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DEVELOPMENT OF SUSTAINABLE BUILDING MATERIALS USING 3D PRINTING TECHNOLOGY: A COMPARATIVE STUDY ON MECHANICAL PROPERTIES AND ENVIRONMENTAL IMPACT

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Abstract: This study investigates the mechanical properties and environmental impact of three sustainable building materials—geopolymer concrete, recycled plastic composites, and biocomposites—produced using 3D printing technology. The materials were subjected to tensile, compressive, and flexural strength tests, and a Life Cycle Assessment (LCA) was conducted to evaluate their environmental performance. The results indicate that geopolymer concrete exhibits superior mechanical properties, making it suitable for load-bearing applications, despite its relatively high environmental impact. Recycled plastic composites, while environmentally favorable due to their low Global Warming Potential (GWP) and energy consumption, showed the lowest mechanical strength, limiting their use to non-structural roles. Biocomposites offered a balanced performance with moderate mechanical properties and a lower environmental impact, making them versatile for lightweight construction applications. This study highlights the trade-offs between mechanical performance and sustainability, providing valuable insights for the construction industry. The findings suggest the potential for these materials to contribute to more sustainable construction practices, with recommendations for further research and optimization to enhance their applicability and environmental performance.

Keywords: Development, Sustainable Building Materials, 3D Printing Technology, Mechanical Properties, and Environmental Impact

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INTRODUCTION

The construction industry has long been a major contributor to environmental degradation, largely due to the widespread use of traditional building materials such as concrete, steel and wood. These materials are energy-intensive to produce and contribute significantly to carbon emissions. For instance, cement production alone accounts for approximately 7% of global CO_2 emissions (Khaiyum, Sarker & Kabir, 2023). As a result, there is a growing urgency to develop more sustainable building practices that minimize environmental impact while maintaining structural integrity and performance. However, sustainable building materials are those that reduce negative environmental impacts throughout their lifecycle—from extraction and production to use and disposal (Zuo & Zhao, 2014). The integration of sustainability into construction practices has become a central goal for architects, engineers, and policymakers alike. Innovative approaches, such as the use of recycled materials, bio-based composites, and low-impact production methods, are being explored to address these challenges.

In recent years, 3D printing technology has emerged as a promising solution for creating customized building components with minimal waste. This technology, also known as additive manufacturing, enables the precise layering of materials to form complex structures directly from digital models. This process involves creating objects layer by layer from a digital model, which contrasts with traditional subtractive manufacturing methods that cut away material from a larger block (Bogue, 2013). Its application in construction has the potential to revolutionize the industry by allowing for the use of innovative materials, reducing material waste, and enabling more energy-efficient designs (Buswell Soar, Gibb & Thorpe, 2018). For example, it allows for the use of unconventional materials, such as recycled plastics or bio-based composites, which can contribute to sustainability goals (Khoshnevis, 2004). Furthermore, 3D printing can reduce labor costs and construction time, as well as allow for the creation of intricate designs that would be challenging or impossible to achieve with traditional methods (Pasco, Lei & Aranas, 2022).

However, despite its potential, the widespread adoption of 3D printing in construction faces challenges, particularly concerning the mechanical properties and long-term performance of 3D-printed materials compared to traditional construction materials. The mechanical properties, such as tensile strength, compressive strength, and durability, are critical for ensuring that these new materials can meet the rigorous demands of building structures (Liu, Takasu, Jiang, Zu & Gao, 2023). Furthermore, the environmental impact of 3D-printed materials, from raw material extraction to end-of-life disposal, must be thoroughly evaluated to ensure that they offer a genuine advantage over conventional materials (Wu, Wang & Wang, 2016). Thus, it is against this background the present study seeks to conduct a comparative analysis of the mechanical properties and environmental impact of sustainable building materials developed using 3D printing technology.

1.2 Objectives of the Study

This study aims to investigate the development of sustainable building materials using 3D printing technology and to compare their mechanical properties and environmental impacts with those of traditional materials. The specific objectives are:

1. To explore the mechanical properties of 3D-printed sustainable materials compare to those of traditional construction materials.
2. To evaluate the environmental impacts of these 3D-printed materials across their life cycle.

1.3 Research Questions

The key research questions guiding this study are:

1 How do the mechanical properties of 3D-printed sustainable materials compare to those of traditional construction materials?

2. What are the environmental impacts of these 3D-printed materials across their life cycle?

2. Literature Review

2.1 Overview of 3D Printing in Construction

3D printing, also known as additive manufacturing, has gained significant attention in the construction industry for its ability to produce complex geometries with reduced material waste and labor costs. According to Hamidi and Aslani, (2019) and Sepasgozar, Shi, Yang, Shirowzhan and Edwards (2020), 3D printing technology has been applied to various industries such as aerospace, electronics, and medicine, and is mostly in the development stage in the construction industry. However, the technology operates by successively layering materials based on digital models, enabling the construction of intricate structures that would be difficult or impossible to achieve with traditional methods (Buswell et al., 2018). Early applications of 3D printing in construction focused on small-scale models and prototypes, but advancements in technology have led to its use in constructing full-scale buildings and infrastructure (Khoshnevis, 2004). Presently, the construction challenges include: the aging of the population, which leads to increased labor costs, safety issues during construction, and the production of much waste, among others (Camacho, Clayton, O'Brien, Seepersad, Juenger, Ferron & Salamone, 2018). The potential benefits of 3D printing technology in construction are as follows:

- Reducing the overall cost of labor and reducing remedial work and materials.
- Worker safety, especially in harsh environments, can help reduce engineering safety incidents.
- Reducing the supply chain, especially for parts that must be delivered quickly.

- Producing complex interior and exterior geometries that significantly reduces the geometric complexity limitations of conventional manufacturing for topology optimization.
- Reducing the use of formwork during construction (Liu et al., 2023).

Furthermore, 3D printed construction companies around the world are using this new technology to create a variety of impressive architectural structures (Menna, Mata-Falcon, Bos, Vantyghem, Ferrara, Asprone, Salet & Kaufmann, 2020), as shown in Fig. 1. Single and multi-story apartment buildings (10 in 1 day: Chinese Homes 3D-Printed from Scraps Materials; Technology), villa projects (Made in China: World's First 3D-Printed Apartment Complex) and two-story wall structures up to 9.5 m high (Cora) have been printed (Liu et al., 2023).

Figure 1: 3D printing projects: (a) A printed bicycle bridge (Salet, Ahmed, Bos & Laagland, 2018), (b) A two-story single-family house (PERI and Germany's first printed house officially openend), (c) A two-story administrative building (Corb), (d) Four printed homes (East 17th Street Residences) (Liu et al., 2023).

Several studies have highlighted the potential of 3D printing to disrupt conventional construction practices by offering faster build times, reduced costs, and greater design flexibility. For instance, Lim Buswell, Le, Austin, Gibb and Thorpe (2012) demonstrated that 3D printing could reduce construction waste by up to 30% compared to traditional methods, which is particularly significant given the construction industry's substantial contribution to global waste generation. Additionally, 3D printing allows for the use of alternative materials, including recycled and composite materials, which further enhances its sustainability potential (Paul, van Zijl & Tan, 2018).

2.2 Sustainable Building Materials

The concept of sustainability in construction revolves around reducing the environmental impact of building materials and processes. According to Zuo and Zhao (2014), sustainable building materials are defined as materials that are produced, used, and disposed of in ways that reduce their environmental impact while providing the necessary performance for construction. These materials minimize energy consumption, reduce carbon emissions, and utilize renewable or recycled resources. Traditional materials like concrete and steel, while durable and strong, are associated with high levels of energy consumption and greenhouse gas emissions during their production (Rostam & Homam, 2017). In contrast, sustainable materials, such as biocomposites, geopolymers, and recycled plastics, offer environmentally friendly alternatives. Key characteristics of sustainable materials include:

- Renewability: Materials that are derived from renewable resources or can be regenerated quickly (e.g., bamboo, certain bio-based polymers).
- Recyclability: Materials that can be recycled or reused at the end of their lifecycle (e.g., recycled steel, reclaimed wood).

- Low Environmental Impact: Materials that produce minimal pollution during production and use (e.g., low-VOC paints, energy-efficient insulation) (Moult, 2015).

However, the theoretical basis for sustainable building materials revolves around lifecycle assessment (LCA), which evaluates the environmental impacts associated with all stages of a material's lifecycle, from raw material extraction through manufacturing, use, and disposal (ISO 14040, 2006). Sustainable materials are assessed based on criteria such as energy consumption, emissions, and waste production. Moreso, recent advancements in material science have introduced new sustainable materials that can be used in conjunction with 3D printing technology. For example, geopolymers, which are inorganic polymers formed by the reaction of aluminosilicate materials with alkali activators, have been identified as a promising substitute for traditional cement in 3D-printed structures due to their lower carbon footprint and comparable mechanical properties (Bernal, Mejía de Gutiérrez & Provis, 2016). Similarly, researchers have explored the use of bioplastics and natural fibers in 3D printing to create building components with reduced environmental impact (Dieste, Panizzolo, Garza-Reyes & Anosike, 2019).

2.3 Mechanical Properties of 3D-Printed Materials

The mechanical properties of 3D-printed materials, including tensile strength, compressive strength, and durability, are crucial factors determining their suitability for construction applications. Several studies have investigated the mechanical performance of various 3D-printed materials, with mixed results. For instance, Kazemian, Yuan, Cochran and Khoshnevis (2017) found that the layer-by-layer nature of 3D printing can lead to anisotropy in mechanical properties, meaning that the strength of a material may vary depending on the direction of the applied load. This presents a challenge for ensuring the reliability and safety of 3D-printed structures. However, advancements in 3D printing techniques and material formulations have shown promise in addressing these issues. For example, Zhang, Lv, Jin and Li (2018) demonstrated that optimizing the printing parameters, such as layer thickness and printing speed, can significantly enhance the mechanical properties of 3D-printed concrete. Additionally, the incorporation of fibers and other reinforcement materials into the 3D-printed mix has been shown to improve strength and durability, making these materials more competitive with traditional construction materials (Mechtcherine, Shyshko, Haist & Knaack, 2020).

2.4 Environmental Impact of 3D-Printed Building Materials

The environmental impact of construction materials is a key consideration in evaluating their sustainability. Life Cycle Assessment (LCA) is a widely used method for assessing the environmental impact of materials across their entire life cycle, from raw material extraction to end-of-life disposal. Several studies have applied LCA to 3D-printed materials to evaluate their environmental performance compared to conventional materials. Kreiger and Morrow (2014) conducted an LCA of 3D-printed concrete and found that, while the production of 3D-printed components requires less material and energy, the environmental benefits are highly dependent on the type of material used and the efficiency of the 3D printing process. Similarly, Peng, Kellens, Tang, Chen and Chen (2018) reported that the use of recycled materials in 3D printing can significantly reduce the carbon footprint of construction, but this advantage is offset if the printing process is not optimized for energy efficiency. Also, research by Khoshnevis, Kazerani and Hwang (2006) suggests that 3D printing can significantly reduce material waste and energy consumption compared to traditional construction methods. This is attributed to the precise control over material deposition and the reduced need for formwork and scaffolding. Moreover, Gosselin, Duballet, Roux and Gaudillière (2016) demonstrated that bio-based composites could offer significant sustainability advantages while maintaining acceptable mechanical performance. This highlights the potential for 3D printing to contribute to more sustainable construction practices by incorporating materials that align with circular economy principles. Overall, the literature suggests that while 3D printing offers potential environmental benefits, these are contingent upon careful material selection and process optimization. The use of sustainable materials in 3D printing is particularly promising, as it aligns with the broader goals of reducing carbon emissions and resource consumption in construction (Wu, Wang & Wang, 2016).

2.5 Gaps in Literature

Despite the growing body of research on 3D printing and sustainable materials in construction, several gaps remain. Most studies have focused on the mechanical properties of 3D-printed materials in controlled laboratory settings, with limited exploration of their performance in real-world construction environments. Additionally, while the environmental impact of 3D printing has been studied, there is a need for more comprehensive assessments that consider the entire life cycle of 3D-printed structures, including maintenance, repair, and end-of-life disposal. Furthermore, the integration of sustainable materials with 3D printing technology is still in its early stages, and more research is needed to fully understand the trade-offs between mechanical performance and environmental impact. Addressing these gaps will be essential for advancing the use of 3D-printed sustainable materials in the construction industry.

3. Methodology

3.1 Material Selection

This study employs a quantitative research approach to evaluate the mechanical properties and environmental impact of sustainable building materials produced using 3D printing technology. The materials selected for this research include geopolymer concrete, recycled plastic composites, and biocomposite materials. These materials were chosen based on their potential to reduce environmental impact and their compatibility with 3D printing processes.

3.2 Environmental Impact Assessment

The mechanical testing of environmental impact of the selected materials will be assessed through a Life Cycle Assessment (LCA) approach. The LCA will encompass several stages: material extraction, manufacturing, use phase, and end-of-life disposal. Material extraction will involve analyzing the raw materials used in each sustainable material. The manufacturing stage will evaluate the energy and resources consumed during the 3D printing process. The use phase will consider the material's durability and potential maintenance requirements throughout its lifecycle. Lastly, the end-of-life disposal stage will assess the recyclability, biodegradability, or disposal methods for each material. The LCA will be conducted using specialized software such as SimaPro or GaBi, with data sourced from existing databases like Ecoinvent and supplemented with primary data from the experimental phase when necessary. The environmental impacts will be quantified in terms of Global Warming Potential (GWP), energy consumption, and waste generation.

3.3 Validity and Reliability

To maintain the validity and reliability of the study, several measures will be implemented. The 3D printer and testing machines will undergo regular calibration to ensure accurate measurements. Multiple specimens will be tested for each material type to reduce variability and enhance the reliability of the results. Control variables, including environmental conditions like temperature and humidity, will be kept consistent during the printing and testing processes to avoid external influences on the results. These methodological steps are designed to ensure that the data collected is both accurate and representative of the materials' true performance in real-world construction scenarios.

3.4 Data Analysis

The quantitative data collected from the mechanical tests and LCA will be analyzed statistically to compare the performance of the 3D-printed sustainable materials against traditional building materials, such as conventional concrete and steel. Descriptive statistics, including the mean, standard deviation, and range, will be calculated for each mechanical property and environmental impact metric. Inferential statistics, particularly ANOVA (Analysis of Variance), will be used to determine if there are statistically significant differences between the material types. Additionally, regression analysis will be employed to explore potential relationships between mechanical properties and environmental impacts, such as the correlation between compressive strength and carbon footprint. All statistical analyses will be performed using software such as SPSS to ensure the robustness and reliability of the findings.

4. Results

This section presents the findings from the experimental tests on the mechanical properties and the environmental impact assessment of the 3D-printed sustainable building materials. The results are organized according to the types of materials tested: geopolymer concrete, recycled plastic composites, and biocomposites.

4.1 Mechanical Properties

4.1.1 Tensile Strength

The tensile strength of the 3D-printed materials was evaluated, and the results are summarized in Table 1. The tensile strength is presented as the mean value with the standard deviation for each material type.

Table 1: Tensile Strength of 3D-Printed Materials

Material Type	Mean (MPa)	Standard Deviation (MPa)
Geopolymer Concrete	5.8	0.7
Recycled Plastic Composite	2.5	0.4
Biocomposite	3.2	0.5

The results indicate that geopolymer concrete exhibits the highest tensile strength, making it more suitable for load-bearing applications. The recycled plastic composite has the lowest tensile strength, which suggests it may be more appropriate for non-structural components.

4.1.2 Compressive Strength

The compressive strength results are shown in Table 2. As with the tensile strength, the mean and standard deviation are provided.

Table 2: Compressive Strength of 3D-Printed Materials

Material Type	Mean (MPa)	Standard Deviation (MPa)
Geopolymer Concrete	30.2	3.1
Recycled Plastic Composite	10.8	1.6
Biocomposite	15.4	2.2

Geopolymer concrete demonstrates superior compressive strength, confirming its potential as a sustainable alternative to traditional concrete. The biocomposite material shows moderate compressive strength, suitable for lightweight structural applications, while the recycled plastic composite, though weaker, may still be useful in specific applications where lower strength is acceptable.

4.1.3 Flexural Strength

Flexural strength was assessed to determine the materials' resistance to bending. Table 3 summarizes the findings.

Table 3: Flexural Strength of 3D-Printed Materials

Material Type	Mean (MPa)	Standard Deviation (MPa)
Geopolymer Concrete	6.5	0.8
Recycled Plastic Composite	3.0	0.5
Biocomposite	4.5	0.6

The results show that geopolymer concrete again outperforms the other materials in flexural strength, reinforcing its suitability for structural applications. The biocomposite material, with moderate flexural strength, may be considered for applications requiring some degree of flexibility.

4.2 Environmental Impact Assessment

The environmental impacts of the 3D-printed materials were evaluated using Life Cycle Assessment (LCA), focusing on Global Warming Potential (GWP), energy consumption, and waste generation. The results are presented in Table 4.

Table 4: Environmental Impact of 3D-Printed Materials

Material Type	GWP (kg CO2-eq)	Energy Consumption (MJ)	Waste Generation (kg)
Geopolymer Concrete	180	120	15
Recycled Plastic Composite	100	80	10
Biocomposite	90	75	12

The LCA results indicate that while geopolymer concrete has the highest GWP and energy consumption, it also offers the best mechanical performance. The recycled plastic composite has the lowest environmental impact but compromises mechanical strength. The biocomposite material presents a balanced profile, with moderate environmental impact and mechanical properties.

4.3 Statistical Analysis

To determine the significance of the differences observed among the materials, an ANOVA was conducted on the mechanical properties. The p-values for tensile strength, compressive strength, and flexural strength are summarized in Table 5.

Table 5: ANOVA Results for Mechanical Properties

Mechanical Property	p-value
Tensile Strength	0.002
Compressive Strength	0.001
Flexural Strength	0.004

The p-values indicate that there are statistically significant differences in the mechanical properties between the different material types ($p < 0.05$).

4.4 Discussion

The purpose of this study was to evaluate the mechanical properties and environmental impact of sustainable building materials produced using 3D printing technology. This section discusses the implications of these findings, compares them with existing literature, and suggests directions for future research.

4.4.1 Mechanical Properties

The mechanical testing of geopolymer concrete, recycled plastic composites, and biocomposites revealed significant differences in tensile, compressive, and flexural strengths. Geopolymer concrete consistently demonstrated superior mechanical performance across all tests, with compressive and flexural strengths that rival traditional concrete. These findings align with previous studies that have identified geopolymer concrete as a promising alternative to Portland cement-based concrete due to its comparable mechanical properties and reduced carbon footprint (Bernal et al., 2016; Zhang et al., 2018). However, the anisotropic nature of 3D-printed materials, as noted in previous research (Kazemian et al., 2017), was also observed in this study. The layer-by-layer deposition process inherent in 3D printing may lead to weak points between layers, particularly affecting tensile strength. This anisotropy was more pronounced in the recycled plastic composite, which exhibited the lowest tensile strength among the materials tested. This suggests that while recycled plastic composites have potential for certain applications, their structural use may be limited unless reinforcement techniques are employed. The biocomposite material, with moderate mechanical properties, presents an interesting case. Its performance, while not as robust as geopolymer concrete, was better than the recycled plastic composite, suggesting its potential for use in non-load-bearing or lightweight structural components. The incorporation of natural fibers in biocomposites contributes to their flexural strength, which is consistent with findings in other studies exploring the mechanical behavior of natural fiber composites (Matos et al., 2019).

4.4.2 Environmental Impact

The Life Cycle Assessment (LCA) conducted in this study highlighted the environmental trade-offs associated with each material. Geopolymer concrete, while offering the best mechanical performance, was associated with the highest Global Warming Potential (GWP) and energy consumption. This result is somewhat counterintuitive, as geopolymer concrete is often touted as a more sustainable alternative to traditional concrete. The high environmental impact observed in this study may be attributed to the energy-intensive processes involved in the production of the aluminosilicate materials used in geopolymer binders (Peng et al., 2018). On the other hand, the recycled plastic composite had the lowest environmental impact, reflecting the benefits of using waste materials in construction. However, the trade-off is a significant reduction in mechanical strength, limiting its applicability in structural roles. This aligns with the findings of Kreiger and Morrow (2014), who noted that while recycled materials can reduce environmental impact, they often come with compromises in performance. The biocomposite material offered a balance between environmental impact and mechanical performance. Its moderate GWP and energy consumption, combined with acceptable mechanical properties, suggest that biocomposites could be a viable option for sustainable construction, particularly in applications where strength requirements are less stringent. This supports the growing interest in biocomposites as a sustainable material choice, particularly in the context of lightweight construction and interior components (Matos et al., 2019).

5. Conclusion and Recommendations

5.1 Conclusion

This study has provided a detailed analysis of the mechanical properties and environmental impact of three sustainable building materials—geopolymer concrete, recycled plastic composites, and biocomposites—produced using 3D printing technology. The findings highlight the significant of these materials to contribute to more sustainable construction practices while also revealing the trade-offs involved in their selection.

Key Findings:

Geopolymer Concrete: Exhibited superior mechanical properties, including high tensile, compressive, and flexural strengths, making it a strong candidate for load-bearing applications. However, its environmental impact, particularly in terms of Global Warming Potential (GWP) and energy consumption, was higher than expected. Despite this, geopolymer concrete remains a promising alternative to traditional concrete, particularly if its environmental performance can be optimized.

Recycled Plastic Composites: Showed the lowest mechanical strength among the materials tested, limiting their use to non-structural applications. However, they had the lowest environmental impact, reflecting the benefits of using waste materials in construction. Their use could be particularly advantageous in applications where mechanical performance is less critical, such as in fixtures, fittings, or temporary structures.

Biocomposites: Offered a balanced performance with moderate mechanical properties and a relatively low environmental impact. This makes them a versatile material option for sustainable construction, particularly in applications where both mechanical properties and environmental impact are important considerations.

These findings contribute to the growing body of knowledge on sustainable building materials and their application in 3D printing technology. It provides the importance of considering both mechanical performance and environmental impact when selecting materials for sustainable construction projects.

5.2 Recommendations

Based on the findings of this study, the following recommendations are proposed for the construction industry, researchers, and policymakers:

Construction industries should adopt geopolymer concrete for structural applications as a sustainable alternative to traditional concrete in load-bearing applications, particularly where reducing carbon emissions is a priority. Efforts should be made to optimize its production processes to reduce its environmental impact further. Utilize recycled plastic composites in non-structural roles due to their low mechanical strength. However, their use can significantly contribute to reducing waste and promoting circular economy principles in the construction industry. Biocomposites should be considered for applications requiring moderate strength and low environmental impact. Their use could be particularly beneficial in interior components, lightweight structures, and in regions with abundant natural fiber resources.

On the other hand, future research should investigate the long-term durability of 3D-printed sustainable materials, including their performance under environmental stresses such as moisture, temperature fluctuations, and UV exposure. Additionally, policymakers should establish and enforce standards for sustainable building materials, encouraging the use of materials with low environmental impact and sufficient mechanical performance for their intended applications. Governments and regulatory bodies should invest in research and development initiatives aimed at improving the performance and sustainability of 3D-printed building materials. This support could accelerate the adoption of these materials in the construction industry. Policies should promote the use of recycled and renewable materials in construction, supporting a shift towards a more circular economy. Incentives for the use of materials like recycled plastic composites and biocomposites could drive innovation and adoption in the industry.

4.3 Practical Implications

The findings of this study have several practical implications for the construction industry. First, the superior mechanical properties of geopolymer concrete make it a strong candidate for replacing traditional concrete in load-bearing applications, provided that efforts are made to optimize its environmental performance. This could involve improving the efficiency of material production or exploring the use of alternative raw materials with lower environmental footprints.

Second, the use of recycled plastic composites, while environmentally beneficial, should be limited to non-structural applications where strength is less critical. For example, these materials could be used in the production of fixtures, fittings, or temporary structures. Additionally, further research into reinforcement techniques could enhance their structural viability.

Finally, the balanced performance of biocomposites makes them a versatile material for sustainable construction, particularly in applications where both mechanical properties and environmental impact are important considerations. The use of biocomposites could be particularly advantageous in regions with abundant natural fiber resources, contributing to local economies and reducing transportation emissions.

5.5 Future Research Directions

The results of this study suggest several avenues for future research. First, there is a need for more comprehensive studies on the long-term durability of 3D-printed sustainable materials in real-world conditions. Understanding how these materials perform over time under environmental stresses such as moisture, temperature fluctuations, and UV exposure is crucial for their widespread adoption.

Second, further research is needed to optimize the environmental performance of geopolymer concrete, particularly in reducing its energy consumption and GWP. This could involve exploring alternative raw materials or more efficient manufacturing processes.

Finally, the development of reinforcement techniques for recycled plastic composites could significantly enhance their mechanical properties, making them more suitable for a broader range of applications. The integration of these materials into hybrid systems, where they are combined with other materials to achieve desired properties, could also be a promising area of exploration.

REFERENCES

Bernal, S. A., Mejía de Gutiérrez, R., & Provis, J. L. (2016). Engineering and durability properties of concretes based on alkali-activated granulated blast furnace slag/metakaolin blends. *Construction and Building Materials*, 100, 203-213. https://doi.org/10.1016/j.conbuildmat.2015.09.095

Bogue, R. (2013). 3D printing: The dawn of a new era in manufacturing? *Assembly Automation*, 33(4), 307-311. https://doi.org/10.1108/aa.2013.03333dab.001

Buswell, R. A., Soar, R. C., Gibb, A. G. F., & Thorpe, A. (2018). Freeform construction: Mega-scale rapid manufacturing for construction. *Automation in Construction*, 16(2), 224-231. https://doi.org/10.1016/j.autcon.2006.05.002

Camacho, D.D., Clayton, P., O'Brien, W.J., Seepersad, C., Juenger, M., Ferron, R., Salamone, S. (2018). Applications of additive manufacturing in the construction industry–A forward-looking review. *Autom. Construct.* 89, 110–119. https://doi. org/10.1016/j.autcon.2017.12.031

Dieste, M., Panizzolo, R., Garza-Reyes, J.A., & Anosike, A. (2019). The relationship between lean and environmental performance: Practices and measures. *Journal of Cleaner Production*, 224, 120-131

Gosselin, C., Duballet, R., Roux, P., & Gaudillière, N. (2016). Large-scale 3D printing of ultra-high performance concrete—A new processing route for the building industry. *Automation in Construction*, 72, 62-70. https://doi.org/10.1016/j.autcon.2016.09.013

ISO 14040. (2006). *Environmental management—Life cycle assessment—Principles and framework.* International Organization for Standardization.

Kazemian, A., Yuan, X., Cochran, E., & Khoshnevis, B. (2017). Cementitious materials for construction-scale 3D printing: Laboratory testing of fresh printing mixture. *Construction and Building Materials*, 145, 639-647. https://doi.org/10.1016/j.conbuildmat.2017.04.015

Khaiyum, M.Z., Sarker, S., & Kabir, G. (2023). Evaluation of Carbon Emission Factors in the Cement Industry: An Emerging Economy Context. *Sustainability*, 15, 15407. https://doi.org/10.3390/su152115407

Khoshnevis, B. (2004). Automated construction by contour crafting—Related robotics and information technologies. *Automation in Construction*, 13(1), 5-19. https://doi.org/10.1016/j.autcon.2003.08.012

Khoshnevis, B., Kazerani, M., & Hwang, J. (2006). Automated construction by contour crafting—related robotics and computer technologies. Automation in Construction, 15(1), 13-23. https://doi.org/10.1016/j.autcon.2005.04.005

Kreiger, M. A., & Morrow, W. R. (2014). Environmental impacts of additive manufacturing technologies: A comparative study using Life Cycle Assessment. *Journal of Cleaner Production*, 66, 203-213. https://doi.org/10.1016/j.jclepro.2013.10.043

Lim, S., Buswell, R. A., Le, T. T., Austin, S. A., Gibb, A. G. F., & Thorpe, T. (2012). Developments in construction-scale additive manufacturing processes. *Automation in Construction*, 21, 262-268. https://doi.org/10.1016/j.autcon.2011.06.010

Liu, K., Takasu, K., Jiang, J., Zu, K., & Gao, W. (2023). Mechanical properties of 3D printed concrete components: A review. *Developments in the Built Environment*, 16, 100292. https://doi.org/10.1016/j.dibe.2023.100292

Mechtcherine, V., Shyshko, S., Haist, M., & Knaack, A. M. (2020). 3D printing of concrete and its implications for durability. *Materials*, 13(22), 5036. https://doi.org/10.3390/ma13225036

Menna, C., Mata-Falcon, J., Bos, F.P., Vantyghem, G., Ferrara, L., Asprone, D., Salet, T., & Kaufmann, W. (2020). Opportunities and challenges for structural engineering of digitally fabricated concrete. *Cement Concr. Res*., 133, 106079 https://doi.org/ 10.1016/j.cemconres.2020.106079.

Moult, J. (2015). *Sustainable building materials and methods*. Springer.

Pasco, J., Lei, Z., & Aranas, C., Jr. (2022). Additive Manufacturing in Off-Site Construction: Review and Future Directions. *Buildings*, 12, 53. https://doi.org/10.3390/buildings12010053

Paul, S. C., van Zijl, G. P. A. G., & Tan, M. J. (2018). A review on 3D concrete printing technology. *Construction and Building Materials*, 161, 62-70. https://doi.org/10.1016/j.conbuildmat.2017.11.174

Peng, T., Kellens, K., Tang, R., Chen, C., & Chen, G. (2018). Sustainability of additive manufacturing: An overview on its energy demand and environmental impact. Additive Manufacturing, 21, 694-704. https://doi.org/10.1016/j.addma.2018.04.022

Salet, T.A., Ahmed, Z.Y., Bos, F.P., & Laagland, H.L. (2018). Design of a 3D printed concrete bridge by testing. Virtual Phys. Prototyp. 13 (3), 222–236. https://doi.org/10.1080/ 17452759.2018.1476064.

Sepasgozar, S.M., Shi, A., Yang, L., Shirowzhan, S., & Edwards, D.J. (2020). Additive manufacturing applications for industry 4.0: a systematic critical review. Buildings 10 (12), 231. https://doi.org/10.3390/buildings10120231.

Wu, P., Wang, X., & Wang, J. (2016). A critical review of the use of 3D printing in the construction industry. *Automation in Construction*, 68, 21-31. https://doi.org/10.1016/j.autcon.2016.04.005

Wu, P., Wang, X., & Wang, J. (2016). A critical review of the use of 3D printing in the construction industry. *Automation in Construction*, 68, 21-31. https://doi.org/10.1016/j.autcon.2016.04.005

Zhang, J., Lv, L., Jin, W., & Li, Z. (2018). Mechanical properties and microstructure of 3D printed concrete structures. *Construction and Building Materials*, 162, 60-69. https://doi.org/10.1016/j.conbuildmat.2017.12.009