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3D Concrete Printing in Kuwait: Stakeholder Insights for Sustainable Waste Management Solutions

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Abstract: Robotic construction using three-dimensional (3D) concrete printing (3DCP) offers significant potential to transform Kuwait's construction industry, particularly in reducing waste. This study explores the feasibility of integrating 3DCP into Kuwait's construction waste management practices by examining the perspectives of key stakeholders. Through a mixed method approach of a comprehensive literature review, a survey of 87 industry professionals, and 33 in-depth interviews with representatives from the Public Authority for Housing Welfare (PAHW), Municipality, private sector, and the general public, the study identifies both the benefits and challenges of 3DCP adoption. The findings highlight key advantages of 3DCP, including increased construction efficiency, cost savings, enhanced design flexibility, and reduced material waste. However, several barriers, such as regulatory limitations, technical challenges in adapting 3DCP to local project scales, and cultural resistance, must be addressed. Results also indicate varying levels of stakeholder familiarity with 3DCP and existing waste management practices, underscoring the need for awareness and educational initiatives. This study makes two significant contributions: first, by providing a detailed analysis of the technical and regulatory challenges specific to Kuwait's construction sector, and second, by offering a strategic roadmap for 3DCP integration, including regulatory reform, research into sustainable materials, and cross-sector collaboration. These recommendations aim to enhance waste management practices by promoting more sustainable and efficient construction methods by achieving SDGs 9, 11, 12, and 13. The study concludes that government support and policy development will be essential in driving the adoption of 3DCP and achieving long-term environmental benefits in Kuwait's construction industry.

Keywords: 3D concrete printing; construction waste management; Kuwait; stakeholder perspectives; regulations

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1. Introduction

The rapid advancement of construction technologies has ushered in a new era in civil engineering, emphasizing sustainability and waste reduction. Among these emerging technologies, three-dimensional (3D) concrete printing (3DCP) is a promising solution that could revolutionize traditional construction methods. 3DCP begins with the process of creating a 3D model of a component, followed by the layer-by-layer deposition of material to complete the structure. To prevent cold joints, the material must not harden immediately.

Therefore, thixotropic materials, which can be smoothly extruded while supporting the weight of subsequent layers, are most suitable for 3D printing applications [1,2].

One of the key advantages of 3DCP technology lies in its ability to fabricate concretes and mortars without the need for a mold, which removes the mold production step from the manufacturing process for offsite manufacturing applications. This has several benefits; firstly, it removes a human craft-based production process, which can increase the reliability of time to procurement; it eliminates a waste stream from the production process in the reduction of mold materials used, and it also enables greater freedom of design in terms of the geometry of the components that can be achieved. This innovative approach offers significant benefits, including enhanced building efficiency, low labor costs, and reduced construction waste compared to traditional methods [3]. Potential applications include affordable housing, military bunkers, and complex architectural designs [4]. Adopting 3DCP in the construction sector presents advantages such as reduced material usage, improved design flexibility, and more efficient construction waste management [5].

However, it is essential to address the challenges that may hinder the practical implementation of 3DCP. Recognizing these limitations provides a more objective view of the technology and prepares stakeholders for its complexities. One significant concern is the lack of consensus on reinforcement in 3DCP structures. The absence of guidelines regarding prestressed reinforcement limits the ability to print bendable span structures, which require enhanced tensile strength and flexibility.

Additionally, the maximum achievable strength of 3D-printed concrete often falls short of that of conventional concrete. This discrepancy raises concerns about the safety and reliability of 3DCP in load-bearing applications. Efficiency is another critical issue. While 3DCP offers unique design capabilities, it may be less efficient and cost-effective than traditional methods for standard structures, particularly when customization is unnecessary. Achieving a smooth surface finish also poses challenges, as the texture of printed layers can impact the aesthetic quality, leading to increased finishing costs and extended timelines. Furthermore, curing printed structures in dry and hot climates is difficult, raising the risk of cracking and inadequate strength development. Lastly, the lack of regulatory frameworks and standardization for 3DCP can impede its adoption. Without established safety and quality guidelines, potential users may be hesitant to integrate this technology into their projects.

Concrete mixtures suitable for 3DCP require 1.5–2 times more cement than traditional casting methods, which may lead to increased CO_2 emissions [6–8]. Cement is recognized as the most energy-intensive component of concrete. Consequently, various studies have explored the use of supplementary cementitious materials (SCMs) as alternatives to ordinary Portland cement (OPC) in 3DCP [9–11]. Geopolymers, for example, are sustainable alternatives produced by activating siliceous binders with alkaline activators. They can be used in concrete production to replace traditional cement, offering significant environmental benefits [12]. Geopolymer concrete enables the incorporation of industrial by-products like fly ash, slag, and metakaolin as raw materials, diverting waste from landfills and reducing its environmental impact [12]. 3DCP is gaining significant interest due to the environmental benefits of replacing ordinary Portland cement [1]. In Kuwait, adopting 3DCP presents a promising approach to revolutionizing construction waste management by incorporating waste materials such as waste glass powder (WGP), SCMs, and plastic waste as eco-friendly substitutes for traditional binders [12–14].

Kuwait, characterized by rapid growth and a thriving construction industry, faces unique waste management challenges. To address these issues, strategic waste management practices are crucial for sustainable resource management and environmental conservation.

Given Kuwait's specific socio-economic and environmental context, a focused examination of innovative technologies like 3DCP is imperative to effectively tackle these challenges [13].

While extensive global studies have explored the advantages of 3DCP in waste reduction [9,15,16], K. B. and Vaitkevičius (2023) noted that 3DCP has the potential to reduce construction waste by 30–60% due to its ability to deposit materials precisely where needed, minimizing excess and off-cuts common in traditional construction methods [17]. This selective deposition optimizes material use and lowers labor costs by 50% to 80% and construction time by about 50%. These efficiencies contribute to a more sustainable construction process, significantly reducing the environmental footprint.

Despite the advantages of 3DCP in reducing construction waste, there is a scarcity of research specifically addressing its applicability and challenges within the Kuwaiti construction industry. Limited exploration into how 3D printing aligns with local waste management practices underscores the need for focused qualitative analysis. This study aims to bridge these gaps by addressing the following research questions:

1. What is the current level of awareness and understanding among Kuwaiti construction stakeholders regarding 3DCP technology?
2. What are the perceived benefits and challenges of implementing 3DCP in Kuwait's construction sector?
3. How can 3DCP be effectively integrated into Kuwait's existing construction waste management practices?

By delving into stakeholder experiences and perceptions, this study seeks to provide practical recommendations for the local implementation of 3DCP in Kuwait. The research also aims to contribute insights that can inform future academic discourse and research endeavors in Kuwait's construction sector.

The overarching aim of this study is to explore the potential of 3DCP technology to transform construction waste management in Kuwait, representing a pioneering effort to address waste challenges in the region through innovative construction methods. This research lays the groundwork for a more sustainable and efficient approach to construction in Kuwait and beyond.

The implementation of 3DCP in Kuwait not only addresses local construction challenges but also aligns with global sustainability goals. By contributing to SDGs 9, 11, 12, and 13, 3DCP represents a transformative approach to construction that fosters innovation, promotes sustainable urban development, encourages responsible resource use, and supports climate action initiatives. This holistic construction approach will help Kuwait meet its sustainability objectives of the Conference of the Parties (COP) while addressing pressing environmental challenges.

2. Methodology

This research employs a qualitative mixed-methods approach, integrating an extensive literature review with surveys conducted through questionnaires and interviews, as illustrated in Figure 1. The following sections provide a comprehensive overview of the research methodology.

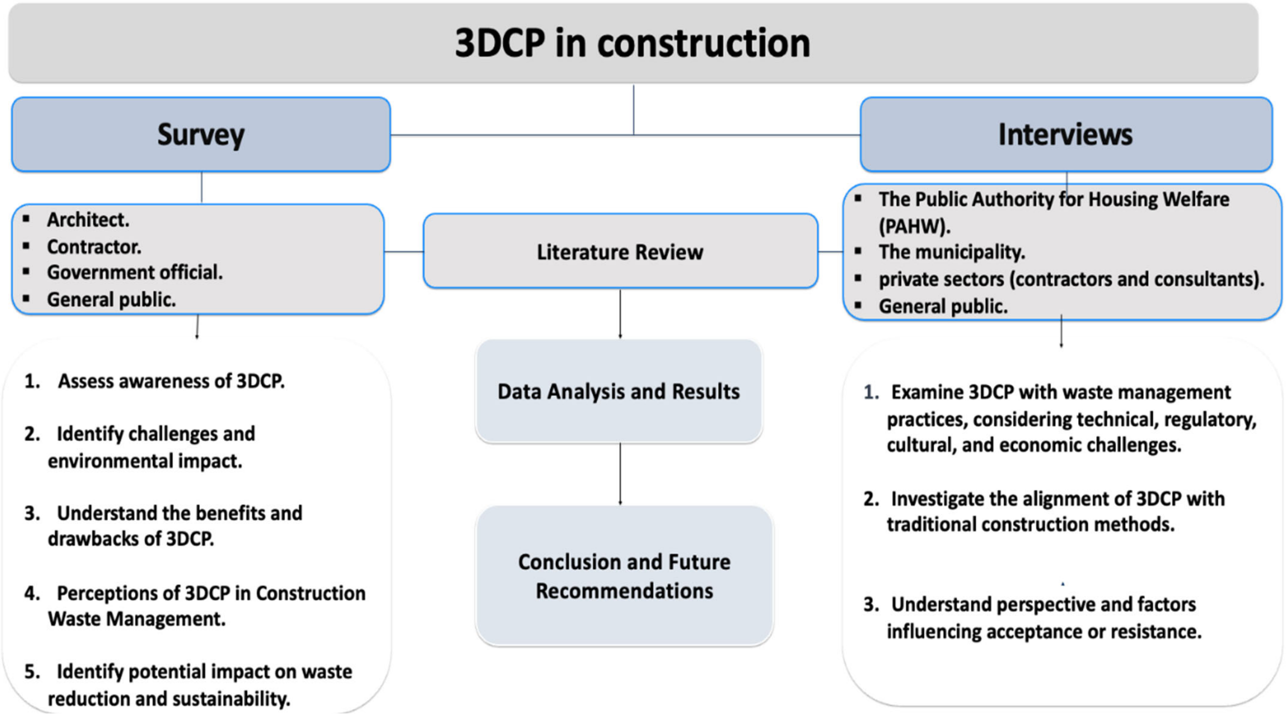

Figure 1. Research Methodology.

2.1. Data Collection

An 87 purposive sampling was employed to efficiently gather diverse perspectives within 3DCP in reducing CDW in Kuwait. The process begins with clearly defining research aims and objectives and establishing a roadmap for subsequent steps. Survey preparation involves designing questions aligned with the research objectives, ensuring clarity and effectiveness, and refining questions based on feedback. The surveys were distributed to a representative sample of stakeholders in the Kuwaiti construction industry, following ethical clearance from Brunel University's ethics committee. Subsequently, survey data were systematically collected and analyzed to address research questions focusing on Identifying challenges, assessing awareness of 3DCP, and understanding the perceived benefits and drawbacks of 3DCP, as shown in Figure 1.

Identification of participants for interviews followed, emphasizing diversity in perspectives and experiences. Interview preparation involved developing semi-structured questions and revisions based on feedback. Conducting semi-structured interviews allowed for exploring technical, regulatory, cultural, and economic challenges, as presented in Figure 2, investigating the alignment of 3DCP with established construction methods, identifying potential conflicts, and understanding perspectives and factors influencing acceptance or resistance. The qualitative data obtained were analyzed narratively, and the integration of survey and interview findings provided a comprehensive understanding, identifying overarching themes and insights.

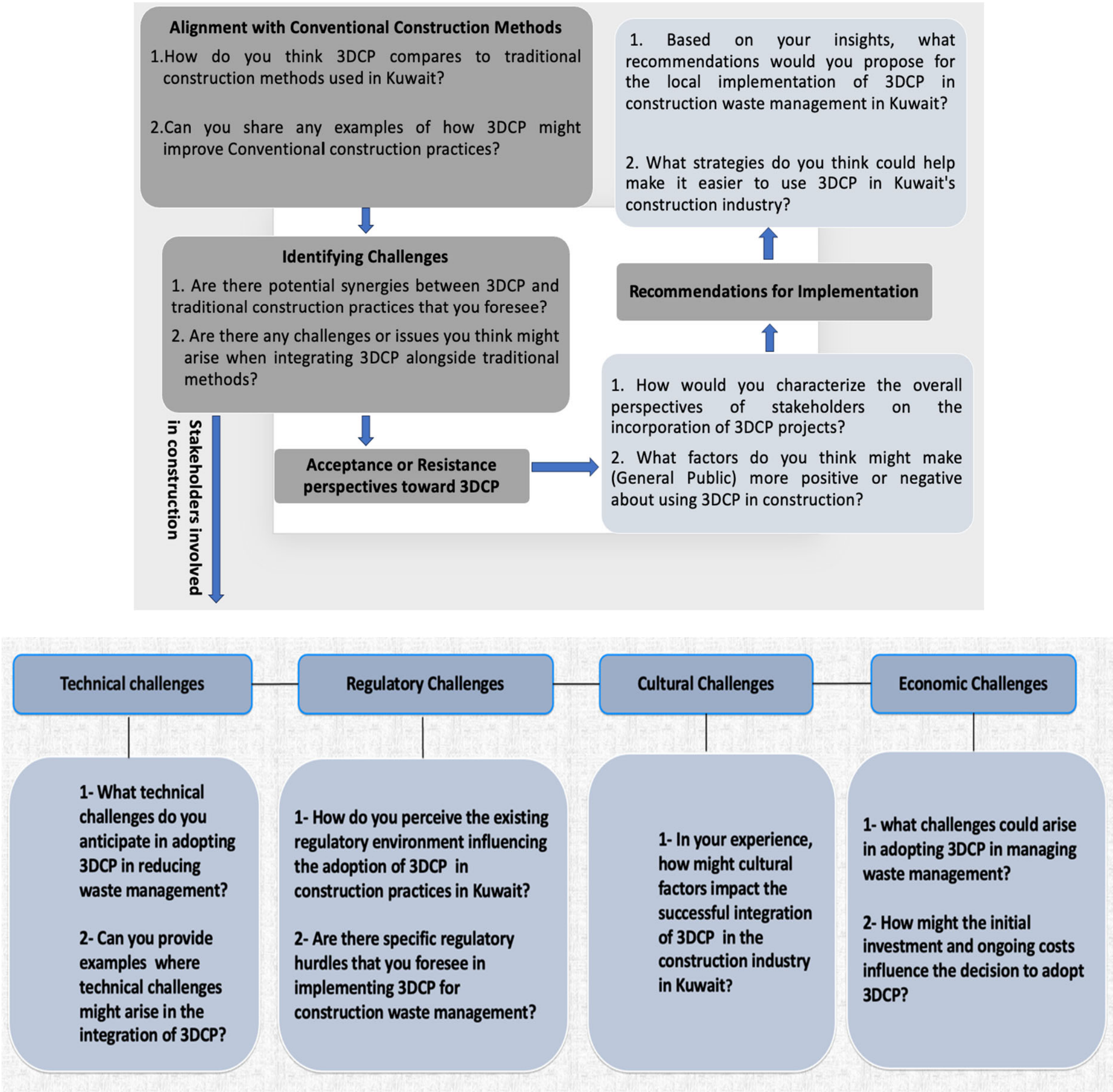

Figure 2. Stakeholder interview questions.

2.2. Questionnaire and Interviews

The questionnaire comprised five distinct sections, each serving a specific purpose. Section 1 gauged respondents' awareness and knowledge regarding 3DCP in construction, while Section 2 explored perceptions of 3DCP in construction waste management. Section 3 focused on challenges and concerns, Section 4 explored alignment with traditional construction practices, and Section 5 investigated anticipated advancements in the Kuwaiti construction industry. Details of the 87 participants and their organizations are listed in Table 1.

The interview process was structured into seven sections covering various aspects, including technical, regulatory, cultural, and economic challenges. Additional sections explored the alignment of 3DCP with established construction methods, Perspectives toward 3DCP, and recommendations for local implementation. These structured interviews allowed for a comprehensive exploration of diverse facets within the context of 3DCP in construction waste management in Kuwait. Table 2 presents the background of the participants; purposive sampling was used to recruit participants, 33 participants, including 3 engineers from PAHW, 4 municipality engineers, 2 from recycling companies, 4 consultants, and 20 general public. Figure 2 illustrates the interviewee's questions.

Table 1. Organizations, titles, and years of work experience of the respondents.

Type of Organization	Position of Participants	Years of Experience	Number of Respondents	Percentage of Total Participants
Architect	The Public Authority for Housing Welfare (PAHW) director	25+	35	40%
General contractor	Private company technical director	20–30	17	20%
Government officials	Elected Representative, Judicial Officials Appointed Officials	23+	26	30%
General public	Eligible citizens and families	15–25	9	10%

Table 2. Interviewee's positions and experiences.

Professional	Years of Experience	Position
Deputy Director General for planning and design Engineer.	+30	Public Authority for Housing Welfare (PAHW)
Director Engineer	+25	Municipality
Executive Vice President contractor	+35	Owners of concrete recycling companies
Chef executive officer integrated solutions	+20	Consultant
General Public		Eligible citizens and families

3. Results and Discussion

3.1. Evaluating Awareness of 3DPC in the Kuwaiti Construction Industry

This study aimed to gauge participants' experience and expertise within the Kuwaiti construction industry. Responses were categorized based on years of experience, ranging from less than 5 years to over 15 years. This categorization provided a nuanced understanding of participants' backgrounds and set the stage for exploring their perspectives on construction waste management practices and familiarity with 3DCP.

The survey revealed diverse insights into respondents' awareness of 3DCP and construction waste management practices in Kuwait. Regarding 3DCP, only 20% of respondents reported a high level of familiarity, suggesting limited awareness of 3D printing techniques and applications. This highlights a crucial gap in knowledge that could impede the broader adoption of 3DCP without targeted awareness-raising initiatives. If industry leaders prioritize education on the benefits and applications of 3DCP, it could catalyze a significant policy shift toward integrating 3D printing technology in construction projects.

Furthermore, 50% of respondents reported moderate familiarity with 3DCP, having heard about it through news sources or demonstration videos, suggesting a reasonable understanding with room for further exploration. This moderate awareness presents an opportunity for further exploration through more formalized channels like workshops, training programs, or demonstration projects. By building on this base of familiarity, stakeholders can foster a cultural shift within the construction industry, gradually increasing acceptance and support for 3DCP. These efforts can be aligned with national sustainability goals, further influencing policy changes.

Conversely, 30% admitted to being unfamiliar with 3DCP, underscoring the importance of targeted educational initiatives. This segment, consisting of key industry stakeholders, represents a vital demographic for driving change, as their buy-in will be critical for the widespread implementation of 3DCP. Addressing this knowledge gap can lead to greater industry cohesion in supporting modern construction techniques that align with both environmental objectives and economic efficiency.

Turning to construction waste management, 35% of respondents, primarily engineers and contractors, considered themselves very knowledgeable, demonstrating a strong understanding of current practices specific to Kuwait's construction industry. However, this expertise remains largely centered around traditional methods, indicating the need to extend their knowledge to include sustainable practices, particularly through the use of 3DCP. Increased awareness and understanding of 3DCP's role in reducing construction waste could prompt a shift in both policy and on-site management practices, encouraging greater sustainability across the industry.

Additionally, 45% rated themselves as moderately knowledgeable in construction waste management, signaling an opportunity for deeper engagement through structured educational programs. These programs could focus on integrating 3DCP technology with waste management strategies, positioning stakeholders to make informed decisions about sustainable materials and processes. This, in turn, could lead to the formulation of regulations promoting 3DCP as a key method for reducing waste.

Finally, 20% of respondents admitted to lacking knowledge in waste management practices, suggesting that there is a significant segment of the industry that requires education on sustainable construction practices. This finding points to the potential for cultural shifts within the sector, driven by policies that mandate training and certification in sustainable practices, including 3DCP.

These findings suggest that while there is some awareness of 3DCP and waste management practices in the Kuwaiti construction industry, there is a significant need for increased education and training to fully utilize these advancements. By addressing these knowledge gaps through targeted campaigns, workshops, and policy initiatives, Kuwait can create an environment that supports the adoption of 3DCP, thereby promoting sustainable practices in the construction sector. These initiatives are critical for fostering a cultural and regulatory shift toward innovative technologies that align with Kuwait's sustainability and waste reduction goals, as detailed in Table 3.

Table 3. Participants' responses regarding both 3DCP and construction waste management in Kuwait.

Questions	Percentage Selecting Each Option		
How many years of experience do you have in the Kuwaiti construction industry?	Less than 5 years (20%)	5–10 years (35%)	More than 15 years (45%)
How would you rate your knowledge of construction waste management practices in Kuwait?	Very knowledgeable (35%)	Moderately knowledgeable (45%)	Not knowledgeable (20%)
Are you familiar with 3DCP in the context of construction?	Very familiar (20%)	Somewhat familiar (50%)	Not familiar (30%)

3.2. Benefits of Integrating 3DCP with Local Practices and Stakeholder Perceptions

Additive manufacturing (AM) is a possibly effective, sustainable manufacturing process. This is especially evident as 3D printing minimizes the need for form works for casting concrete, which reduces waste. It also contributes to cost savings and resource optimization by minimizing material waste and optimizing labor, thus promoting sustainable and cost-effective construction practices [18]. Moreover, 3DCP enables architectural freedom, allowing for intricate and culturally relevant designs that align with local aesthetics and preferences [19]. The technology further supports environmental sustainability by reducing the carbon footprint and promoting green building initiatives [20]. Additionally, its integration fosters local employment opportunities and skill development, creating a workforce capable of leveraging emerging technologies. Furthermore, 3DCP in construction enhances disaster response and reconstruction efforts, ensuring swift and resilient structures [21]. Over the past two decades, the environmental impact of human activities has gained prominence in global discussions, leading to significant international agreements targeting climate change, energy consumption, CO_2 emissions, and sustainability. The Conference of the Parties (COP), the supreme decision-making body of the UN Framework Convention on Climate Change (UNFCCC), plays a vital role in these initiatives.

The study reveals diverse stakeholder perceptions regarding the integration of 3DCP into construction waste management in Kuwait. Survey results indicate that 35% of government officials express high confidence in 3DCP's potential to significantly reduce waste. This group likely believes that 3DCP offers innovative solutions that align with Kuwait's construction industry needs and SDGs. For instance, the 3D construction of the "Office of the Future" in Dubai used 50% less manpower compared to traditional buildings and produced 60% less waste. The printing process took 17 days, with two additional days for in situ installation and three months to complete the building [13]. Although the adoption of additive manufacturing in construction may present initial disruptions, its long-term benefits as an eco-innovative solution are increasingly evident [22]. Contractors interviewed anticipate that "3DCP will deliver various improvements, such as reduced surplus material, decreased waiting times, minimized unnecessary travel, and enhanced execution quality. Additionally, 3DCP is expected to mitigate issues related to storage, material transport, overproduction, and excessive material use, while also addressing the mismanagement of skills and promoting creativity and team cohesion". These anticipated benefits align with findings from Anjum et al., who demonstrated that 3D printing in India's construction industry led to substantial reductions in time by 81.4%, material waste by 79.3%, construction costs by 68.1%, and labor dependency by 77.5%, while also improving construction safety and efficiency by 75.6% [23].

However, about 50% of participants consider 3DCP moderately suitable for addressing construction waste management issues. This group acknowledges the benefits of 3DCP but may also recognize certain limitations or challenges that need to be addressed before widespread adoption can occur. They likely believe that while 3DCP shows promise, further research, development, and implementation are necessary to optimize its effectiveness in managing construction waste in Kuwait, consistent with existing research, which suggests that further procedural development and technology integration are essential to achieving successful adoption in the market [3]. A smaller group, comprising 15% of general public stakeholders, expressed skepticism, raising concerns about the feasibility and practicality of implementing 3DCP in Kuwait's unique construction environment.

Responses to the question "What potential benefits do you foresee in using 3DCP for construction waste management in Kuwait?" were analyzed and summarized to provide insights into participants' perspectives on the topic. Table 4 showcases the diverse range of anticipated benefits identified by the respondents, highlighting key themes and recurring ideas.

Table 4. Summary of participants' opinions on the potential benefits of using 3DCP for construction waste management in Kuwait (open-ended).

Participant	Comments
P1	(Resource Efficiency) Noted the ability of 3DCP to utilize construction waste materials effectively, reducing the consumption of virgin resources. Although the initial cost of geopolymer concrete may be higher, its long-term benefits, such as reduced maintenance and extended service life, can offset these costs
P2	(Rapid Construction Capability) Highlighted the potential of 3DCP to accelerate project timelines and on-demand construction and reduce labor costs, reduced transportation and packaging waste
P3	(Waste Reduction and Environmental Sustainability) Expressed optimism about 3DCP's ability to divert waste from landfills. Lower energy consumption in the production of geopolymer concrete compared to traditional concrete further contributes to its environmental benefits. This aligns with Kuwait's vision and sustainable development goals (SDGs 9, 11, 12, 13)
P4	(Importance of Innovation and Technological Advancement) Viewed the adoption of 3DCP for construction waste management as a sign of progress within the construction industry and potential job creation, positioning Kuwait as a leader in sustainable building practices

3.3. Challenges in Adapting 3DCP for Construction Waste Management

While 3DCP offers numerous benefits, adapting it for effective construction waste management presents several challenges: technical, regulatory, cultural, and economic challenges that must be addressed to fully realize its potential in this area.

3.3.1. Regulatory Challenges

Adopting 3DCP for construction waste management in Kuwait faces several challenges, with regulatory hurdles being a significant concern, accounting for 40% of the difficulties, as shown in Figure 3. The absence of regulatory frameworks specifically tailored for 3DCP in construction presents a major obstacle. Established standards and regulations are crucial for setting operational and management benchmarks, ensuring quality and safety, and minimizing risks associated with skill and product instability.

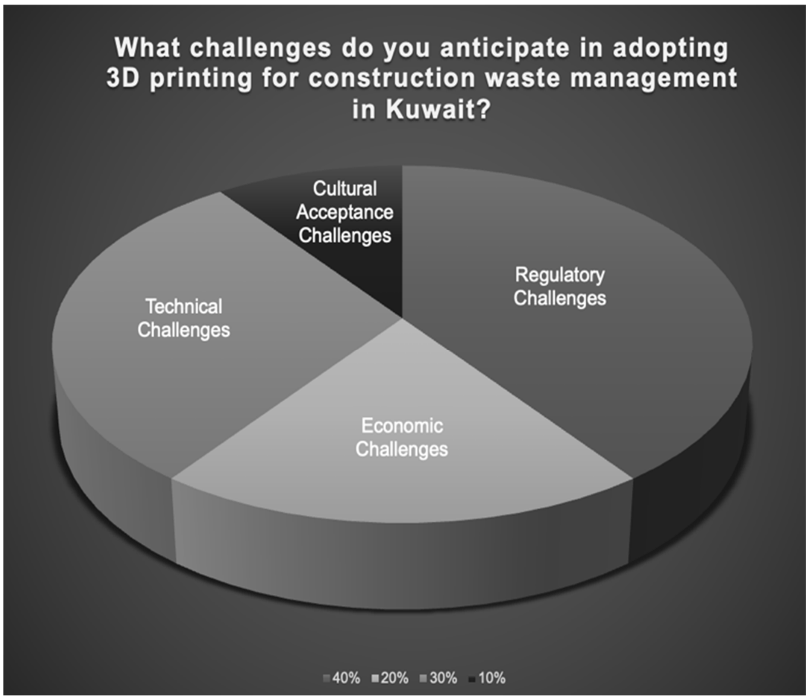

Figure 3. Holistic perspective of the adaption of 3D printing challenges in Kuwait.

The complex regulatory landscape complicates the integration of existing construction codes with the innovative aspects introduced by 3DCP [24,25]. Currently, structures built using this technology are classified as experimental, highlighting the urgent need for further characterization of printing materials, clarification of construction practices, and the incorporation of these practices into existing building codes [24]. The construction industry in Kuwait is governed by various regulations that may not yet accommodate 3DCP, making it challenging for companies to navigate the approval process for new construction methods. This can lead to time-consuming and costly delays, discouraging investment in 3DCP technology without supportive legislation and clear guidelines.

The consultant emphasizes that "The Kuwaiti government can look to advanced technology programs in developed countries as a model for building Generic Technology Research and Development (R&D) systems. R&D involves activities companies and organizations undertake to innovate and introduce new products or services". R&D aims to generate new knowledge, technologies, or processes that can lead to the creation of new products, enhancements to existing products, or new methods of conducting business. R&D is essential for the growth and sustainability of companies, especially in industries like technology, pharmaceuticals, and manufacturing, where innovation is key to staying competitive [26].

Despite these challenges, some stakeholders view the establishment of regulatory policies as an opportunity to create a niche market. Three-dimensional printing buildings have great market potential because of their design flexibility. Furthermore, Kuwait's green building evaluation standards should add extra points for 3D-printed buildings to enhance the technology's market appeal.

By building confidence in recycled 3DCP products, there is potential to enhance the industry's sustainability and innovation.

3.3.2. Technical Challenges

Adopting 3DCP faces significant technical challenges, which account for approximately 30% of the obstacles in its implementation. These challenges underscore the need for specialized equipment and expertise throughout the 3DCP process, with material selection being a primary concern. The concrete used must be sufficiently workable to pass through the robot's nozzle, often necessitating specific types of concrete that may be of lower quality and higher cost.

A promising alternative to traditional Portland cement is geopolymer cement, which can be formulated to cure rapidly, with some mixes achieving most of their ultimate strength within 24 h [25,27]. Geopolymer cement forms strong chemical bonds with silicate rock-based aggregates, enhancing its overall performance. This rapid curing and bonding capability makes geopolymers attractive for various construction applications [28].

Geopolymers offer superior properties compared to traditional Portland cement, including better chemical resistance, high-temperature resistance, low shrinkage, and lower carbon emissions [29].

Despite these advancements, the limited availability of suitable materials remains a significant disadvantage. Current technology indicates that 3D-printed buildings may not fully meet end users' expectations due to constraints in design and materials. For instance, a contractor reported that a house in Al Mutlaa City was built and printed in just three days with no construction waste; however, traditional methods were used for the columns due to technical challenges, particularly concerning reinforcement. Unreinforced concrete lacks the necessary ductility and strength, limiting its application, as shown in Figure 4. To address these limitations, various types of reinforcement can be incorporated to enhance the ductility, tensile strength, load-bearing capacity, and crack resistance of concrete. Research has indicated that fiber reinforcement can be added to 3DCP mixtures to minimize drying shrinkage, highlighting the need for further advancements in 3DCP technology.

Overcoming technical challenges related to adapting 3DCP for construction waste management, printability of materials, scalability, structural integrity, and the lack of standardized codes and regulations is crucial [30]. For example, replacing natural aggregate with brick aggregate can enhance the buildability of the mixtures, allowing for more layers to be printed without failure [29,31]. These hurdles emphasize the importance of addressing both technical and regulatory barriers to fully harness the potential of 3D printing in construction waste management. The integration of geopolymer technology in 3DCP represents a significant step towards more sustainable building practices. However, continued research and innovation are essential to address existing challenges and enhance the technology's viability in the construction industry.

Figure 4. The first on-site 3D-printed house in Kuwait by Abyan Building Construction Company.

3.3.3. Economic Challenges

Economic challenges account for an additional 20% of the obstacles faced in adopting 3DCP technology in Kuwait's construction industry. These challenges include concerns regarding the initial investment for technology acquisition and ongoing costs such as maintenance. Currently, the high initial equipment costs make 3DCP a more expensive option than traditional construction methods. Additionally, transportation costs for the 3D printers pose logistical and financial difficulties [11].

The construction sector in Kuwait is traditionally conservative and resistant to change, which complicates the introduction of innovative technologies like 3DCP. Convincing stakeholders, clients, and investors of the advantages of 3DCP over conventional methods is essential. There is skepticism regarding the durability and reliability of 3D-printed structures, which can impede market acceptance and slow the adoption of this technology.

A contractor has pointed out that "a lack of maturity in skills and products is a significant barrier to promoting 3D printing". He advocates for thorough research and investigation before implementing incentives to avoid resource wastage. Nevertheless, 3DCP has demonstrated potential for cost savings in specific projects. For instance, the building engineering company Abyan has successfully constructed the first on-site 3D-printed water tanks in Kuwait using a "COBOD" 3D construction printer. This method achieved a 25% reduction in the use of concrete and reinforcement materials compared to traditional casted tanks. These tanks, which stand 4.5 m tall and have a diameter of 7 m, were printed using low-cost concrete in just five days and incorporated macro fibers for reinforcement, as shown in Figure 5 [32].

Figure 5. The first on-site 3D printed water tanks in Kuwait by Abyan Building Construction Company.

One of the advantages of 3D printing is the flexibility it offers in modifying wall thicknesses, which is often limited in traditional construction. With 3DCP, engineers can create thicker bottom walls and thinner upper walls, enhancing material efficiency and sustainability. Recent developments have also achieved lightweight printable mixtures for 3D printing wall elements with optimal load-bearing properties [33].

The success of 3DCP relies on a supportive and comprehensive research and development environment that fosters technological collaboration among various research entities. This collaborative effort is crucial for overcoming the existing barriers and enhancing the effectiveness of 3DCP in the construction industry.

3.3.4. Cultural Challenges

The cultural acceptance aspect constitutes around 10% of the total challenges. There is cultural resistance to adopting new technologies, particularly in Kuwait, where traditional construction methods are deeply rooted. Overcoming this resistance requires demonstrating the reliability and benefits of 3DCP to stakeholders, including architects, builders, and the general public. The social drawbacks are evident in the adverse impact on the existing construction workforce. The adoption of 3DCP is expected to reduce the demand for a significant number of construction workers. While this is considered advantageous for cost savings, it concurrently poses a disadvantage for those workers whose employment is at risk.

Integrating 3DCP technology with traditional construction methods and architectural styles is crucial to maintaining cultural authenticity. This can be achieved by incorporating historical design elements, using locally sourced materials, and involving the local community in the design and construction process. The contractor said, “The government should support entrepreneurship to foster advancements in 3D printing technology and diversify the products available in the 3D printing construction sector”. Moreover, key factors influencing 3D printing adoption, such as building codes, top management commitment, and liability considerations, must be carefully addressed to facilitate widespread adoption [34].

To address these challenges, a holistic approach is required that balances regulatory, economic, technical, and cultural factors. Collaboration between stakeholders, including architects, engineers, construction workers, and local communities, is essential for the successful implementation of 3DCP while preserving cultural identity and ensuring a smooth transition for the existing workforce.

3.4. Perspectives on 3D Concrete Printing

Understanding the perspectives of stakeholders, including contractors and consultants, on the integration of 3DCP in Kuwait's construction projects is essential. Survey results indicate that 35% of respondents are "very receptive" to adopting this technology, while an additional 45% reported being "somewhat receptive", reflecting a generally positive inclination toward 3DCP. However, while these numbers show enthusiasm, a more critical assessment is needed to explore how realistic the large-scale implementation of 3DCP is within Kuwait's specific context. One area where 3D printing aligns with traditional construction methods is in constructing basic building structures. Conventional methods typically involve using concrete blocks or reinforced concrete to construct walls and floors. Integrating robots in 3D printing, along with real-time material sorting, contributes to reduced labor costs and material wastage [35]. CAD models hold promise for additive manufacturing in building construction, allowing materials to be systematically layered using tools and fixtures.

However, the digitization of the construction sector is progressing slowly under the banner of "Construction 4.0". Large-scale 3D printers capable of printing structural elements can streamline the construction process by directly printing walls and floors layer by layer [24]. This capability reduces the need for manual labor and accelerates construction timelines. Additionally, 3DCP's ability to produce customized and complex designs more efficiently is an appealing factor for Kuwait's urban planning and infrastructure development.

The Deputy Director General of the PAHW emphasized the importance of spreading knowledge about 3DCP. He stated, "Resistance to its application will decrease as people's understanding of the technology increases, significantly aiding its development. Promoting market initiatives and encouraging entrepreneurship are essential". He suggested that 3DCP could initially explore niche markets, such as villas and distinctive landscapes, as entry points to establish its presence. These small-scale projects, which have lower strength and size requirements, align well with the current technological capabilities of 3DCP. This would resonate particularly well in an economic environment that is increasingly conscious of both cost efficiencies and environmental impacts.

3.4.1. Challenges in the Kuwaiti Environment

Despite these advantages, there are challenges where 3D printing diverges from established methods. Ref. [1] highlights environmental benefits, such as reduced material wastage and energy efficiency, as well as challenges, like regulatory barriers and material compatibility. Traditional construction in Kuwait often relies heavily on skilled labor for tasks such as masonry and carpentry. In contrast, 3D printing requires expertise in operating and maintaining the printing equipment, which may necessitate retraining or hiring specialized personnel. Additionally, ensuring the availability of suitable printing materials and maintaining structural integrity while complying with local building codes are unique challenges for 3D printing. The lack of legislation and certification further limits its use.

3.4.2. Economic Considerations and Sustainability

The economic feasibility of 3DCP in Kuwait's construction sector is closely tied to material innovation and government policy. Material costs for 3DCP represent about 70% of total construction expenses, primarily due to the high amounts of cement and admixtures used. The current mixtures lack aggregate fractions larger than 2.0 mm, with the cost breakdown being approximately 80% for cement, 15% for admixtures, and 5% for water and aggregates [12]. To mitigate the high material costs, some stakeholders have proposed incorporating industrial waste and alternative materials, such as recycled concrete aggregates or geopolymer mixes, into 3DCP. This could help reduce both the environmental impact and economic burden of cement consumption. The potential of 3DCP to reduce construction waste and lower carbon emissions aligns well with Kuwait's sustainability goals, particularly in terms of transitioning towards a circular economy. However, achieving this level of material innovation requires further research, investment, and government support.

On the sustainability front, 3DCP has the potential to decrease material waste by up to 30–60%, with some proponents suggesting even greater reductions in carbon emissions. Still, the environmental impact of high cement consumption, a significant drawback of 3DCP, must be addressed. By utilizing local aggregates and recycling waste materials, such as glass or organic matter, Kuwait could reduce its reliance on cement and improve the overall sustainability of 3DCP processes [12].

3.4.3. Cultural and Industry Resistance

A minority of stakeholders, constituting 20%, expressed being "not receptive at all" to the integration of 3DCP in Kuwait's construction projects, indicating a level of resistance within the community, as shown in Table 5. Their concerns primarily revolve around potential adverse effects, including a lack of transparency in the industry, market instability, and widespread skepticism. Many clients, designers, and contractors remain skeptical about the potential of 3D printing in construction, with a significant barrier being the difficulty in understanding the technology [36].

Table 5. Participants' responses regarding the alignment of 3D printing with traditional construction in Kuwait and its reception.

Questions	Percentage Selecting Each Option		
To what extent do you think 3D printing aligns with traditional construction practices in Kuwait?	Complete alignment (25%)	Partial alignment (60%)	Does not align at all (15%)
How receptive do you believe local stakeholders (contractors, clients) would be to the integration of 3DCP in construction projects in Kuwait?	Very (35%)	Somewhat (45%)	Not at all (20%)

Additionally, the reliance on precise digital modeling in 3DCP, while an advantage in terms of efficiency and accuracy, diverges from traditional methods that allow for more on-site modifications. This flexibility is particularly valued in Kuwait's construction industry, where last-minute design changes are common. Therefore, the digital rigidity of 3DCP may be viewed as a limitation for more dynamic construction projects [37].

3.4.4. Future Prospects for 3DCP in Kuwait

The successful integration of 3DCP in construction requires a new set of skills for workers, including the setup, operation, monitoring, and maintenance of 3D printers. However, acquiring these essential skills is not readily accessible within conventional construction sites [31]. These insights into stakeholder attitudes provide valuable information for understanding the diverse perspectives that shape the reception of 3DCP within the Kuwaiti construction industry.

The questionnaire aimed to gather stakeholder opinions on the expected advancements in the Kuwaiti construction industry over the next five years, particularly focusing on the role of 3DCP. These insights provide a nuanced understanding of the diverse perspectives shaping the reception of 3DCP within the Kuwaiti construction industry, highlighting both the opportunities and challenges that lie ahead. Table 6 presents the summarized participants' perspectives below.

Table 6. Summary of participants' opinions on the advancements in the construction industry in Kuwait in the next 5 years and how 3D printing might contribute to these changes (open-ended).

Participant	Comments
P1	Increased Adoption of 3DCP: The integration of 3DCP is expected to lead to faster construction and more customized structures, facilitating innovative architectural designs while aligning with sustainability goals by reducing construction waste.
P2	Government Support and Technological Integration: Strong government backing and the integration of 3D printing with other technologies will further propel the transformation of the industry. This shift will necessitate skills development and foster international collaboration.
P3	Economic Growth: Recognizing 3DCP as a disruptive technology is crucial for driving economic growth and competitiveness in Kuwait's construction sector. It has the potential to enhance productivity, reduce costs, and position Kuwait as a leader in technological advancement and sustainable development. Environmental Benefits: 3DCP significantly reduces construction waste and carbon emissions through its layer-by-layer printing process, which minimizes material wastage. The technology allows for the creation of energy-efficient structures while optimizing space and material use.
P4	Sustainable Materials: To ensure sustainability and contribute to a circular economy, it is essential to explore the use of geopolymer, recycled concrete aggregates, or waste materials in the mix design for 3DCP. Moreover, Modular and Prefabricated Construction: There is an increasing emphasis on modular and prefabricated construction methods to speed up project delivery and reduce on-site labor requirements. 3DCP is seen as a game-changer in this context, enabling rapid and cost-effective production of prefabricated building elements.

3.5. Factors Influencing the Alignment of 3DCP with Construction Practices

This study examines the compatibility of 3DCP with traditional construction methods in Kuwait. The finding revealed that 60% of respondents believe that 3DCP only partially aligns with current industry practices. These respondents expressed that 3DCP, while innovative, cannot yet fully replace existing systems and should be considered a complementary technology. Government officials emphasized the importance of improving the compatibility of 3D printing with concrete materials to unlock its full potential in the construction sector.

Proponents of 3DCP argue that it could reduce pollution and construction waste by 30–60%, with some suggesting even higher potential reductions in carbon emissions and waste [38]. For instance, the Holstebro House in Denmark addresses 3DCP roof issues by using precast slabs, though more sustainable alternatives like solar roofs could further enhance environmental benefits [18]. Public opinion suggests that government support, including financial incentives, is crucial for promoting the adoption of 3DCP in small-scale housing projects. An engineer from PAHW highlighted the importance of government leadership, funding, and regulatory policies in fostering innovation and integrating 3DCP into local practices.

Conversely, 25% of respondents indicated complete alignment, asserting that 3DCP can reduce the environmental impact by 50% compared to cast concrete. The environmental impact of 3D printing is negligible compared to the material production process. 3DCP can decrease material usage by 40% and material waste by 30% [39]. Additionally, it can also lower fuel consumption, transportation impact, and associated emissions by reducing the need for heavy construction equipment. While high cement consumption, which generates significant CO_2 emissions, is a drawback of 3DCP, using local aggregates and recycling waste materials, such as glass and organic materials, can reduce cement content and improve the sustainability of 3DCP [18].

A consultant stated that "geopolymers provide a compelling alternative to traditional Portland cement, with significant environmental advantages. These benefits include reduced carbon emissions, enhanced waste utilization, improved energy efficiency, and greater durability. As the construction industry strives for sustainability, geopolymer concrete emerges as an attractive solution to mitigate the environmental impact of concrete production". The 3D printing of concrete–geopolymer hybrids offers a promising approach for environmentally friendly building construction [12,28]. The production of geopolymer concrete results in 70–90% lower carbon dioxide emissions compared to traditional Portland cement-based concrete [37]. This is achieved by utilizing industrial by-products or natural materials instead of energy-intensive Portland cement.

For example, AICT "builds world's first 3D printed park with recycled aggregates" (2021). AICT's 3D printing technology incorporates advanced digital systems and robots, performance-based cementitious mixtures, and parametric design to construct large-scale structures. The company uses six-axis robotic multi-arm technology along with a special construction material to create low-cost, aesthetically pleasing structures. AICT's 3D-printed concrete consists of nearly 50% sand that can be sourced locally, reducing transportation costs and potential carbon emissions. In addition to 3D-printed homes and small-span bridges, AICT's latest project was the construction of a public park covering an area of 5523 m^2 [40].

Additionally, there are records in the company that state different levels of success when printing buildings. For example, ten homes were 3D printed in just 24 h in 2014, according to WinSun, a Chinese construction company. Together with a concrete composition reinforced with unique fiberglass, a large-scale 3D printer measuring 150 m long, 10 m wide, and 6 m deep was utilized. The world's first 250 m^2 3D printed workplace was shown by WinSun in 2016 [22].

While 15% stated "no alignment at all" and expressed skepticism about the potential of 3DCP to fully replace traditional construction methods, as illustrated in Table 5, the discussion reveals both the advantages and limitations of each approach. Traditional construction methods offer flexibility for design changes during the construction process. In contrast, 3DCP relies on precise digital modeling created upfront, which can restrict on-site modifications. This reliance on accuracy can be seen as an advantage; however, it may also limit the adaptability that traditional methods provide.

According to the municipality's engineer, "3DCP presents both opportunities and challenges in aligning with traditional construction methods prevalent in Kuwait. While there are certain aspects where 3DCP aligns well with established practices, there are also areas where it diverges significantly, Skilled operators, careful handling, and proper cleaning are required for 3D printers". Currently, no standardized tests evaluate concrete's buildability and interlayer bonding [41].

Discussion around "project scale and printer size" have emerged as significant factors influencing stakeholders' receptiveness to 3D printing. The general public pointed out that "the acceptance of 3DCP might vary based on the scale of the construction project. Larger-scale projects garnered a higher degree of openness among stakeholders, as they recognized the potential efficiencies and advantages offered by 3DCP". In contrast, for smaller-scale projects, stakeholders expressed a more cautious approach, possibly due to concerns about scalability, initial investment, and adapting to the technology. The general public opinions on "the optimal size of 3D printers for construction projects varied, with some emphasizing the need for larger printers for sizable projects and others highlighting the practicality of smaller printers for more confined construction settings". These nuanced insights underscore the importance of tailoring 3DCP implementations to suit the specific needs and characteristics of diverse construction projects in Kuwait.

4. Strategies and Recommendations for Transforming Kuwait's Construction Industry with 3D Printing Technology

By involving these key stakeholders in the development of standards and regulations for 3D-printed construction, Kuwait can create a robust framework that promotes innovation while prioritizing safety, quality, and regulatory compliance.

4.1. Developing Standards and Regulations for 3D Printed Construction

Key government agencies, including the Kuwait Institute for Scientific Research (KISR), Environmental Protection Authority (EPA), Public Authority for Industry (PAI), and PAHW, must collaborate to create robust standards for 3DCP. Each agency plays a critical role:

- KISR should provide scientific research to ensure safety standards;
- EPA should integrate 3DCP into the National Waste Management Strategy (KNWMS) 2040;
- PAHW should oversee housing project standards, ensuring alignment with 3DCP;
- PAI must establish industrial standards to ensure material and process quality;
- Kuwait Municipality should integrate 3DCP into urban planning codes.

4.2. Enhance the Capabilities and Quality of 3D Printing Technology

To improve the adoption of 3D printing technology in construction:

1. Establish R&D Programs: Collaborate with universities to develop innovative materials suited to Kuwait's conditions;
2. Material Innovation: Explore waste materials and recycled concrete for 3D printing;
3. Sustainable Practices: Focus on materials that reduce the carbon footprint;
4. Process Optimization: Develop strategies for faster, more efficient printing and implement BIM;
5. Collaborative Framework: Foster collaboration between research institutions, the private sector, and regulatory bodies for certification and standardization.

4.3. Empowering Kuwait's Construction Sector

Key strategies include the following:

1. Awareness Campaigns: Promote 3D printing technology through media, workshops, and demonstrations;
2. Training Programs: Develop educational initiatives to build a workforce skilled in 3D printing;
3. Pilot Projects: Showcase 3D printing's practical applications through pilot projects demonstrating efficiency and cost-effectiveness;
4. Industry Partnerships: Establish partnerships between educational institutions and industry leaders to provide internships and real-world experience;
5. Infrastructure Development: Create dedicated research centers for 3D printing.

5. Conclusions and Actionable Recommendations

Integrating 3DCP into Kuwait's construction industry presents a unique opportunity to address waste management challenges, but its adoption requires a clear and structured roadmap. Below is a detailed and actionable set of recommendations for the phased adoption of 3DCP:

1. Immediate Term (1–2 years):
    - Regulatory Development: Establish a task force led by the Public Authority for Housing Welfare (PAHW) and the Kuwait Institute for Scientific Research (KISR) to draft initial regulations and safety standards for 3DCP;

  - Pilot Projects: Launch small-scale pilot projects under the oversight of the Kuwait Municipality and Ministry of Public Works (MPW) to demonstrate the technology's feasibility and cost-effectiveness;
  - Awareness Campaigns: Begin targeted awareness campaigns and workshops for key stakeholders (contractors, consultants, engineers, etc.) through the Kuwait Society of Engineers (KSE).
2. Medium Term (3–5 years):
  - Regulatory Implementation:
    Finalize and implement specific regulatory frameworks for 3D-printed construction in collaboration with the Public Authority for Industry (PAI) and the Environmental Protection Authority (EPA), ensuring alignment with sustainability goals;
  - Material Innovation and R&D:
    Invest in research for locally appropriate 3D printing materials through partnerships with KISR and local universities. Focus on low-carbon, sustainable materials that are compatible with Kuwait's climate;
  - Industry Training Programs:
    Develop training programs to build expertise in 3D printing technology, collaborating with universities and industry professionals;
3. Long Term (5+ years):
  - Full-scale Adoption and Integration:
    Integrate 3DCP into larger public infrastructure projects, leveraging the Ministry of Public Works for large-scale implementation;
  - Infrastructure and Facility Development:
    Establish specialized 3D printing hubs and labs to enhance technological capabilities, supported by cross-sector collaboration between the private sector and academic institutions;
  - Continual Review and Innovation:
    Create a review board to update regulations and standards, considering advances in technology and material science.

This study contributes significantly to both academic literature and practical industry applications by providing a detailed analysis of the feasibility of adopting 3D concrete printing in Kuwait. It offers the following:

- For the Academic Community: A framework for future research on the integration of 3DCP into waste management practices and the challenges faced in regions with unique environmental and industrial contexts, such as Kuwait;
- For the Kuwaiti Construction Industry: Practical insights into the technical and regulatory hurdles to adopting 3DCP and a strategic roadmap that can serve as a guide for industry stakeholders;
- For Policymakers: Actionable recommendations on developing a regulatory framework, fostering industry collaborations, and promoting sustainable construction practices through 3DCP, aligning with Kuwait's long-term environmental and sustainability goals.

The findings in this study provide valuable insights into the potential of 3DCP to significantly impact waste management in Kuwait by focusing on efficient resource utilization and fostering collaboration between the government and private sectors. By integrating 3DCP with waste management strategies, Kuwait can enhance the efficient use of materials and reduce construction waste. This research contributes to helping policymakers explore the specific needs of the 3DCP industry. Policy creation should prioritize knowledge exchange, encourage industry collaboration, and establish partnerships between the construction sector, waste management, and other external industries.

The alignment of 3DCP with established construction methods in Kuwait varies based on project scale, printer size, and stakeholder perspectives. While larger-scale projects show greater openness to 3D printing technology, smaller-scale projects may require more cautious approaches due to scalability and investment considerations. Tailoring 3DCP implementations to suit the specific needs of diverse construction projects is crucial for maximizing its benefits and overcoming adoption barriers.

Regulatory hurdles, technical limitations, cultural acceptance, and skill development are critical areas requiring attention to facilitate the successful integration of 3DCP in Kuwait's construction sector. Stakeholder attitudes towards 3D printing indicate both opportunities and barriers to adoption. While there is enthusiasm for the technology's transformative potential, there is also skepticism that necessitates education and awareness initiatives.

Looking ahead, the future of 3D printing in Kuwait's construction industry appears promising but contingent upon concerted efforts to address challenges and capitalize on opportunities. Recommendations include developing tailored regulations, researching new materials, improving printing processes, and fostering collaboration among stakeholders. It is unlikely that 3D printing will completely replace traditional construction methods in the near future; rather, it will likely complement conventional approaches, especially for complex projects.

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