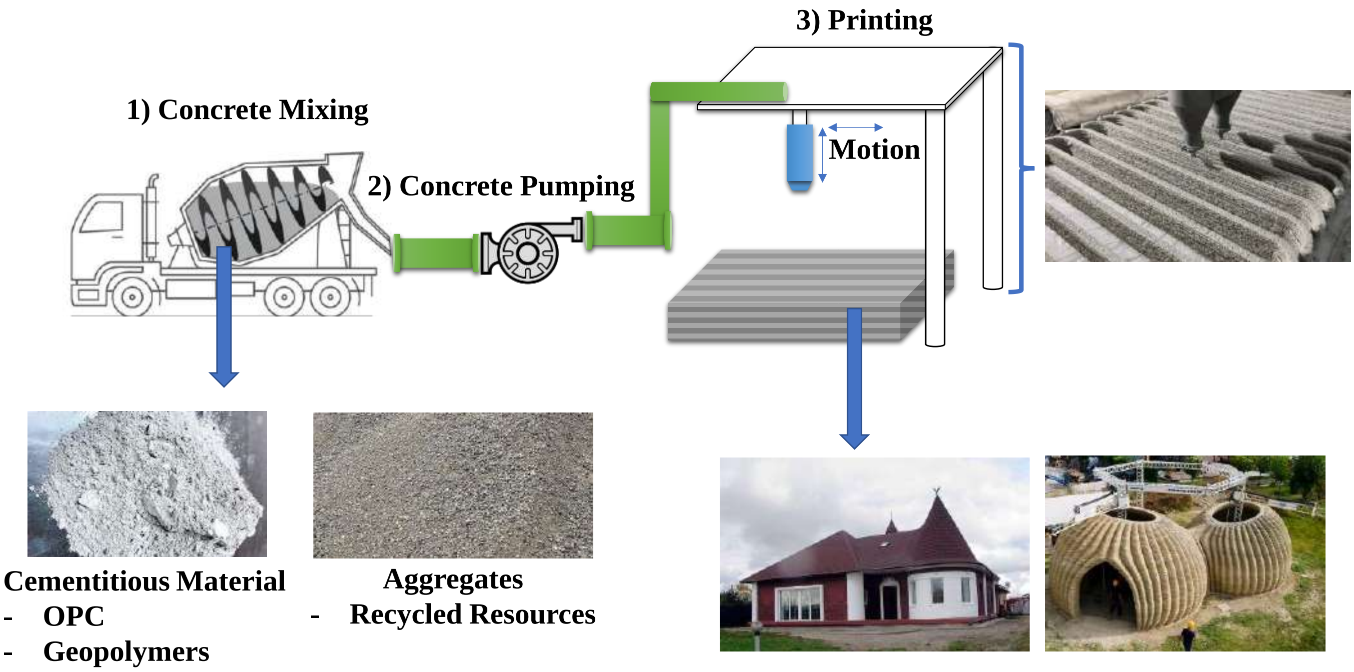

Figure 3. 3DCP Process [29–36].

A 3DCP pilot project was commenced in the Dutch city of Eindhoven, which is essentially a commercial housing project that is the fruition of a collaboration between a local construction firm "Houben & Van Mierlo Architecten" and the "Eindhoven University of Technology". One of the houses that was included in the plan is a 95-square-meter, three-room, single-floor house that was said to be followed by multi-story houses [37]. Moreover, the lifetime of this structure is said to be measured in decades. The novel boulder design of this house makes it blend in with the surrounding environment. The house consisted of 24 elements that were printing at the Eindhoven University of Technology, with a total printing time of 120 h, transported to the targeted site, and securely placed on pre-built foundations [38].

Project Virginia, taking place in Virginia, United States, is a 200-house 3D printing project that is planned to take place over the next 5 years. The project will utilize the Black Buffalo 3D' NEXCON printer, that weighs 19,000 kg (19 tons) and can print structures up to three stories high. A test run that included the first 3D-printed house was completed with 28 h of printing time, reducing the gap between prints by a month, and costs by 15% per square foot. These savings were attributed to the reduced labor and lumber requirements. The houses are said to have costs ranging between USD 175 and 350 thousand [39].

Iberdrola, a renewable energy company with more that 1.2 million km of electric transmission and distribution power lines, has initiated a collaboration with "Hyperion Robotics" and "Peikko Group" to apply 3DCP in order to enhance the construction of their transmission lines. Given the shortage of labor and the lack of automation in the current construction industry, the 3DCP solutions offered by Hyperion Robotics propelled the vision of this project, given how 3DCP is cheaper, faster, and safer than conventional construction methods. The transmission structures were printed with a 75% reduced material requirement. Moreover, with implementing recycled materials such as FA, SF, and slag, a 90% reduction of these structures' carbon footprint can be achieved [40].

Researchers from the US Army Corp. of Engineers utilized 3DCP to erect a 9.5 ft-tall concrete wall for a 32 ft × 16 ft barracks, with the ultimate goal of creating structurally safe 3D printed units in the future; they have stated that a structural testing to show the level of safety in the scope of these projects has yet to be done. Additionally, they stated that building temporary housing in disaster areas takes from five to ten days using conventional methods, a timespan that can be brought down to a single day using 3DCP. Moreover, it is said that a single simultaneous crew of three trained workers, with three separate shifts would be required to carry out such an operation [41].

4. Challenges and Limitations

4.1. Economic and Financial

In general, 3DCP is a rising technology, which incurs relatively high capital costs due to the requirement for new equipment and infrastructure. Moreover, the size of the printed structure is a crucial factor in enhancing the economy of the project and bringing the overall cost down. Additionally, the financial aspects of 3DCP are affected by the cement paste that is used as the construction material. For example, OPC is a widely available material that is easily accessible which means that the overall associated cost is less compared to pastes that are based on recycled aggregate-based OPCs due to the scarcity of the related materials, and geopolymers which require costly processing techniques and high purity additives.

4.2. Technical

3DCP projects are faced with limitations regarding their size, building (printing) speed, and efficiency. Moreover, due to the tradeoff relationship between the various cement binders and aggregates that affect the rheological properties, as well as the consistency of these materials, and the curing procedure for 3DCP processes, limits the performance of 3DCP-based structures in comparison to conventional construction techniques [9]. Furthermore, the corrosive nature of OPC can cause damage to the printing equipment in the long run and incur costly maintenance costs. In terms of recycled aggregate-based pastes, the aggregates properties vary with the source and affect the durability of the final product. Finally, geopolymers are more sensitive to ambient environmental conditions in comparison to conventional cement pastes, which shortens their lifetime.

4.3. Social and Environmental

3DCP requires the intense use of non-renewable sources, such as sand, to produce a suitable cement paste, which can lead to its exhaustion as well as adverse environmental impacts due to the energy required to extrude and print the pastes [42]. Moreover, 3DCP can potentially lead to job displacement due to the reduced labor requirements. Additionally, 3DCP pastes such as OPC bear negative impacts on the environment due to the emission of greenhouse gases, as well as the intense usage of water. Although recycled aggregate-based OPC and geopolymers have an attenuated impact on the environment, their usage is far from being green.

4.4. Regulatory and Policy Limitations

Due to 3DCP being a rising technology, regulations and policies have yet to be fully developed, which hinders the fast commercialization of this technology and induces drawbacks to its full adoption. Moreover, the permittance of the usage of OPC is governed geographically, which could potentially affect its availability and legal usage. Furthermore, recycled aggregates fall under standards and regulations of usage, which can potentially prevent their implementation in concrete mixtures in some regions. Finally, given that geopolymers are not as well established as OPC, the regulations that control their usage are not fully mature.

4.5. Institutional and Administrative

At this stage, trained personnel to operate 3DCP equipment could be lacking in some countries and regions, as well as administrative complexities for obtaining approvals to commission 3DCP projects due to regional codes of conduct. Figures 4 and 5 provide a summary on the challenges faced by 3DCP as a technology in comparison to conventional construction, as well as the different materials involved, respectively.

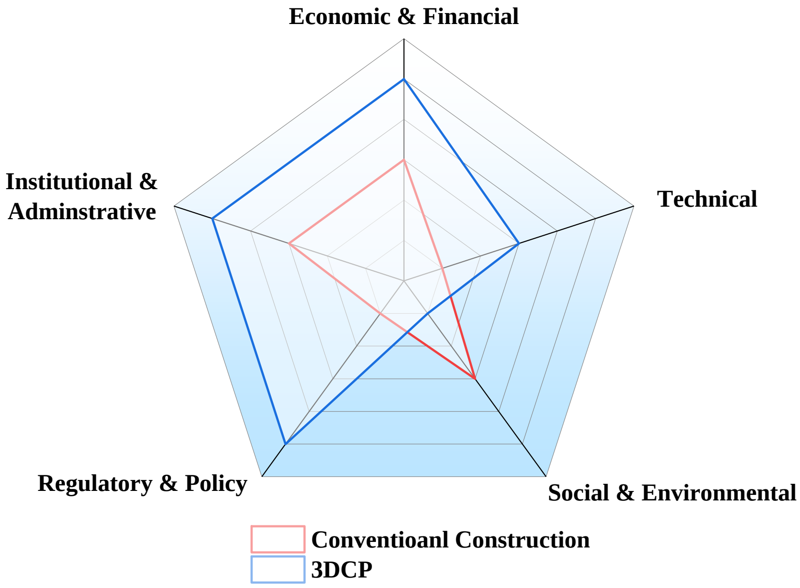

Figure 4. Comparison of Degree of Limitations between Conventional Construction and 3DCP.

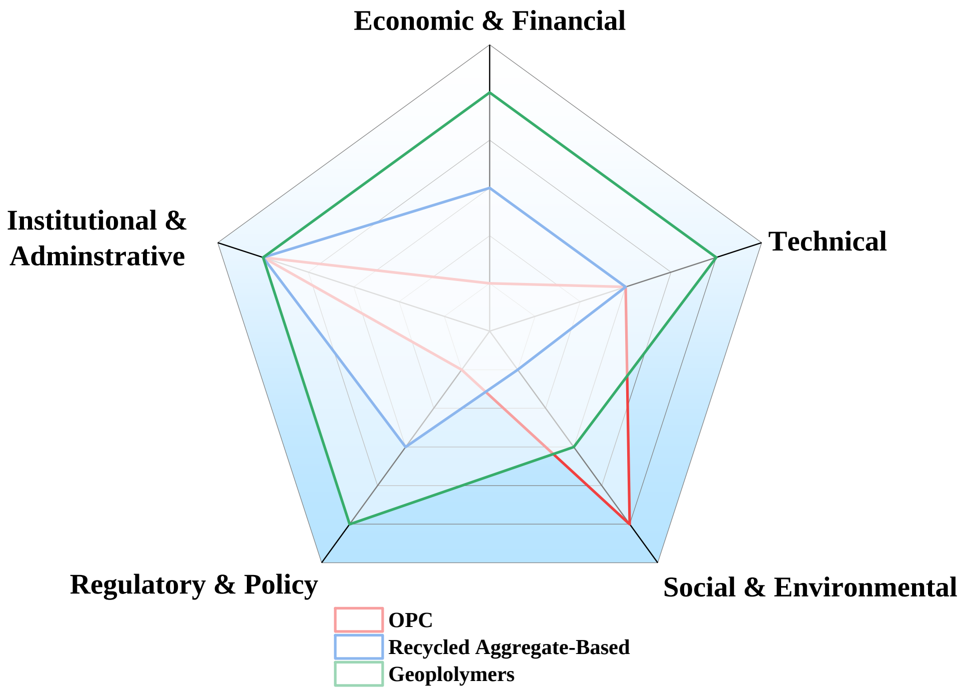

Figure 5. Comparison of Degree of Limitations between OPC, Recycled Aggregate-Based Cement, and Geopolymers for 3DCP.

Having discussed the various technical aspects of the materials involved in 3DCP, as well as their applications, challenges, and limitations, it is essential to further explore this technology's impact on the SDGs. With the multitude of challenges imposed on the world, which include poverty, climate change, and environmental degradation, innovative solutions to mitigate and reduce their impact are of upmost importance. 3DCP is a technology that has a very high potential to contribute positively to achieve these goals on a broad scale. In the following section, the impact of 3DCP on the SDGs and its role in a more sustainable future will be examined.

5. Role of 3DCP in Achieving the SDGs

3DCP has substantially influenced the economy, society, environment, and infrastructure, as mentioned in Section 4. These impacts prove that 3DCP has a significant role in achieving Sustainable Development Goals (SDGs), especially SDGs 1, 3, 4, 6, 7, 8, 9, 11, 12, 13, and 17, which are summarized in Figure 6. As a result, the following sections include a detailed discussion of 3DCP's role in achieving these specific SDGs.

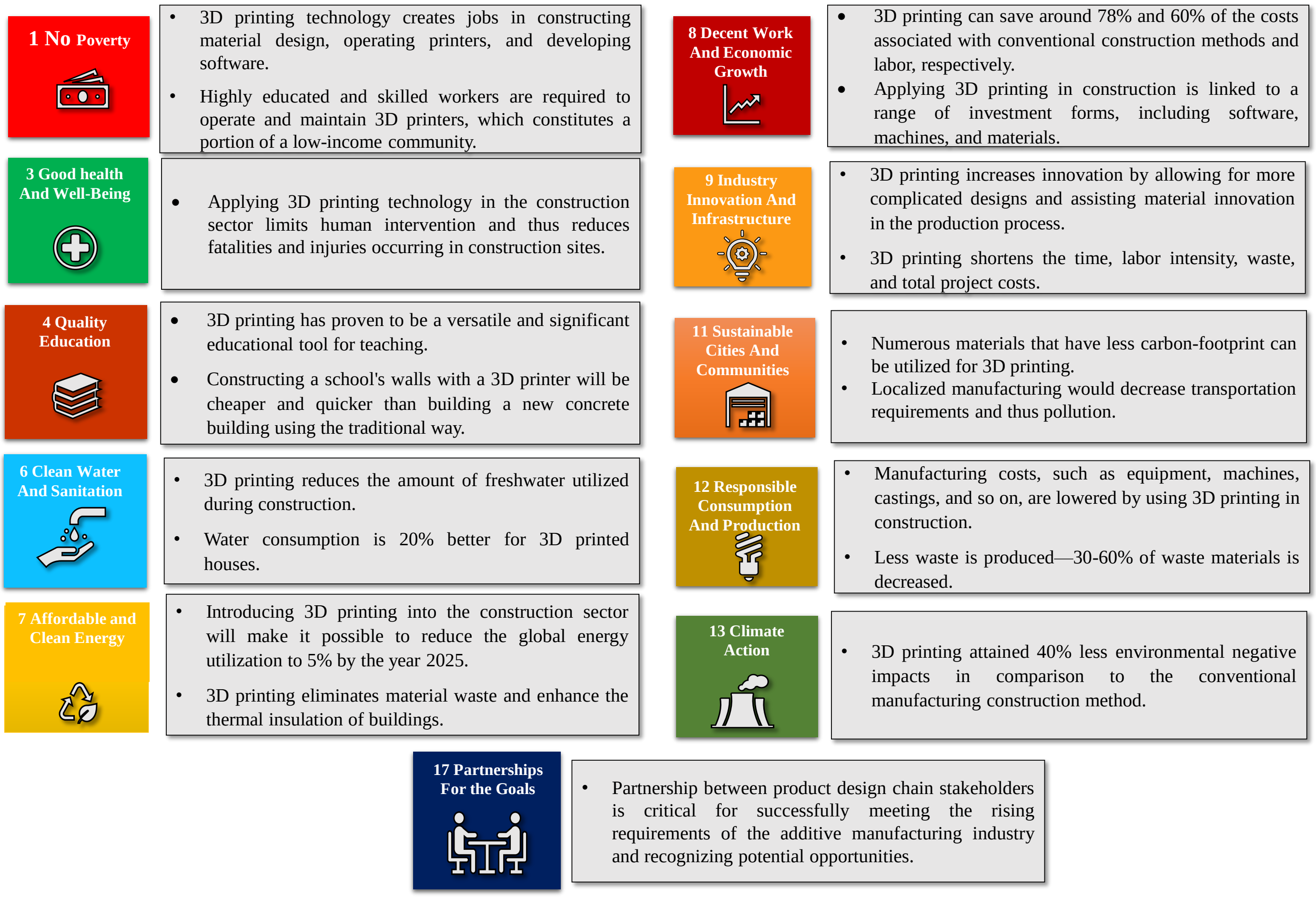

Figure 6. Summary of 3DCP impact on SDGs.

5.1. SDG 1

The aim of SDG 1 is to eradicate poverty in every form and location. Poverty is now understood as a complex notion with various dimensions. For instance, the UN's Multidimensional Poverty Index, which is utilized in the UN's Human Development Reports, encompasses various disadvantages that individuals may face regarding their health, education, and living standards. SDG 1 concentrates primarily on reducing poverty related to consumption by aiming to eliminate extreme poverty defined by a monetary standard. Nonetheless, it also considers other facets of poverty, acknowledging that poverty can be defined and measured differently by each country. The objectives in SDG 1 outline ways to alleviate poverty, such as ensuring that social protection systems cover those who are impoverished, guaranteeing the economic rights of impoverished individuals to resources, essential services, and property ownership, and improving their resilience to financial, social, and environmental disruptions [43].

The construction sector is ever-growing in several countries; it is responsible for around 6.1%, 5.5%, and 9% of the gross domestic product in the UK, Japan, and Oman, respectively. Due the maturity of the construction sector in different countries, it is perceived as the primary source of jobs. As a result, the amount of investment in the construction sector rose from USD 9.5 to 14 trillion from 2014 to 2023 [44]. The introduction of 3D printing presented numerous benefits, including enhanced safety, time savings, and improved customization. Nevertheless, 3D printing resulted in a decrease in the number of employees required to construct a facility [45]. For instance, a house can be easily constructed by 3D printers via minimal staff instead of a multidisciplinary team [46]. Consequently, 3D printing applications in construction has reduced job opportunities and thus threatened societal employment and social stability, especially for low-income regions or countries [47]. Furthermore, the need for sufficient skills and knowledge regarding this new technology is another hurdle that limits job creation for construction workers [48]. All these jobs removed by the introduction of the 3D printing technology in the construction sector has negatively influenced the global poverty level. Despite all these drawbacks, 3D printing technology creates jobs in various areas for construction material design, operating printers, and developing software [43]. Even though 3D printing for construction does not require the intervention of workers, skilled workers are still required to operate and maintain 3D printers [49]. Although 3D printing technology offers jobs for the community, these jobs target highly educated and skilled individuals, which might constitute a small portion of a low-income community. Hence, these jobs do not impact the poverty level of the community as a whole.

5.2. SDG 3

SDG 3 aims to secure good health and well-being for all individuals, throughout their lives. It encompasses nine targets, which can be categorized into several overlapping groups. These groups include reducing illness and death rates for susceptible groups, decreasing the prevalence of both communicable and non-communicable diseases, decreasing the presence of risk factors, ensuring universal health coverage, and reinforcing the healthcare industry [50]. Furthermore, more actions are needed to stop the spread of diseases and address health problems, which can be achieved by increasing investment in healthcare facilities and systems, improving sanitation, and ensuring easy access to healthcare workers [51].

The United States Department of Labor reported that every year, 10% of workers in the construction sector sustain injuries [49]. However, this number substantially decreased with the introduction of the 3D printing technology in the construction sector. The application of 3D printing technology in the construction sector limits human intervention and thus it reduces fatalities and injuries occurring at construction sites [48]. Moreover, the use of 3D printing has the potential to result in work sites that are cleaner and less noisy for the people living in surrounding areas [49]. Despite all the advantages 3D printing offers for the well-being of construction workers, it still induces negative impacts on the health of workers who are responsible for managing 3D printers. Hence, workers that engage with 3D printers are prone to exposure to toxic elements that might potentially result in eye allergies and irritation [52]. Furthermore, workers are constantly exposed to nickel and lead due to the production of gases from 3D printers [53]. Nevertheless, the amount of pollutants released from 3D printers is much lower than the pollutants emitted in conventional construction sites. As a result, the use of 3D printing enhances the health of workers, potentially increasing their lifespan [54]. However, there is a significant risk of mass injuries occurring due to the malfunction of large-scale on-site 3D printing equipment or the disintegration of buildings that have been printed [55,56].

5.3. SDG 4

The goals of SDG 4 aim to establish accessible and equal quality learning for everyone and encourage lifelong learning, and intends to advance all stages of education around the world, from pre-primary to university and above. Targets 4.a attempts to build and improve education facilities that are adaptive to children, disabilities, and gender, and offer secure, non-violent, equitable, and effective educational environments for everyone [57]. The incorporation of 3D printing into the construction sector has resulted in a productivity renaissance, potentially arising from the shortened manufacturing and production processes. Construction waste is also minimized because materials are simply controlled and adjusted while being manufactured [49]. 3D printing has proven to be a versatile and significant educational tool for teaching, particularly in the STEM field. Students can observe and touch the real-world manifestations of their imaginations, as well as the transition from simulated CAD design to printed product. As a result, there will be more eagerness, inspiration, optimism, and focus created around lessons that include 3D printing. For several years, environmental and sustainability education has actively functioned with the SDGs and similar goals to make education more environmentally friendly, laying the foundation for the transition to incorporate these particular properties and their 3D printed models into the education sector in high schools and universities [58]. This calls for the adoption of 3D printing in education, and thus, achieving the SDG 4 goals. Furthermore, constructing a school's walls with a 3D printer will be cheaper and quicker than building a new concrete building from the ground up, which would take 2 years to complete. In April 2022, a 3D printed school was opened in Fianarantsoa in Madagascar which is 700 square feet with a capacity of 30 students. This helps in contributing to the interest in building more 3D-printed educational facilities.

5.4. SDG 6

In 2016, agriculture accounted for the largest proportion of annual water withdrawals, followed by industry and households. However, water usage and pollution cannot be treated as separate issues for sustainable development. Around 80% of wastewater from different sources is released into water bodies without adequate treatment, resulting in a decrease in the accessibility of clean water for various purposes, including drinking. Therefore, specific measures were needed to ensure the sustainability of freshwater. These measures were listed in SDG 6 which ensures the sustainability and availability of water and sanitation for all. SDG 6 is a significant milestone for the water sector as it acknowledges the need for comprehensive water management, not limited to water supply, sanitation, and hygiene. It addresses various aspects of the water cycle, including water scarcity, quality, efficiency, and ecosystems. The goal promotes Integrated Water Resources Management (IWRM) that goes further than national boundaries and recognizes the importance of transboundary water management. It also emphasizes a basin approach to water management and recognizes that water has an impact on various aspects of development [59].

The UN states that the construction sector accounts for 12% of worldwide freshwater usage [60]. In order to reduce the amount of freshwater utilized during construction, 3DCP technology was proposed. When comparing the water consumption of the conventional construction methods to the 3D printing technology, it was found that the former had a higher impact on water consumption, with a consumption of 233.35 m^3, while the latter consumed 183.95 m^3. The high water usage in construction was primarily due to the addition of water during concrete manufacturing. In the case of 3D-printed concrete houses, the water consumption was 184 m^3 per functional unit, mainly due to the water demand during 3D mortar preparation. As a result, water consumption is only 20% better for 3D printed houses, as high water usage during cement production processes was common in both conventional construction methods and 3D printing [42].

5.5. SDG 7

SDG 7 is a goal that strives to guarantee access to energy that is modern, sustainable, affordable, and dependable for everyone. It comprises five targets, which include ensuring access to energy services that are affordable, reliable, and modern for all (7.1); increasing the use of renewable energy sources (7.2); doubling the rate of energy efficiency improvement globally as stated in target 7.3; improving international cooperation on clean energy research as implied in target 7.a; and expanding infrastructure and technology development as presented in target 7.b [61].

The construction sector is responsible for approximately 48% of the global energy consumption and for significant amounts of wastes [42,60,62,63]. However, the introduction of 3D printing into the construction sector will make it possible to reduce the global energy utilization to 5% by the year 2025 [42]. 3D printing technology is an additive process that eliminates material waste by only using the necessary materials for the structure and eliminating the requirement for material formwork. Electric printers can function using solar power or a generator, making them useful in isolated and remote regions, while the traditional approach requires more energy consumption and mainly depends on diesel-powered equipment [60]. According to a study conducted by Agustí-Juan and Habert [64], the main source of energy utilization from the process of constructing walls and roofs via 3D printing is the process of material production. Furthermore, the utilization of 3D printing has the potential to enhance the thermal insulation of buildings and decrease energy usage, resulting in structures that provide improved thermal comfort. This can be achieved by printing geometries that are specifically designed for superior thermal insulation, such as cellular or lattice structures, or by altering the printing mix to include aerogels or air bubbles [9].

5.6. SDG 8

SDG 8 aims to achieve sustainable, inclusive economic growth, productive employment, and decent work opportunities for all. Its twelve targets cover a wide range of areas, such as a 7% annual GDP growth in the least developed countries, technological innovation and diversification, and support for small- and medium-sized businesses. The goal also seeks to decouple economic growth from environmental degradation and promote full and productive work opportunities, equal pay, and the eradication of forced labor. Additional targets include sustainable tourism, increased aid for developing countries, and a global strategy for youth employment [65]. In general SDG 8 focuses on the ideas of economic growth, employment, resource efficiency, decent work, environmental protection, and productivity [66].

The construction sector has been one of the primary drivers for economic growth in various countries, especially the United Arab Emirates (UAE). In 2015, the UAE invested around USD 5 billion in the construction sector [67]. Accordingly, the construction sector accounts for approximately 15% of the UAE's Gross Domestic Product (GDP) [68]. Moreover, the construction sector has led to the creation of up to 1.64 million jobs across the UAE [69]. However, the application of 3D printing in construction will slow down the economic advancements induced by the construction sector. 3D printing technology is a cost-effective alternative to conventional construction methods, with 3D printing saving around 78% and 60% of the costs associated with conventional construction methods and labor, respectively [42]. Furthermore, Weng et al. [70] conducted a study to examine the material usage, electricity usage, labor costs/productivity, and installation time of 3D printing and precast methods. The findings indicated that using 3D printing to fabricate a bathroom unit resulted in a 25.4% reduction in total costs, an 85.9% decrease in CO_2 emissions, and an 87.1% reduction in energy consumption compared to using precast methods. However, in many cases, the reduction of construction costs may not be as significant as initially thought. On-site printing, for instance, incurs additional financial strain on construction companies in terms of transportation and installation costs for the printer, which can impact the cost-effectiveness of the technology [49]. Generally, the cost of 3D printing stems from various factors, including the cost of materials, software, machines, hardware, and operation and maintenance expenses. Hence, the application of 3D printing in construction is linked to a range of investment forms, including investments in software, machines, and materials [71,72].

5.7. SDG 9

The contribution of SDG 9 is to establish robust infrastructure, encourage sustainable and equitable industrialization, and support creativity. As a result, prompt industry guidelines that consider inequality and sustainability are required to achieve SDG 9 [73]. 3D printing increases innovation by allowing for more complicated designs and assisting material innovation in the production process [74]. People all over the world gain from 3D printing because it provides designers, engineers, and producers with local, on-demand abilities that enable businesses and companies of all types to enhance their lives anywhere [75]. In the UAE, the 3D printing approach has aided the manufacturing and industrial sectors in growing rapidly while reducing added expenses spent on manpower and other overhead costs. Manufacturing industries in the UAE contribute to 9% of the gross domestic product (GDP), and it has been reported that the adoption of enhanced 3D technology has aided in the development and expansion of the UAE's manufacturing and construction industries [76]. Several private, industrial, and academic institutions are investigating the potential implementation of concrete 3D printing in the construction sector. A 400 m^2 two-story house in Beijing, a five-story apartment building in Suzhou, China, and a 250 m^2 building in Dubai are some concrete examples. It is obvious that this promising method of construction will ultimately revolutionize the construction sector as it offers numerous opportunities for construction process innovations by shortening the time, labor intensity, waste, and total project costs [77]. All of these factors help in contributing to the SDG 9 targets.

5.8. SDG 11

"Sustainable Cities and Communities" is the aim of SDG 11 which aspires to establish equitable, secure, robust, and sustainable urban and individual communities by expelling slum-like instances, creating affordable transit alternatives, reducing urban overdevelopment, strengthening urban management engagement, boosting cultural wealth management, and tackling urban adaptability and global warming challenges. By 2050, cities' total population is predicted to reach 6.5 billion people. Sustainable development cannot be possible if urban regions are constructed and operated as they are presently [78]. Deploying 3D printing in construction is directly related to SDG 11. The goal of sustainable construction is to fulfill current infrastructure, residential, and workplace environment desires without impacting future generations' capability to fulfil their own needs in the future. This entails ensuring that resources are employed in an effective manner that benefits both the world and the communities. Numerous materials that have smaller carbon footprints can be utilized for 3D printing. The market has been using green materials such as fly ash, geopolymers, and reprocessed glass. Furthermore, the energy utilized during the manufacturing process, as well as the energy consumed in its processing after building, are both critical. Passive designs can significantly minimize energy consumption, and this is a field in which 3D concrete printing could play an important role due to the simplicity of constructing a complicated design [79]. Seriously reconsidering urbanization by improving the way we produce, utilize, and live in cities for direct waste degradation is essential. Similar to how the digital economy allows anybody to market globally, technological advances such as 3DCP enable us to revise the methods we use to create things [80]. Additionally, localized manufacturing would decrease transportation requirements and thus pollution [74].

5.9. SDG 12

SDG 12 calls for ensuring sustainable production and consumption. Recent advancements in manufacturing technologies contribute significantly to the economy's growth while also supporting the 12th SDG for liable production and consumption. The advantages of 'clean manufacturing and environmental impact avoidance' are associated with waste minimization and raw material efficiency, production expandability, shortening and simplification of processing stages, and maintenance [81]. The materials utilized in the 3D printers in construction are only consumed as required. As a result, fewer materials are consumed; manufacturing costs, such as equipment, machines, castings, and so on, are lowered; and less waste is produced—30–60% of waste materials is decreased [49]. This will all help in accomplishing the sustainable management of chemicals and all waste materials across their entire lifespan, and greatly decrease their discharge into the air, water, and soil in an attempt to reduce their negative effects on humans and the eco-system. In addition, it will induce businesses, particularly large and multinational corporations, to implement sustainability initiatives and incorporate environmental practices into their implementation period, and facilitate developing countries in strengthening their technical and scientific capabilities in order to transition to more environmentally friendly consumption and production paths [82].

5.10. SDG 13

In 2019, the highest recorded temperatures and levels of greenhouse gas emissions were observed. In 2020, due to COVID-19 restrictions on travel, greenhouse gas emissions decreased by 6%. However, this improvement is only temporary, and as the economy recovers from the pandemic, greenhouse gas emissions are expected to rise again. The excessive greenhouse gas emissions are a major contributor to climate change, which is having a negative impact on the world population by altering weather patterns, increasing sea levels, and leading to natural disasters. As a result of the negative impacts of climate change, it has become necessary to take drastic actions. The Paris Agreement was established in 2015 with the goal of reducing global temperatures below 2 °C, and SDG 13 was created to urgently address climate change and its effects [83].

The construction sector accounts for 28% of greenhouse gas emissions [60] and 38% of CO_2 emissions [6]. Consequently, 3D printing technology has been introduced to the construction sector to reduce the production of greenhouse gasses. One of the 3D printing technologies, additive manufacturing, attained 40% less environmental negative impacts in comparison to the conventional manufacturing construction methods [84]. Moreover, conventional construction methods are associated with a climate change impact of 75%, while the impact of the 3D printing is negligible at only 2%. Climate change is a significant environmental issue due to the greenhouse gas emissions that occur during the material production, manufacturing, transport, and construction phases of conventional construction [85]. When comparing the conventional construction method to 3D printing, it was found that the conventional method had higher environmental impacts. Specifically, the conventional method had a global warming potential of 1154.20 kg CO_2 eq and non-carcinogenic toxicity of 675.10 kg 1,4-DCB. In contrast, the 3D printing method had lower impacts, with a global warming potential of 608.55 kg CO_2 eq and non-carcinogenic toxicity of only 11.9 kg 1,4-DCB [42].

5.11. SDG 17

SDG 17 calls for enhancing implementation mechanisms and helping to promote the worldwide sustainable development partnership. Accomplishing Agenda 2030′s ambitious goals will necessitate mobilizing political will and strengthening collaborations among government, the corporate sector, and societal organizations [86]. 3D printing technology in construction contributes directly to SDG 17 and its targets. To date, several initiatives have been taken to incorporate 3D printing into existing design regulations. In China, for example, multiple companies are working with the Chinese National Construction Standards Department to alter building standards to accommodate 3D printing. Specifically, concrete 3D printing has been proposed as a potential intriguing alternative to activate remote advancement, strengthen the abilities of local and national industries of manufacturing and construction, and provide rapid improvement in post-disaster circumstances [87]. 3D printing advancements also emphasize the major impact every factor in this process has on the rest. Governments, for instance, are making substantial developments in the industry by encouraging the use and sale of 3D printing products and services via public contracting [88]. A new house is being built in a Houston, Texas, neighborhood using a 3D printer to print concrete layers. The project is a 2-year partnership among engineering, design, and construction companies, with the builders hoping that this technology will one day allow them to construct multi-family houses and apartments more cheaply and quickly [89]. Partnerships between product design chain stakeholders are critical for successfully meeting the rising requirements of the additive manufacturing industry and recognizing potential opportunities [90].

6. Conclusions

This study highlights the potential of 3D concrete printing (3DCP) to revolutionize the construction industry and contribute towards achieving the relevant sustainable development goals (SDGs) set out by the United Nations. The research reveals that 3DCP offers significant advantages over conventional construction methods in terms of cost and water consumption, with a potential to save up to 78% and 60% of the associated costs with conventional construction and labor, respectively. Furthermore, 3DCP has the potential to reduce global energy utilization by 5% by 2025, making it a promising solution for achieving sustainability targets. However, despite the lower climate change impact of 3DCP compared to conventional construction methods, further work is required to improve its sustainability. By exploring the recent progress and limitations of the three dominant types of cementitious mixtures, this study provided insights into the potential of 3DCP to contribute towards achieving the SDGs. Therefore, continued research and development of 3DCP technology are necessary to overcome its limitations and unlock its full potential for the construction industry. Overall, this study emphasized the importance of adopting innovative and sustainable approaches to construction, such as 3DCP, to address global sustainability challenges and achieve the SDGs.

Author Contributions: Conceptualization, A.H.A., M.A.A.; methodology, M.A., H.A., S.A.; software, H.A., S.A., M.A.; formal analysis, A.H.A., A.G.O., M.A.; investigation, M.A., M.A.A.; resources, A.G.O., M.A.A.; data curation, A.H.A., A.G.O.; writing—original draft preparation, A.H.A., A.G.O., M.A., H.A., S.A., M.A.A.; writing—review and editing, A.H.A., A.G.O., M.A., H.A., S.A., M.A.A.; visualization, A.H.A., A.G.O., M.A.A.; supervision, A.H.A., A.G.O., M.A.A.; project administration, A.H.A., A.G.O., M.A.A.; funding acquisition, A.H.A., A.G.O., M.A.A. All authors have read and agreed to the published version of the manuscript.

Funding: The authors would thank university of Sharjah for the support of the current work through project No. 447/2022 "Development of metallic meshes as electrodes for third generation photovoltaics".

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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