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The 3D Eye: From Blueprint to Build – Unveiling the Lifecycle and Future of 3D Printing in Sustainable Construction

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Abstract: The construction industry is facing growing pressures to improve sustainability and reduce its environmental impact. 3D printing technology has emerged as a promising solution, offering the potential to revolutionize construction by enhancing efficiency, reducing waste, and utilizing sustainable materials. This paper provides a critical evaluation of 3D printing's impact on sustainable construction, examining the technology's application across the entire lifecycle of construction projects. Data was attained using secondary data through a systematic review and analysis of key case studies. The findings illustrate the alignment of 3D printing with global sustainability development goals (SDGs), particularly SDG 9 (Industry, Innovation, and Infrastructure), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). This research paper develops a 3D Eye model to map the SDGs to the stages of the project lifecycle. It identifies the key challenges to the application of 3D printing in sustainable construction. Future work may consider the evaluation of 3D printing in more cases and practices.

Keywords: Construction projects, sustainability development goals, sustainable materials, three dimensional printing.

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1. Introduction

The first appearance of 3D printing in the literature was in 1986 as a patent by Hull and UVP Inc. (1986). Before making its way into the construction industry, the 3D printing was used for prototyping in automotive and aerospace industries (Sakin and Kiroglu, 2017). It has been encouraged to use 3D printing in combination with sustainability principles to reduce CO_2 emissions, and encourage time reduction and resources conservation (Kaszyńska and Skibicki, 2023; Habibi et al., 2024).

Traditional construction methods are known for their high level of energy use and resources consumption. This called for more sustainable and innovative practices that address project efficiency while maintaining environmental and regulatory issues. 3D printing technology offers a great opportunity to revolutionize the traditional construction practices into more sustainable processes. Using 3D printing technology can offer sustainable advantages over traditional methods such as the reduction of waste, the resources use, the energy consumption, and the need for temporary works (El-Sayegh et al., 2020). In addition, it helps to improve safety in the construction site and even has potential benefits on the society (El-Sayegh et al., 2020).

In spite of the previous mentioned opportunities and advantages, many challenges and limitations are still affecting the wide spread of 3D printing technology. Examples include the materials limitations to specific properties and texture, the printer limited scale and geometry, the need for sophisticated software, architectural, structural and MEP design capabilities, the high initial cost, lack of related codes and regulations, and the need for new 3D printing skilled workers (El-Sayegh et al., 2020).

Some projects have successfully combined sustainability principles with 3D printing in construction. For example, a company called WinSun in China has implemented 3D printed structures by using recycled concrete made from industrial and construction waste material, and reinforced with fiberglass (Ma and Winsum, 2015; Liang Feng et al., 2014). Their ability to produce recycled concrete that sets quickly after printing allowed them to have continuous 3D printing with reduced cost and time of construction operations (Wilson et al., 2023).

In 2019, the Chinese construction company WinSun in collaboration with the Dutch architects DUS have completed the first fully habitable 3D printed house in Europe (3D Printing Dublin Team, 2023) by using a large-scale 3D printer that used recycled plastic and natural fibers as material (3D Printing Dublin Team, 2023). The use of 3D printing allowed the project to be completed with sustainability benefits including reduced time, waste and transport cost; and high level of detail and customization to meet customers' taste and needs (New Material Award, 2014; The Index Project, 2015).

Integration of Building Information Modeling (BIM) with 3D printing has proved to enhance the processing and provide sustainability advantages (Sakın and Kiroğlu, 2017). This can help providing better implementation of plans and higher level of accuracy for the design details, with improved energy efficiency and cost reduction (Sakın and Kiroğlu, 2017; García-Alvarado et al., 2024; Asaad and Suleiman, 2024; Asaad and Suleiman, 2025).

The application of 3D printing in construction is still in its early stages and lacks adequate numbers of research works addressing the different aspects and challenges of its large-scale implementation. However, research into the use of 3D printing in construction is growing, as shown in Figure 1, and promises to revolutionize structures and attain more sustainability benefits. This paper seeks to fill the gap by addressing the sustainability implications of 3D printing in the construction projects, and providing insights into its potential to improve the future of construction practices.

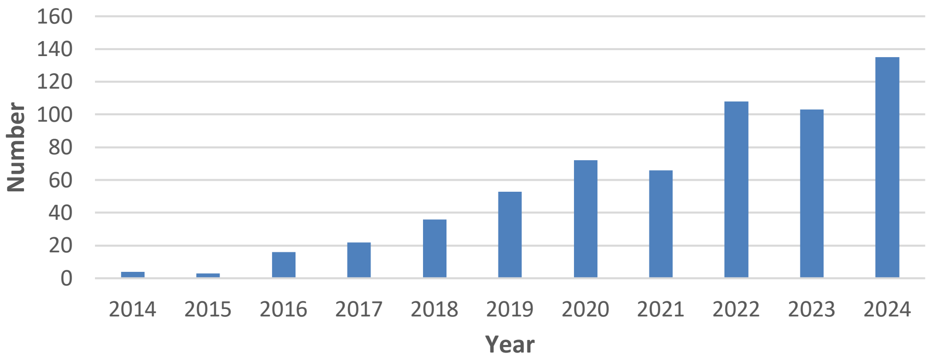

Fig. 1. Annual published work using the query ("3D Printing" and (Construction or Concrete)). Source: Scopus Library

2. Methodological Approach

This paper employs a systematic review and evidence-based research approach to critically assess the relationship between 3D printing technology and the sustainable construction practices. Figure 2 illustrates the research design of the study. The methodological framework is designed to ensure that the analysis is rooted in robust, well-documented, and reliable sources, providing a comprehensive understanding of how 3D printing contributes to sustainability in the construction sector.

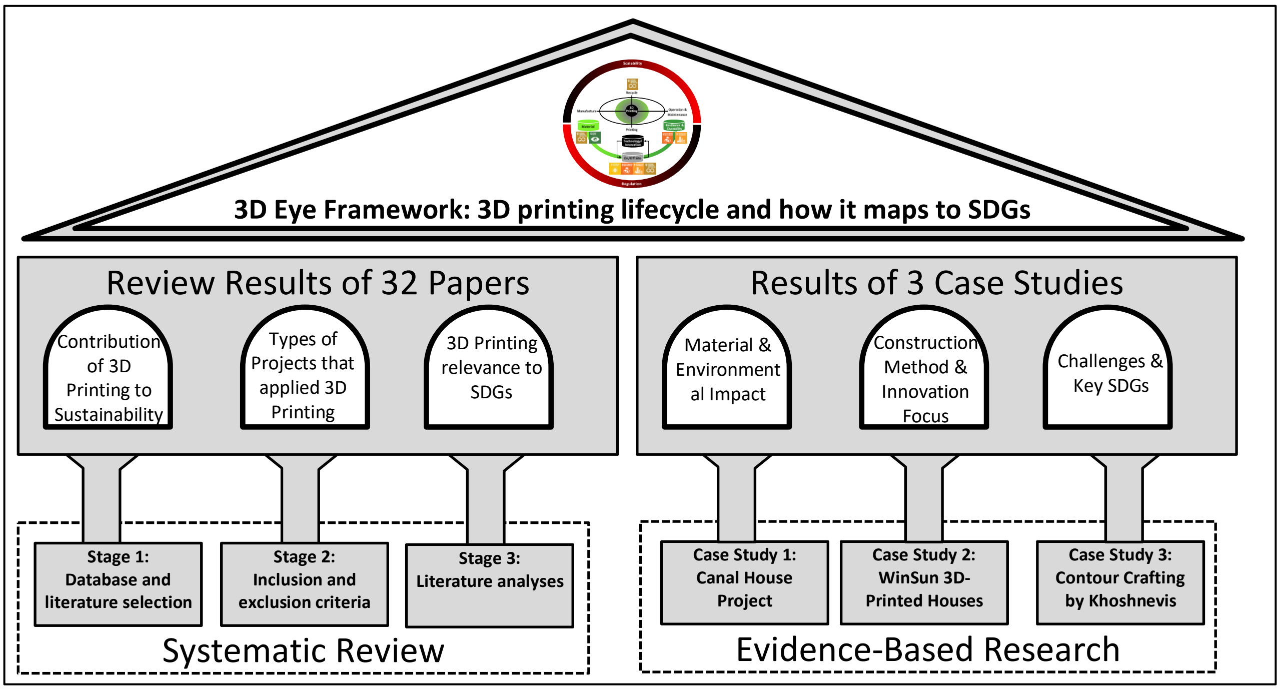

Fig. 2. The research design of the study

2.1. Systematic Review

The systematic review serves as the foundation for this research, focusing on the identification, evaluation, and synthesis of existing literature on 3D printing technology in construction. A structured search was conducted across academic databases and industry publications, selecting peer-reviewed articles, case studies, technical reports, and relevant industry documents.

2.1.1. Database and literature selection

The literature search was conducted using Scopus database, recognized for including high quality peer-reviewed journals and conference proceedings. It was chosen for its ability to provide high quality, multidisciplinary research outputs, particularly in the fields of engineering, construction, and environmental sustainability. Search terms included "3D printing in construction," "additive manufacturing," and "sustainable construction," with results filtered to focus on studies published between 2000 and 2024.

2.1.2. Inclusion and exclusion criteria

The studies resulted from the preliminary search of the database were filtered to include only papers that addressed the practical application of 3D printing technology in construction operations, particularly those related to the building sustainability. The papers that discuss theoretical investigations without empirical evidence were excluded. The selected papers included peer-reviewed published journals, case studies, and conference articles. The final dataset of the selected papers depended mainly on the 3D printing of housing projects related to sustainability practices, benefiting from sustainable and recyclable materials, and focusing on energy efficiency and resources conservation.

2.2. Evidence-Based Research

In this research, the evidence-based method was applied for 3D printing projects or companies. Three case studies were selected depending on their relevance to the application of 3D printing technology for sustainable construction operations. The three case studies are as follows:

- The Canal House Project (Amsterdam, Netherlands): This project exemplifies the use of biodegradable thermoplastics and on-site 3D printing techniques, significantly reducing waste and transportation costs. The analysis of this case focuses on the environmental benefits and practical feasibility of 3D printing in urban residential construction (Benyoucef and Razin, 2022; New Material Award, 2014; The Index Project, 2015; 3D Printing Dublin Team, 2023).
- WinSun 3D-Printed Houses (China): WinSun's series of projects in China highlight the use of industrial waste, fiberglass, cement, and other recycled materials to produce 3D-printed houses. These projects are analyzed for their ability to reduce construction time, costs, and material waste, while also demonstrating scalability and potential cost savings for affordable housing (Benyoucef and Razin, 2022; Ma and Winsum, 2015; Liang Feng et al., 2014; Wilson et al., 2023).
- Contour Crafting by Khoshnevis: Behrokh Khoshnevis has invented a 3D printing method called Contour Crafting, a technique that is cheaper, less time-consuming and has fewer risks than traditional construction practices (Benyoucef and Razin, 2022).

3. Analysis and Results

3.1. Systematic Review

In total, 32 papers were identified to be relevant to the research scope where each paper was respectively analyzed against relevance to environmental sustainability, type of the project where 3D was applied and finally relevance to sustainability development goals (SDGs). To demonstrate clear and coherent understanding, the analysis is divided into three primary themes: contribution to environmental sustainability, project type, and relevance to SDGs, as shown in Table 1.

3.1.1. Environmental sustainability

One of the recurring topics in 3D printing research studies, particularly in construction applications, are environmentally friendly with focus on material use, energy consumption, and waste minimization. The goal of environmental friendly construction material in traditional building material comes by the action of the researcher in the utilization of biodegradable plastics, magnesium oxide cement and recycling wastes. For example, Yu et al. (2024) have called for the incorporation of the use of bio-degradable thermaplasts in construction materials that are 3D printed with construction materials derived from processes that are resource intensive. This use of biodegradable materials will also go a long way in cutting the costs of transportation, since the materials can be printed on site, cutting down the emissions that would otherwise be caused during the transportation processes.

Another major advancement to sustainable environment is the work done on energy conservation. In Jiang et al. (2023), the authors introduced the application of an optical fiber sensing technology in actual 3D printed furniture to reduce the overall energy footprint of the goods by tracking the current environmental status in real time. This makes the furniture responsive to the changing environmental conditions and thus improves energy efficiency and comfort level for those using the furniture. Furthermore, the concept of automation and robotics is discussed in Haghighi et al. (2021) where large-scale construction can be implemented by using multi-robotic 3D printing, which lower the energy requirements commonly found with traditional construction equipment.

The reduction of materials wastage also receives attention in many of the studies. For instance, Khalil et al. (2020) discussed the applicability of magnesium oxide cement in 3D printing that has about 40% lower CO_2 emissions than the common Portland cement. In addition, Magnesium oxide cement needs less energy to be produced, and structures constructed from this material are more durable, hence consuming fewer resources in their lifetime. In the same vein, Wong et al. (2024) examined the possibility of using bamboo fibers within a 3D printing system, providing an example on how biodegradable products can be a substitute for non-degradable resources in construction. This is in line with the current trend of encouraging the circular economy in the globe, where wastes should become a resource to be brought back to the production line.

One of the main concerns for sustainable environmental improvements within the construction business is the recognition of waste throughout the building process, which contributes significantly to landfill and pollution. On the same note, De Rubeis et.al (2023) help in solving this problem through carrying out a study on using waste material in 3D printing for thermal insulation of; sawdust, wool and hemp. This also helps reduce wastage in the structure, and modifies the structure to consume less energy in its operations and have a better carbon footprint.

Overall, the studies described above contribute better understanding of how to improve environmental sustainability of construction through better materials, energy efficiency and waste management. The conventional building materials can be substituted with biodegradable and recycled products, and this will reduce environmental footprint of construction operations globally to conform to the sustainable development goals in its effort to fight against climate change. These innovative methods in 3D printing show that green construction has a viable and healthy future for the benefit of the societies.

3.1.2. Project type

The integration of 3D printing technology in construction is employed in several categories of constructions including housing, business, actual structures, and extraterrestrial constructions. A very popular topic throughout the literature is housing construction with an emphasis on urban and suburban settings. In their work, Mogaji et al. (2023) pointed out that 3D printing makes construction more sustainable due to the short construction time, low material cost, and low waste of construction materials, especially when it comes to building construction, particularly in housing.

This has great implications where the provision of cheap houses is concerned, particularly in regions where retrenchment and urbanization go hand in hand in a manner that while demand for housing is rapidly on the increase, the sources of funding are rapidly declining. 3D printing offers high efficiency when it comes to construction time and cost of labor. It also automates construction activities required in the construction of houses, ideal for use by residential developers to meet housing needs and at the same time conserve the environment.

Table 1. Analysis of the 32 papers identified against relevance to environmental sustainability, project type and SDGs

Authors	Title	Year	Contribution to Environmental Sustainability	Project type	Relevance to SDGs
Yu H.; Wen B.; Zahidi I.; Fai C.M.; Madsen D.Ø.	*"Constructing the future: Policy-driven digital fabrication in China's urban development"*	2024	Focuses on energy efficiency or resource	Infrastructure	SDG 9, SDG 12, SDG 13
Jiang W.; Lu D.; Zhao N.	*"A new design approach: applying optical fiber sensing to 3D-printed structures to make furniture intelligent"*	2023	Focuses on energy efficiency or resource	N/A	SDG 7, SDG 9
Wong J.; Aşut S.; Brancart S.	*"3D printing with Bamboo: An early-stage exploration towards its use in the built environment"*	2024	Focuses on sustainable materials (e.g., recycled, eco-friendly)	N/A	SDG 11, 12, 13
Mogaji I.J.; Mewomo M.C.; Toyin J.O.	*"Key barriers to the adoption of 3D printing innovation in construction: A review of empirical studies"*	2023	Focuses on sustainable materials (e.g., recycled, eco-friendly)	Building/housing project	SDG 8, SDG 9, SDG 11
Khalil A.; Wang X.; Celik K.	*"3D printable magnesium oxide concrete: Towards sustainable modern architecture"*	2020	Focuses on sustainable materials (e.g., recycled, eco-friendly)	N/A	SDG 9, SDG 12, SDG 13
De Rubeis T.; Ciccozzi A.; Pasqualoni G.; Paoletti D.; Ambrosini D.	*"On the use of waste materials for thermal improvement of 3D-printed block—An experimental comparison"*	2023	Focuses on sustainable materials (e.g., recycled, eco-friendly)	Building/housing project	SDG 12, SDG 13
Moghayedi A.; Le Jeune K.; Massyn M.; Byron P.	*"Establishing the indicators of sustainable building materials"*	2022	Focuses on sustainable materials (e.g., recycled, eco-friendly)	Building/housing project	SDG 9, SDG 12
Francese, D. and Oliva, E.M.	*"Experimental ecological composite for 3D printing of a small community hospital"*	2022	Focuses on sustainable materials (e.g., recycled, eco-friendly)	Building/housing project	SDG 11, SDG 12

Table 1. Analysis of the 32 papers identified against relevance to environmental sustainability, project type and SDGs (continued)

Authors	Title	Year	Contribution to Environmental Sustainability	Project type	Relevance to SDGs
Yuan S.; Duan D.; Sun J.; Yu Y.; Wang Y.; Huang B.; Peng J.; Mohamed S.; Wang X.	*"Mechanical, alkali excitation, hydrothermal enhancement of 3D printed concrete incorporated with antimony tailings"*	2024	Focuses on sustainable materials (e.g., recycled, eco-friendly)	N/A	SDG 9, SDG 12
Imhof B., Waclavicek R., Davenport R., Sgambati A., Berg M., Daurskikh A., WEISS P., Sorschag R., Zimmermann B., Binns D., Gilbert C., Makaya A.	*"Smart resource management based on internet of things to support off-earth manufacturing of lunar infrastructures (SMARTIE)"*	2021	Focuses on sustainable materials (e.g., recycled, eco-friendly)	Building/housing project	SDG 9, SDG 12
Tohidi A.; Gomaa M.; Haeusler M.H.; Shiel J.	*"3D printing self-shading wall structure with earth: Enhancing thermal properties in earthen architecture through computational tool path design, inspired by nature and vernacular architecture"*	2024	Focuses on sustainable materials (e.g., recycled, eco-friendly)	Building/housing project	SDG 7, SDG 11
Žarnić, R., Rajčić, V., & Skordaki, N.	*"A Contribution to the Built Heritage Environmental Impact Assessment"*	2015	Focuses on energy efficiency or resource conservation	Building/housing project	SDG 7, SDG 11
Haghighi A.; Mohammed A.; Wang L.	*"Energy efficient multi-robotic 3D printing for large-scale construction - Framework, challenges, and a systematic approach"*	2021	Focuses on energy efficiency or resource conservation	N/A	SDG 7, SDG 9
Kamra J.; Mani A.P.; Tripathi V.M.	*"3D printing: A Boon or a Bane for sustainable construction"*	2024	Focuses on sustainable materials (e.g., recycled, eco-friendly)	N/A	SDG 9, SDG 12, SDG 13
Tay Y.W.D.; Panda B.N.; Ting G.H.A.; Ahamed N.M.N.; Tan M.J.; Chua C.K.	*"3D printing for sustainable construction"*	2019	Focuses on sustainable materials (e.g., recycled, eco-friendly)	Building/housing project	SDG 11, SDG 12
Waqar A.; Othman I.; Pomares J.C.	*"Impact of 3D printing on the overall project success of residential construction projects using structural equation modelling"*	2023	Discusses innovative construction methods or processes	Building/housing project	SDG 9, SDG 11
Estévez A.T.; Abdallah Y.K.	*"The new standard is biodigital: Durable and elastic 3D-printed biodigital clay bricks"*	2022	Focuses on sustainable materials (e.g., recycled, eco-friendly)	Building/housing project	SDG 9, SDG 12
Agustí-Juan I.; Habert G.	*"An environmental perspective on digital fabrication in architecture and construction"*	2016	Focuses on sustainable materials (e.g., recycled, eco-friendly)	Building/housing project	SDG 12, SDG 13
Kajzr D.; Myslivec T.; Černohorský J.	*"Modelling, analysis and comparison of robot energy consumption for three-dimensional concrete printing technology"*	2024	Focuses on energy efficiency or resource conservation	Building/housing project	SDG 7, SDG 9
Moscatelli M.	*"Preserving tradition through evolution: Critical review of 3D printing for Saudi Arabia's cultural identity"*	2024	General contribution to environmental sustainability	Building/housing project	SDG 11, SDG 12
Khan S.A.; Jassim M.; Ilcan H.; Sahin O.; Bayer İ.R.; Sahmaran M.; Koc M.	*"3D printing of circular materials: Comparative environmental analysis of materials and construction techniques"*	2023	Focuses on sustainable materials (e.g., recycled, eco-friendly)	Building/housing project	SDG 9, SDG 12, SDG 13
El Inaty F.; Baz B.; Aouad G.	*"Long-term durability assessment of 3D printed concrete"*	2023	General contribution to environmental sustainability	Building/housing project	SDG 9, SDG 12

Table 1. Analysis of the 32 papers identified against relevance to environmental sustainability, project type and SDGs (continued)

Authors	Title	Year	Contribution to Environmental Sustainability	Project type	Relevance to SDGs
Panţiru A.; Luca B.I.; Bărbuţă M.	*"Experimental study of mixture proportions and fresh properties of concrete with fly ash and silica fume as a replacement for cement for 3D printing"*	2023	Focuses on sustainable materials (e.g., recycled, eco-friendly)	Building/housing project	SDG 12, SDG 13
Sgambati A.; Berg M.; Rossi F.; Daurskikh A.; Imhof B.; Davenport R.; Weiss P.; Peer M.; Gobert T.; Makaya A.	*"Urban: Conceiving a lunar base using 3D printing technologies"*	2018	Focuses on sustainable materials (e.g., recycled, eco-friendly)	Infrastructure Project	SDG 9, SDG 12
McNeil-Ayuk N.; Jrade A.	*"Integrating Building Information Modeling (BIM) and sustainability indicators and criteria to select associated construction method at the conceptual design stage of buildings"*	2021	Focuses on energy efficiency or resource conservation	Building/housing project	SDG 9, SDG 11
Fico D.; Rizzo D.; De Carolis V.; Montagna F.; Palumbo E.; Corcione C.E.	*"Development and characterization of sustainable PLA/Olive wood waste composites for rehabilitation applications using Fused Filament Fabrication (FFF)"*	2022	Focuses on sustainable materials (e.g., recycled, eco-friendly)	Building/housing project	SDG 12, SDG 13
Verian K.P.; Ashcroft J.; Ziemlaski J.; Brodesser T.; Ladouceur J.; Carli M.D.; Bright R.P.; Maandi E.	*"The assessment of the buildability and interlayer adhesion strength of 3D-printed mortar"*	2021	Focuses on sustainable materials (e.g., recycled, eco-friendly)	Building/housing project	SDG 9, SDG 12
Agustí-Juan I.; Habert G.	*"Environmental design guidelines for digital fabrication"*	2017	Focuses on sustainable materials (e.g., recycled, eco-friendly)	Building/housing project	SDG 12, SDG 13
Ibrahim A, M. and Kumar N, S.	*"3D printed concrete using Portland pozzolana cement - fly ash based"*	2024	Focuses on sustainable materials (e.g., recycled, eco-friendly)	Building/housing project	SDG 12, SDG 13
Hunbus A.; AlMangour B.	*"A critical review of construction using 3D printing technology"*	2023	Focuses on sustainable materials (e.g., recycled, eco-friendly)	Building/housing project	SDG 9, SDG 12
Oberti I.; Plantamura F.	*"Additive technology: A contribution to the environmental sustainability"*	2021	Focuses on sustainable materials (e.g., recycled, eco-friendly)	Building/housing project	SDG 12, SDG 13
Dunn K.; Haeusler M.H.; Zavoleas Y.; Bishop M.; Dafforn K.; Sedano F.; Yu D.; Schaefer N.	*"Recycled sustainable 3D printing materials for marine environments"*	2019	Focuses on sustainable materials (e.g., recycled, eco-friendly)	N/A	SDG 12, SDG 14

In contrast, some work is concerned with infrastructural projects. Imhof et al. (2021) discussed the use of 3D printing in construction for lunar habitats where off-Earth construction is suggested to be amongst some of the ways of meeting space exploration issues. It is well understood that the nature of these environments provides a perfect use of 3D small construction printing for structures and facilities using local materials such as the lunar regolith instead of transporting large and heavy construction elements from Earth. Besides simplifying the problems connected with space construction, this concept also shows an environmentally friendly approach towards resource utilization due to the use of local materials. The ability to future expand the use of 3D printing to infrastructural space settlements is a momentum for a career shifting of the construction industry as well as space research. Some of the other research covered topics of commerce buildings and other infrastructural projects. Tay et al. (2019) discussed how 3D printed concrete can bring certain patterns and shapes to the commercial constructions that could be challenging to implement by conventional building construction. An advantage of using digital models in 3D printing is that it minimizes the requirement for extra material by directly printing complex structures based on the designed shapes. Another advantage is that the flexibility of design increases, affording a chance to integrate such features for energy efficient requirements of buildings. This is in line with the development that demands sustainable architecture with low operational energy consumption to achieve net-zero energy targets in many countries.

In general, the possibility of using 3D printing in various types of projects, including residential construction, infrastructure, and space habitats, proves the ability of 3D printing to introduce changes in construction. The authors assume that as the cellular concrete technology develops, it will penetrate both normal construction and specialized construction industries as a versatile, ecological, and relatively cheap solution to the world's existing and future infrastructure demands.

3.1.3. Relevance to SDGs

The applicability of 3D printing technology to the SDGs is evident, mainly concerning sustainable industrial processes, resource innovation, and climate-friendly consumption. Several research papers directly addressed SDG 9 technology for (Industry, Innovation and Infrastructure) by focusing on the technological transformations originating from 3D printing in the construction industry. For example, Kajzr et al. (2024) identified the robotic-aided 3D printing capabilities to minimize energy use, construction time, and labor in massive construction projects. This type of innovation falls under SDG 9 because high efficiency manufacturing techniques can boost the economic growth without damaging the environment.

Besides technological advancement, numerous papers support SDG 12 (Sustainable Consumption and Production) by addressing the problems of construction waste and the reuse of construction materials. Khan et al. (2023) investigated the utilization of Construction and Demolition Waste (CDW) in 3D printing to establish how these materials can be reused in constructing building parts. In both the use of the concrete printer and in the reinforcement of the structures, 3D printing can reduce the amount of raw materials and substantially minimize the volume of waste that ends up in landfill. This is a move towards a sustainable production system in the construction industry, which is among the leading industries in the production of waste globally.

Referring to SDG 13 (Climate Action), the prevention of carbon emissions plays a major role in many studies, specifically on the employability of other construction materials. For instance, Khalil et al., 2020 b states that magnesium oxide cement associated with environmental advantages as the raw material generates much less carbon dioxide compared with ordinary Portland cement. This material is not only an emission-free substitute for concrete, but it also makes buildings last longer, which means less repainting and repairs – both of which are emission sources. In addition, Wong et al. (2024) pointed out that the use of biodegradable material such as bamboo in construction contributes positively to the environment. Bamboo is a renewable material and this makes it suitable in the achievement of SDG 13's goal of sustainable use of natural resources while also eliminating greenhouse gases usually produced by 'normal' construction materials.

Other kind of projects, for example, Recycled Sustainable 3D Printing Materials for Marine Environments by Dunn et al. (2019), supports SDG 14 (Life Below Water) since sustainable marine structures and infrastructure are an important and relevant concern. The paper shows the ability of 3D printing to construct structures that improve the presence of marine life, for example, bio shelters that encourage the development of marine forms while offering solutions such as water treatment and carbon capture. This is a major improvement and an excellent progression for marine construction, a field where conventional techniques lead to destruction of habitat as well as the environment. This means that sustainable resources along with the 3D printed structures should harmonically fit to the ocean and support the concept of SDG 14.

Furthermore, more attention should be paid to how 3D printing supports SDG 8 (Decent Work and Economic Growth). Research such as that of Waqar et al. (2023) seek to understand how the adoption of 3D printing technology increases the chances of successful completion of residential construction projects through promoting the safety of employees, focusing on the minimization of manual work, and developing new jobs for specialized employees in construction technologies. This is in line with the goals of SDG 8 to enhance the creation of safe and productive workplaces. Hence, by providing more opportunities to adopt such technologies in production and creating more opportunities for skilled workforce, 3D printing is driving economic growth to new heights.

In conclusion, the role of 3D printing in achieving the Sustainable Development Goals is broad, with the most helpful in providing sustainable and eco-friendly industrial practices, access to housing for all, and ocean protection. This technology is therefore very important in solving climate change and ensuring that communities are sustainable through the reduction of wastage, optimization of energy and use of environmentally friendly materials. As the technology becomes more developed, one can reasonably expect further improvement of the technology's capabilities to help achieve the SDGs, thereby providing new opportunities for addressing some of the most urgent global environmental and social issues.

3.2. Evidence-Based Case Studies

In ddition to the above, and to demonstrate practical implications, the authors have selected three case studies of different features, to support more holistic view of 3D printing and its impact. The primary rationale behind selection of the case studies is that each represents a different aspect of how 3D printing can transform the construction industry. The Canal House emphasizes sustainability through innovative materials and on-site 3D printing, while WinSun focuses on large-scale applications using industrial waste. Contour Crafting explores the automation of construction, significantly reducing labor and material waste. Together, these case studies highlight the diverse ways in which 3D printing is contributing to more efficient, sustainable, and cost-effective construction methods aligned with global SDGs. The comparative analysis conducted is shown in Table 2.

One of the key features across these projects is the innovative use of materials. The Canal House employs biodegradable thermoplastics, which reduce long-term waste and environmental damage, contributing to SDG 12 (Responsible Consumption and Production). However, concerns about the durability of these materials in more complex structures remain. In contrast, WinSun uses industrial waste, fiberglass, and cement to construct large-scale buildings. This approach helps tackle both waste management and resource efficiency issues, aligning with SDG 9 (Industry, Innovation, and Infrastructure) and SDG 12, though the reliance on cement limits its environmental benefits.

Table 2. Comparative analysis between three 3D printing based projects

Feature	Canal House	WinSun Projects	Contour Crafting
Location	Amsterdam	China	Researched by Behrokh Khoshnevis from the University of Southern California, USA
Materials Used	Biodegradable thermoplastic	Industrial waste, fiberglass, cement, hardening agents	Primarily concrete, but could use various materials
Environmental Impact	Reduces transportation costs and waste	Recycles industrial waste, reduces carbon footprint	Minimizes waste and labor through automation
Construction Method	3D printing on-site	Large-scale 3D printing of residential/commercial buildings	Automated 3D printing for faster construction
Innovation Focus	Sustainability and reducing transportation costs	Recycling waste materials and cost-efficient construction	Automation, labor reduction, and faster construction times
Challenges	Durability of biodegradable materials	Regulatory acceptance, structural durability	Scaling, technical limitations, regulatory adoption
Key SDGs	SDGs 9, 11, 12	SDGs 9, 11, 12, 13	SDGs 8, 9, 11

Contour Crafting utilizes robotic construction machinery for automated laying of materials in accurate shapes and forms, and in addition, does not require a huge amount of material and human resources. Its potential application, which includes low-cost structures that can be built quickly, can be of great importance in the event of disasters. Analysing the environmental aspect of these projects affirms the role of these projects in implementing one of the sustainable development goals, the SDG 13 (Climate Action). Canal House moved equipment on-site to have 3D printed houses and therefore has no transportation emission and on the WinSun part, the company incorporates recycled materials, thus they do not affect virgin resources or damage the environment. Contour Crafting brings down wastage incidences in constructions by following precise material measures and thus brings down the energy required during construction.

In construction method each example demonstrates the versatility of the 3D printing technology. The Canal House features on-site printing, ensuring that changes can be made efficiently, as well as for its ability to store and distribute materials, local to small-scale projects in urban environments. On the other hand, WinSun proves the applicability of 3D technology in off-site constructions, after which the structures are assembled on site, for constructing multiple storey buildings and even entire cities. Contour Crafting concentrates on computer controlled machines, thus providing a very efficient means to realize inexpensive, quickly built shelters. These projects result in achieving the innovation focus of SDG 9 for technological innovation in construction. Canal House experiments with the usage of materials in ways that is sustainable though risky, WinSun best exemplifies recycling of industrial waste primarily for large scale structures; and Contour Crafting relies on technology for repetitive transferring of material. Combined, these innovations exemplify the potential of 3D printing in constructing structures that utilize less material, build faster and at lower cost. However, while these projects evidence meaningful benefits of 3D printing, there are also other issues presented. At Canal House, there is an issue of sustainability of biodegradable materials, while WinSun faces problems of authoritative permission on the usage of industrial waste. Contour Crafting, as with most fast growing technologies, has its drawbacks which include being suitable only for simple structures, especially the low rise ones. On a broader scale, these cases will establish the prospect of 3D printing in supporting sustainable construction to redesign resource use, waste management and housing that is more affordable by responding to the intended goals of SDG 9, SDG 12 and SDG 13.

4. Discussion and Practical Implications

4.1. Lifecycle of 3D Printing in Projects

This paper discusses the life cycle of 3D printed construction and infrastructure projects covering materials sourcing to disposal, which provide important insights into the application of this technology in terms of sustainability and efficiency. This has been made significantly clear in the systematic review as well as in the three case organizations, namely, Canal House, WinSun Projects and Contour Crafting. All these have revealed that the type of material utilized in the construction project lifecycle bears a very close and direct relationship with the overall effect on the environment. For example, the biodegradable thermoplastic materials, which were used in the Canal House project, counteract the long-term impact on all outlined by the Sustainable Development Goal 12 (Responsible Consumption and Production) (Yu et al., 2024). Nevertheless, questions have been raised about the sustainable performance and structural stability of such materials during the life cycle of a building, it is, therefore, imperative to undertake more studies on their applicability for more massive and complex construction. Unlike the WinSun production process, using industrial waste and cement mixtures which involves the disposal of waste material and thus enhancing the circular economy, but disappointed by using carbon concrete, a persistent dilemma with regard to SDG 13 (Climate Action) (Khalil et al., 2020).

The Canal House and WinSun Projects based success show that customization and the efficient use of materials are best achievable in the design and construction phases of the 3D printing lifecycle. Regarding the flexibility of this technique in solving the problems of urban sustainability, it is necessary to mention that 3D printing reduces transportation emissions due to manufacturing large and complex structures directly at the Canal House, where basic structural elements combined to construct unique structures that can be easily adjusted to existing urban environment (Yu et al., 2024). While achieving economies of scale through off-site 3D printing, arrayed in on-site integration, WinSun has also experienced challenges surrounding transport movements and emissions (Mogaji et al., 2023).

The type of automation apparent in Contour Crafting is much closer to the actual appreciation of the construction process being done more efficiently. This method not only minimizes the usage of labor but also makes the most efficient use of materials and helps minimize wastage which is very helpful when it comes to the construction through 3D printing (Haghighi et al., 2021).

Because the aesthetic aspects are most often resolved during the construction phase, when these projects have entered the operational phase, issues of life span of structures and maintenance of the materials used come to the forefront. As for the biodegradable materials suggested in the case study of Canal House, these may disintegrate more rapidly compared to ordinary materials that in turn may undermine the overall stability of a building after some time (Yu et al., 2024). The construction of WinSun Projects are made from fiberglass and industrial waste which may attract regulatory measures on the environmental impacts and products performance in long run, particularly in high rise buildings (Khalil et al., 2020). Hence, the sustainability of 3D printed structures can be determined by the durability of the structures at each stage of their existence.

Finaly, the disposal or recycling of 3D-printed structures at the life cycle's final stage needs investigation. Thus, Canal House demonstrates how the use of biodegradable materials can be properly disposed to fit the principles of circular economy (Wong et al., 2024). While industrial waste in WinSun's printers seems to be recycled, there is a potential to recycle them again at the end of the building's lifespan by developing better systems and/or better plans, and legal frameworks to support it (Mogaji et al., 2023). Knowing how it is possible to breakdown 3D-printed components and recycle them is therefore important to ensure that such initiatives are environmentally sustainable and do not just shift the problem from one stage of the 3D-printed components lifecycle to another.

4.2. Future of 3D Printing: Regulation, Innovation, and Scalability

Three other headings that need to be discussed are regulation, innovation and scalability. The future of 3D printing in construction will be shaped by several key factors: regulatory policies, the advancement in technology, and the potential to implement and advance such technologies to address global facilities and sustainability factor demands. To date, regulations have been one of the most critical factors of 3D printing in construction due to its absence in this industry. As witnessed in the WinSun Projects, incorporation of industrial waste into construction materials proves recklessness in respect to structural stability and longevity of the structures, especially in a multi-story project development (Khalil et al., 2020). Although, over the time, WinSun has achieved a great leap in the utilization of recycled material, the formalities for getting legal approvals to incorporate such innovations are still quite complex and region-sensitive (Mogaji et al., 2023). Likewise, Contour Crafting has issues concerning the governmental laws governing the method of automation in construction because it is relatively new in the construction industry (Haghighi et al., 2021). Indeed, future policy measures shall encompass novel materials, and advanced automated methods for 3D printing to remain safe and implement sustainable strategies (Moghayedi et al., 2022). National and international authorities will have to compromise with factories' representatives and the scientific community to create standards that will encourage experimental work, and ensure that human safety is considered at the same time.

Technological advancements, particularly in the construction sector, have seen 3D printing as technology that can transform the construction industry through optimizing the use of material and minimizing wastage. But future prospects will most possibly deal with the search for new materials that withstand higher loads as well as possessing improved durability and reliability, and all that with less negative impact to the surrounding environment. For instance, despite the benefits exhibited by various materials that were used in the Canal House project, biodegradable thermoplastics may take some years to generate large-scale and long-term prospects. New developments in low-emission cement or recycled materials, which have been employed by WinSun Projects, are essentially important in combating energy emissions of construction while at the same time ensuring that 3D printed buildings meet the structural demands of contemporary architecture (Khalil et al., 2020). Also, the advancement in automation and robotic systems will continue to be important for further increased efficiencies where labor costs and construction times are of paramount importance, as in the case with Contour Crafting (Haghighi et al., 2021).

Furthermore, the question of size matters when it comes to large scale construction of infrastructure. Although 3D printing has been praised for its capabilities in production, it still has some limitations that have not fully been fully exploited to its optimum extent. Canal House shows that on-site 3D printing is viable in the construction of small and compact residential buildings in urban environments (Yu et al., 2024); WinSun Projects showed that off-site construction using 3D printing as a construction tool is scalable to much larger structures such as multi-story buildings and urban infrastructures (Mogaji et al., 2023). Nonetheless, transport-related emissions and regulatory permit issues still affect the optimization of benefits 3D printing offers in infrastructure projects across the globe (Haghighi et al., 2021). For 3D printing to become a mainstream solution for large-scale construction, significant investments in policy support, public-private partnerships, and technological innovation will be required. Moreover, as the demand for sustainable urban development grows, 3D printing will need to demonstrate that it can meet the cost, efficiency, and sustainability goals of modern cities while contributing to global efforts such as SDG 9 (Industry, Innovation, and Infrastructure) and SDG 11 (Sustainable Cities and Communities) (Mogaji et al., 2023).

In summary, the lifecycle of 3D printing projects in construction demonstrates clear linkages to the SDGs, particularly in terms of resource efficiency, energy savings, and material innovation. However, to ensure that these technologies can sustainably transform the construction industry, greater emphasis must be placed on ensuring material durability, scalability, and the development of robust recycling systems. The integration of SDGs such as SDG 7, SDG 9, SDG 11, SDG 12 and SDG 13 within the lifecycle framework highlights the potential for 3D printing to advance sustainable infrastructure and contribute meaningfully to global sustainability efforts. Figure 3 illustrates the framework proposed as a result of findings from the study, which provides an overlook on 3D printing-based projects across the lifecycle.

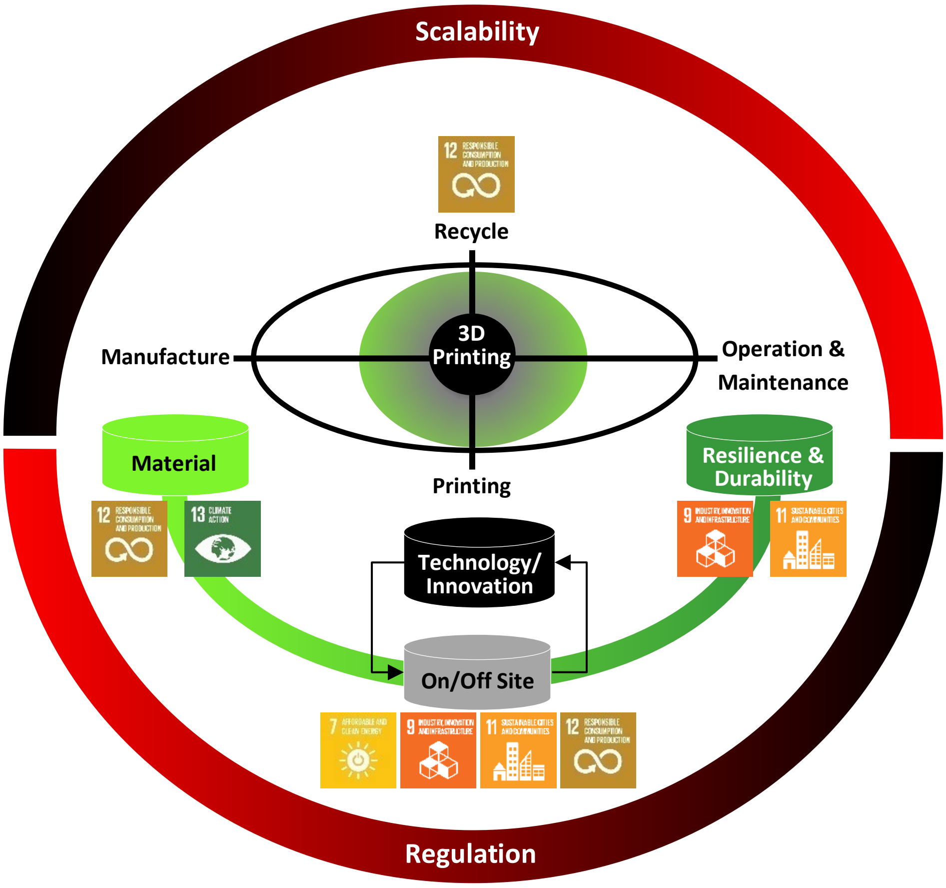

Fig. 3. "The 3D Eye" framework illustrating considerations in the lifecycle of 3D printing project

5. Conclusions and Future work

To sum up, this research has provided a critical evaluation of 3D printing technology and its transformative potential within the construction industry, particularly in promoting sustainable practices. By examining the lifecycle of 3D printing projects — encompassing material sourcing, design, construction, operation, and end-of-life — the study has highlighted the significant environmental and practical benefits that 3D printing offers. Through both the systematic review and detailed case studies, it is evident that 3D printing addresses key sustainability challenges, such as material conservation, waste reduction, and the integration of recycled and biodegradable materials. Key findings suggest that 3D printing aligns closely with many SDGs across the lifecycle, which demonstrates the long-term value. However, despite its advantages, the research has also identified several challenges that limit the full potential of 3D printing in construction. Issues related to material durability, regulatory barriers, and the scalability of 3D printing projects remain significant hurdles. The research proposes "The 3D Eye" framework, which illustrates different considerations that encompass the lifecycle of a 3D printing project.

Looking ahead, the future of 3D printing in construction appears bright, but achieving its full potential will require a collaborative effort across industries, governments, and academic institutions. Continued research into new materials, the development of recyclable components, and the creation of scalable frameworks for both residential and infrastructure projects will be critical in transforming 3D printing from an innovative niche technology to a mainstream sustainable solution. With the right investments in innovation, policy support, and cross-industry collaboration, 3D printing can play a pivotal role in addressing global challenges in sustainable infrastructure and contributing to a more resilient, environmentally conscious construction industry.

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Author Contributions

Hesham Rabayah contributes to conceptualization, methodology, draft preparation, manuscript editing, supervision, and funding acquisition. Mohammad Mayouf contributes to conceptualization, methodology, validation, analysis, data collection, draft preparation, and supervision. Rusl Abu Qalbin contributes to methodology, software, analysis, draft preparation, investigation, data collection, draft preparation, and visualization. All authors have read and agreed with the manuscript before its submission and publication. Fuad El-Qirem contributes to conceptualization, validation, supervision, manuscript editing, and funding acquisition.

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