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# 3D-PRINTED HOUSE CONSTRUCTION METHODOLOGY IN PAKISTAN: A STRUCTURED LITERATURE REVIEW AND IMPLEMENTATION FRAMEWORK

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## Abstract
*Three-Dimensional Concrete Printing (3DCP) has opened up new opportunities for a digitally coordinated housing delivery. But the ability to make a house using a machine that prints concrete walls is not the only measure of the viability of a printed house. The successful development of a credible 3D-printed housing project demands close collaboration between the architectural design, material rheology, structural engineering, site logistics and regulatory compliance. This study is aimed to create a structured construction methodology for 3D-printed housing specifically for the contextual realities of Pakistan. A structured literature review and design-science methodology were used to synthesize evidence on extrusion-based concrete printing, printable material requirements, digital toolpaths and quality control into a stage-gated implementation framework. The proposed methodology defies the current 3D printing narrative, which suggests that 3D printing is a direct and straightforward replacement for traditional construction. Rather, 3DCP is described as a mixed production system that necessitates clear stage gates, from feasibility and system-boundary definition through plant mobilisation, real-time print control and post-occupancy evaluation. The article suggests a gradual implementation process for the construction industry in Pakistan. This includes local material validation, climate responsive envelope design in line with Energy Conservation Building Code (ECBC-2023), early engagement with authorities and clear pilot projects. In conclusion, this article offers a practical approach for construction managers, designers, and regulators aiming to responsibly adopt 3D-printed housing, ensuring geometric achievements are complemented by structural safety, durability, and whole-building integration.*

**Keywords:** Three-Dimensional Concrete Printing (3DCP); Additive Manufacturing; Construction Methodology; Digital Construction; Residential Housing; Construction Management; Quality Assurance; Pakistan.

## Introduction
The construction industry is in the midst of a radical change from the traditional labour-intensive and trade-based construction methods to digitally integrated and automated production systems (Buswell et al., 2018). One of the most promising technologies for the modern building construction is construction-scale additive manufacturing, especially Three-Dimensional Concrete Printing (3DCP). Extrusion-based 3DCP is a process that deposits cementitious material layer by layer based on a digital model and toolpath, which is controlled by a digital system and a robot, and does not require conventional formwork, which can achieve high geometric precision and high degree of process automation (Bos et al., 2016). The combination of digital design, automated fabrication, and real-time quality documentation

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provides a great opportunity to boost productivity, minimise material waste and optimise construction processes that have been traditionally disjointed and reliant on manual processes. Despite these benefits, there is a widespread misunderstanding in the industry and the public that a 3D printer can print a whole house by itself. However, the current 3DCP technologies can only be used to print certain structural components, most often load-bearing or non-load-bearing wall systems. The use of conventional or semi-industrialized construction techniques is still used for critical building elements, such as foundations, structural reinforcement, roofing systems, windows and doors, mechanical, electrical and plumbing (MEP) services, waterproofing, insulation and interior finishes (Mechtcherine et al., 2020). The question is not whether 3D printing can completely replace traditional construction techniques, but how the 3D printed structural elements can be effectively designed, integrated, inspected and coordinated into a complete, safe and code-compliant building system.

The printed wall elements can be very precise, but there are many technical issues that are not apparent in the print that need to be addressed during the construction process. These include consistency of materials, sufficient interlayer bonding, structural reinforcement, service penetrations and continuous structural load paths (Mohan et al., 2021). These challenges are interdependent and directly affect the structural performance and durability of printed buildings. The printable concrete mixtures, in particular, have to meet very high requirements in terms of their rheological properties: they should be sufficiently fluid to be pumped and extruded, but also have a sufficiently high yield stress and buildability so that successive layers can be deposited without deformation or collapse immediately after deposition (Roussel, 2018). Therefore, in addition to the high level of printing equipment, the material properties, printing parameters and quality control during construction must also be strictly controlled to ensure the successful implementation of 3DCP.

The potential to solve the housing shortage problem in the world and at the same time enhance environmental sustainability has been a major driver of the development of Three-Dimensional Printed Concrete (3DPC). The recent studies show that the construction waste can be reduced by around 30-60% by using automated concrete extrusion method than the conventional construction method using formwork (Hassan et al., 2025). Moreover, digital fabrication can help to reduce construction time, manpower, geometric flexibility and construction efficiency. However, the successful laboratory demonstrations have not been easily replicated in the field because of the variability of the environment, equipment constraints, quality control needs, and project management issues. Automated construction processes need to be supported by comprehensive implementation frameworks that can assess the structural performance, operational risks, economic feasibility, and construction quality throughout the project lifecycle, however, to facilitate mainstream adoption (El-Sayegh et al., 2020).

The challenges are especially pertinent in Pakistan, where the population growth, rapid urbanization, and huge housing shortage have created a demand for innovative and affordable construction technologies. The National Housing Policy 2025 focuses on providing affordable, secure, sustainable and climate resilient housing, which will provide conducive environment for industrialized construction methods (Ministry of Housing and Works, 2025). But the experiences of other countries are not sufficient to ensure successful implementation of 3DCP as the housing projects in Pakistan are subject to different climatic conditions, availability of construction materials, skill of the workforce, regulatory approval process, and energy-performance requirements defined in the Energy Conservation Building Code (NEECA, 2023). Hence, it is essential to establish a local construction approach that would be able to adapt the international best practices into a structured implementation framework that would be appropriate in Pakistan's technical, regulatory and socio-economic environment.

Although there is an increasing amount of research internationally on 3D concrete printing, the research work is mostly limited to specific aspects like material development, printer technologies, structural behaviour or specific case studies. Focusing on a single coordinated approach to the development of comprehensive construction methodologies that incorporate planning, material qualification, digital modelling, printing operations, structural integration, quality assurance, inspection and project handover is comparatively limited. The absence of an end-to-end implementation methodology is a major challenge for the practical implementation of 3DCP, especially in developing countries where regulatory frameworks, construction methods and resources are quite different from those of developed economies.

Hence, the objective of this study is to create a practical and evidence-based construction methodology for planning, printing, integration and commissioning of 3D printed residential buildings in the context of Pakistan. The proposed methodology does not view 3D printing as a stand-alone technological innovation, but rather as a very controlled construction process with well-defined stage gates, digital verification processes, quality-control requirements, decision criteria based on evidence, and stop-work protocols. This is a paradigm shift from the subjective management of a site based on experience to a digitally controlled production system in which material qualification, automated fabrication and as-built verification are seamlessly integrated throughout the construction process (Bos & Wolfs, 2023).

This study aims to critically review the existing techniques, technologies and limitations of construction scale 3D concrete printing, to identify the material, digital, structural, regulatory and quality control requirements for the successful implementation of 3D printed housing in Pakistan and to develop a staged construction methodology for the housing sector in Pakistan. The proposed framework combines these elements to create a construction roadmap that is traceable, and has a clear planning process, execution stages, quality assurance process and decision making criteria. In conclusion, this study goes beyond just proving the feasibility of the technology to creating a comprehensive construction management framework that can facilitate the safe, efficient, and sustainable deployment of 3D-printed homes in Pakistan.

## Literature Review

Additive manufacturing (AM) has been a research hotspot for the last ten years and is a new digital construction technology that has the potential to revolutionize the way buildings are constructed.Construction-scale additive manufacturing (CSAM) has received significant research interest in the last decade as a new digital construction technology with the potential to transform conventional building practices. Different additive manufacturing techniques have been explored such as particle-bed binding, shotcrete systems, printed formwork and concrete printing by extrusion. Of these, extrusion-based Three-Dimensional Concrete Printing (3DCP) is the most technically developed and commercially viable solution for low-rise residential buildings due to its relatively simple production process, scalability and compatibility with cement-based materials (Lowke et al., 2018). Extrusion-based systems involve a continuous pumping of a cementitious mixture through a hose and the deposition of the material layer-by-layer with the help of a robotic arm or gantry system following a digitally generated toolpath (Buswell et al., 2018; Lidhiya & Soundhirarajan, 2026). But researchers have always maintained that the quality and structural integrity of the printed part is not only dependent on the printing machine, but also on the synchronized performance of the entire production chain, such as material preparation, pumping, extrusion, nozzle movement, and deposition parameters (Mechtcherine et al., 2020).

One of the most widely studied fields of 3D concrete printing is the behaviour of the material. Conventional concrete has to meet a number of conflicting performance requirements, but printable cementitious mixtures have to meet all of these requirements plus the requirement for the mixture to have a long enough open time to be pumped during the printing process. These properties are controlled by the rheological parameters of the material, including yield stress, viscosity, thixotropy, elastic modulus and structural build-up, which must allow the material to flow through the delivery system without any problems and at the same time have enough stability to support the next layers as soon as they are deposited. Therefore, traditional concrete quality measures, like slump and compressive strength, are not adequate to qualify printable mixtures. Recent studies have thus suggested the use of fresh-state rheological testing coupled with full-scale trial printing to assess the actual printing performance under realistic construction conditions (Roussel et al., 2022; Tay et al., 2019). This holistic approach allows researchers to make direct links between lab material characterization and printing behaviour in the field.

In addition to the performance of the materials, digital workflow management is now acknowledged in the literature as one of the most important factors for successful implementation of 3D printing. The construction process starts with Building Information Modeling (BIM), Design for Additive Manufacturing (DfAM), slicing and automated toolpath generation. The authors of Paolini et al. (2019) state that digital models created for traditional construction cannot be directly applied to 3D printing without modifications due to the geometric and operational constraints of 3D printing. The nozzle accessibility, collision avoidance, continuous material deposition, layer sequencing and print direction should all be taken into account at the design phase. In addition, the slicing algorithms always introduce start-stop locations and path intersections which can decrease the structural continuity if not optimized well. Therefore, researchers stress the need for strict version control and digital change-management processes, as even minor changes after the approval can have a big impact on the structural behaviour, material usage and construction sequence.

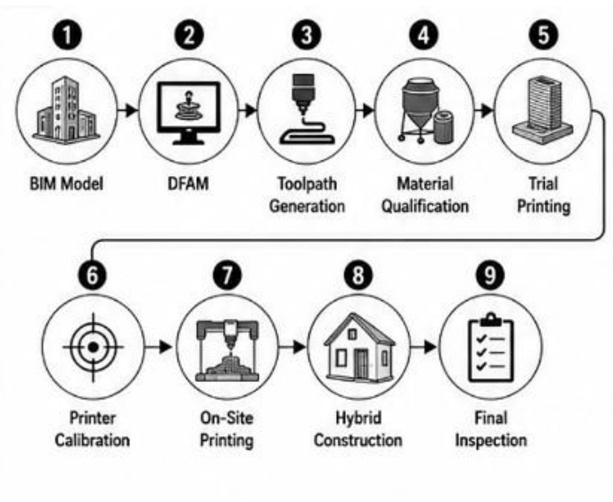
While digital automation is a great way to increase geometric accuracy, structural performance is one of the main challenges that still need to be overcome before 3D concrete printing becomes more widely adopted. Many studies have shown that printing wall elements does not necessarily mean that they can withstand gravity, wind, seismic or service loads (Mohan et al., 2021). The current reinforcement methods involve the use of vertical reinforcing bars in printed cavities, horizontal reinforcement in the printed concrete, using printed concrete as permanent formwork for conventionally reinforced cores, and hybrid structures that integrate printed walls with reinforced concrete or steel structures (Vasilic, 2024). Of these challenges, interlayer bonding has been the focus of special interest as printed concrete has an inherent anisotropic mechanical behaviour. Wolfs et al. (2019) conducted experimental studies that showed that the interface strength is very sensitive to the gap between the deposited layers, nozzle stand-off distance, and moisture on the surface. Too long of a time between layers or too early moisture loss will lead to low bond strength, resulting in cold joints and weak interfaces, which will affect the durability and structural strength (Le et al., 2012b). The results show that both process control and material performance are crucial for structural reliability.

Construction management factors are not just about the structural behaviour, but also operational planning, site logistics and health and safety management. Conventional construction has new operational risks of automated robotic systems, high-pressure pumping equipment, continuous material delivery, and chemical exposure in 3DCP ( Zhang et al., 2026; Hassan et al., 2025). Unexpected interruptions like hose blockages, equipment failure, or poor weather conditions can impact print quality and lead to expensive rework because of the need to have continuous material flow during extrusion-based printing. In addition, researchers warn against judging 3D printing by its speed of printing or the savings in labor. Whole-life assessments show that while formwork waste can be significantly reduced, there are other environmental impacts such as trial prints, washout waste, rejected batches, equipment mobilisation, calibration and integration with conventional construction activities (Ghaffar et al., 2018; Bhattacherjee et al., 2021). Thus, it is necessary to consider the project performance throughout the entire construction process, not only during the printing process.

Another major hurdle to 3D-printed buildings is the regulatory landscape. The current structural design codes and concrete testing standards were designed for conventionally cast concrete and are not suitable for addressing the layered and anisotropic nature of additively manufactured structures (Vasilic, 2024). Therefore, the quality assurance systems need to be transformed from the traditional inspection systems. Bos and Wolfs (2023) suggest digital quality management frameworks that create full traceability from approved digital models and qualified material batches to real-time process monitoring to as-built verification. Instead of developing new regulations, recent literature indicates that compliance with the structural, fire safety and durability requirements can be demonstrated by performance-based testing and documented evidence, which can help to gain regulatory acceptance while ensuring public safety.

Although the government of Pakistan is keen on industrialized construction, research on construction-scale 3D printing is still limited within the context of Pakistan. The National Housing Policy 2025 acknowledges the need of affordable, sustainable and scalable housing solutions in Pakistan (Ministry of Housing and Works, 2025). At the same time, the Energy Conservation Building Code (ECBC-2023) prescribes the minimum thermal performance requirements for the building envelope of residential buildings (NEECA, 2023). The developments in these policies indicate that there is a lot of potential for 3D concrete printing, but it needs to be adapted to local conditions and not copied from international practices. The literature suggests that localized implementation should include building design that is responsive to climate, use locally available aggregates and binders, consider local curing conditions, build capacity of the workforce, and engage with regulations through evidence-based pilot projects. Thus, technological capability is not the only factor that is crucial for effective implementation in Pakistan, but the integration of construction management, environmental performance, regulatory compliance, and local industry practices in a comprehensive implementation framework is also crucial.

Figure 1: Digital Construction Workflow



Although there has been significant progress in material science, digital fabrication, structural behaviour and printing technologies, the literature is still quite disjointed, with most studies focusing on individual technical aspects of the process, but not the entire construction process. There are few studies that suggest a methodology that integrates planning, material qualification, digital modelling, printing operations, structural integration, quality assurance, inspection, regulatory compliance and project handover in a single construction management. This is especially true in developing countries like Pakistan where there is a lack of local implementation strategies. In this context, the present study aims to fill this gap by proposing a complete, step-by-step construction methodology for 3D printed residential buildings, which incorporates the best practices from around the world and considers the technical, regulatory and environmental conditions in Pakistan.

## Methodology

A structured literature review was used in this study to combine with a design science research (DSR) approach to create a practical construction methodology for Three-Dimensional Concrete Printing (3DCP) in residential housing. This methodology was chosen because of the multi-disciplinary aspects of construction-scale AM, which involves materials science, structural engineering, robotics, digital construction and construction management. The primary goal was to create a framework for implementing the project based on evidence, not to assess a specific construction project, so an empirical case study or field experiment would not have been enough to cover the wide spectrum of technical, managerial and regulatory needs. Therefore, a systematic review was conducted to consolidate the knowledge and to translate the knowledge into a structured construction methodology.

The literature review was carried out following the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) to guarantee transparency, reproducibility and methodological rigor (Page et al., 2021). A thorough search strategy was carried out in the major scientific databases (Scopus, Web of Science, ScienceDirect, IEEE Xplore and Google Scholar) and internationally recognised technical standards and policy documents. The Boolean search strings used keywords were 3D concrete printing, construction-scale additive manufacturing, extrusion-based printing, rheology, buildability, interlayer bonding, digital construction, Building Information Modeling (BIM), quality assurance, construction management, and Pakistan. This search strategy was designed to cover as much as possible both technical and managerial aspects of 3DCP.

Explicit inclusion and exclusion criteria were developed before the review to enhance the quality and relevance of the evidence base. Only peer-reviewed journal articles, conference proceedings, international standards, technical reports and government policy documents that directly address construction-scale 3D printing were included. Only studies that were focused on material characterization in the laboratory and did not have a construction implication, conceptual media reports, commercial promotional material and publications that did not provide enough methodological detail were excluded. Empirical studies reporting material properties, digital workflows, structural performance, quality-control procedures, implementation challenges and practical construction applications were given special attention. After article selection, data were extracted from the selected articles with the help of a standardized review template to ensure uniformity in data extraction from all the articles. The information gathered comprised publication information, printing technology, construction application, characteristics of printable materials, digital workflow, reinforcement strategy, quality assurance procedures, reported limitations, implementation challenges and implications for construction management. This systematic extraction process allowed the findings from the different studies to be compared systematically and reduced reviewer bias.

The evidence extracted was then analysed thematically, with similar findings clustered into the main implementation domains. The analysis resulted in four main themes: (i) digital planning and design, (ii) material qualification and process control, (iii) printing operations and quality assurance, and (iv) structural integration and project completion. These themes in totality were the key phases needed to make 3D-printed residential construction a success and served as the conceptual basis for the proposed methodology.

Based on these synthesized results, the study used the design science research method to develop a practical construction management framework from the theoretical knowledge. The research was not just a summary of the existing literature, but it was a methodology that was developed for the implementation of 3D concrete printing in residential applications in Pakistan based on the empirical evidence. The proposed framework outlines the necessary inputs, stakeholders, verification processes, evidence needed, quality control measures, decision criteria and explicit stop work rules that must be met prior to moving onto the next construction stage. This structured approach makes digital planning, material qualification, automated printing, structural integration and final inspection an integrated production system instead of individual construction activities.

An important aspect of the proposed approach is the use of real-time process control to reduce the amount of material and structural failure during the layer-by-layer deposition. The framework incorporates monitoring measures to avoid plastic collapse caused by excessive vertical deformation, and elastic buckling that can occur during the printing of successive layers (Suiker et al., 2020). Furthermore, the quality-control process includes continuous monitoring of the rheological properties, the geometry of the layers, the pressure of the extrusion, the movement of the nozzle and the time intervals between the layers. Previous work has shown that the deformation of the lower printed layers is not only related to the self-weight, but also to the extrusion pressure, printing speed and time between the layers (Ashrafi et al., 2021). The proposed methodology, therefore, sets up the operational thresholds and the stop-work criteria, which will guarantee dimensional stability, structural integrity and overall construction quality, whenever the parameters are not within the acceptable limits.

In general, the research methodology adopted is a systematic and evidence-based process that can be used to integrate the technical knowledge that is not yet in one system into a comprehensive construction management system. The study combines systematic literature review techniques and design science principles to create a practical methodology which is scientifically sound and can be directly applied to the planning, construction, quality assurance and regulatory implementation of 3D-printed residential buildings in the context of the Pakistani construction industry.

## Findings

The main finding of this study is the creation of a holistic implementation methodology for planning, implementation and verification of 3D printed residential construction, which is divided into nine stages. The proposed framework is different from the current ones, which mainly focus on the printing technology or the performance of the printing material, and considers the 3D concrete printing as a construction management process. The methodology does not aim to encourage continuous printing, but rather a series of stage gates, each of which is based on evidence and requires a series of technical, managerial and quality-control criteria to be met before moving to the next stage of construction. This strategy helps to reduce the risks of a project proactively, avoiding the spread of defects through the construction process (Bos & Wolfs, 2023).

The methodology starts with Stage 0 (Project Definition and Feasibility) and Stage 1 (Site and Regulatory Due Diligence) that provide the strategic and regulatory underpinning of the project. In Stage 0, project goals, stakeholder needs, financial viability and construction options are carefully considered and assessed to decide if the best value is a full print, hybrid or traditional construction method. Also, the exact range of the printed components is precisely defined, which differentiates them from the traditionally manufactured components. Stage 1 then assesses site access, geotechnical, climatic, utility and equipment logistics and begins to engage with local regulatory agencies. By coordinating the proposed construction methodology with the Energy Conservation Building Code (ECBC-2023), municipal approval processes, and relevant structural design standards, early regulatory coordination ensures that the proposed building methodology is compliant with the code and regulatory requirements.

Once the project is approved, the methodology moves on to Stage 2 (Design for Additive Manufacturing) and Stage 3 (Structural and MEP Integration) where the architectural ideas are converted into buildable construction information. Design for Additive Manufacturing (DfAM) optimizes the geometry of the build to be built layer by layer, defining the thickness of the layers, paths of the nozzle, printing sequences, geometries of corners, and pauses in the operation without causing any collisions between the machine and the built object. Structural and MEP integration then integrates reinforcement systems, structural load paths, foundation connections, service penetrations and mechanical, electrical and plumbing installations into the digital model. This coordinated planning prevents the need for unplanned changes after printing, which might affect the structural integrity or construction efficiency.

Material verification is the crucial step between the digital planning and physical construction. In Stage 4 (Material Qualification and Trial Printing), the printable concrete mixtures must be qualified under site conditions, not just in the laboratory, using the anticipated conditions. The qualification involves rheological testing, trial extrusion, dimensional accuracy assessment, interlayer bonding evaluation and representative wall printing to determine acceptable operating limits for pumpability, buildability, extrusion pressure and open time (Rahul et al., 2019). The operational readiness is confirmed in Stage 5 (Plant Mobilisation) by equipment calibration, printer positioning, material traceability, safety checks, foundation tolerance checks and the setting up of exclusion zones prior to production.

The key part of the framework is Stage 6 (Printing Operations and Real-Time Control), where the entire printing process is controlled by continuous quality monitoring. The proposed methodology is different from the traditional construction inspection methods that are performed after the construction is completed, as it allows for real-time monitoring of the extrusion pressure, print speed, environmental conditions, dimensions of the layers, performance of the equipment and any interruptions in the construction process. One of the most important innovations of the framework is the use of predefined Stop-Work Rules, where printing is immediately stopped if the process parameters are outside of the acceptable range. This can be caused by too much deformation of the layers, interruption of material flow, nozzle blockage, equipment failure or bad weather. These decision thresholds minimize the chances of interlayer defects and local failures from affecting the structural integrity of the finished wall system (Wolfs et al., 2019).

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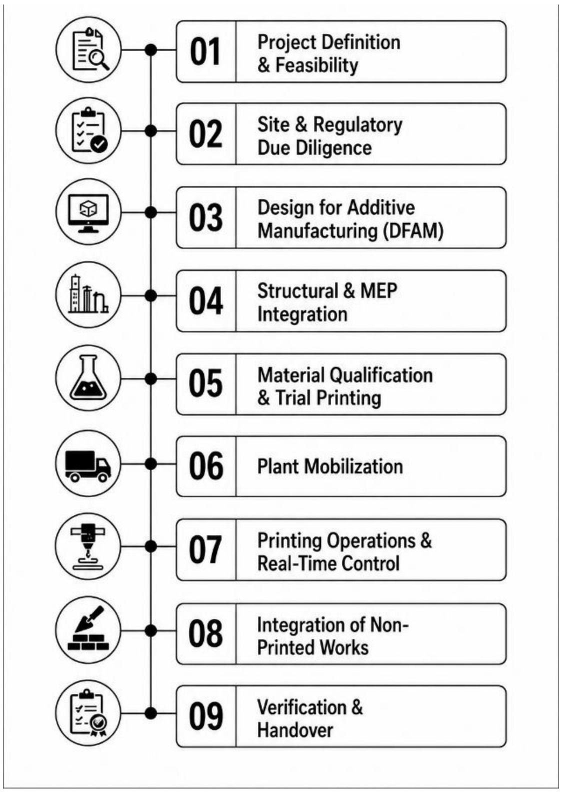
Figure 2: Stage Implementation Framework




After the printed structure is completed, the building lifecycle is completed in Stage 7 (Integration of Non-Printed Works) and Stage 8 (Verification and Handover). Stage 7 involves coordinating the installation of traditional building elements such as roofing systems, reinforcement, windows, doors, insulation, finishes and MEP services, as well as ensuring that the early age printed concrete is not subjected to excessive loading and unintended damage. The final phase sets up a comprehensive verification process with dimensional checks, structural quality checks, material batch records, approved digital toolpaths, construction records, non-conformance records and as-built verification. As 3D concrete printing is a new technology, the methodology also suggests the monitoring of thermal performance, comfort, durability and maintenance after the construction to continuously enhance future projects based on the lessons learnt.

The proposed nine-stage implementation methodology is summarized in Figure X. The framework shows the logical sequence of project planning and regulatory assessment, digital design, structural integration, material qualification, equipment mobilization, printing, conventional construction and final verification. The proposed framework is different from the current technical workflows, which are mainly concerned with the printing process itself, by incorporating engineering design, digital manufacturing, construction management, quality assurance and regulatory compliance into a single implementation model. Thus, it offers a practical guide for the implementation of 3D concrete printing in the residential construction industry in Pakistan without compromising engineering standards, construction regulations and best management practices.

## Discussion and Conclusion

The results show that the adoption of 3D concrete printing in Pakistan is not just about the technology but also about creating a robust construction management system that can seamlessly integrate digital fabrication with traditional construction methods. While international projects have proven the technical viability of printing structural wall systems, there is little likelihood that the same approach to foreign construction models will be successful in Pakistan due to climatic conditions, building materials, labor skills, regulatory frameworks, and housing needs. The proposed methodology is therefore more about adaptation than technological imitation, as it focuses on the local level.

One of the key findings of this research is the difference between the idea of standardization. Digital construction allows for the standardization of design data, material batching procedures, machine operations and quality assurance documentation, but does not mean that all residential buildings should be standardized. Each housing project is unique and will be influenced by site-specific factors such as geotechnical, local climate, seismic, municipal and client requirements (Ministry of Housing and Works, 2025). Thus, 3D-printed wall systems should be seen as a standardised building element that is part of a customised hybrid building system, not as a universal and ready-to-use house.

One of the greatest challenges for large-scale implementation is material qualification. The locally available aggregates, cementitious materials, ambient temperature and humidity conditions in Pakistan are significantly different from those in international case studies, which have a direct impact on the printable concrete rheology, buildability and interlayer bonding (Le et al., 2012a). Thus, a comprehensive characterisation and validation of the local material and supply chain is necessary prior to commercialisation. In addition, the Energy Conservation Building Code (ECBC-2023) mandates that printed wall systems must not only provide flexibility in design, but also play a role in the energy performance of the building through climate-responsive design features like optimized thermal mass, integrated insulation cavities, passive shading and natural ventilation (NEECA, 2023).

Based on these findings, this study suggests a roadmap for the phased implementation in Pakistan. The initial phase should focus on lab testing of printable materials and assessment of local supply chains. The second phase should be the development of non-occupied prototype components for testing printing parameters, quality control processes and performance of the printed structure under local environmental conditions. The third phase should include pilot housing projects, which are to be independently reviewed, and which include detailed post-occupancy monitoring of structural behaviour, energy performance and occupant comfort. The fourth phase (commercial scale deployment) should only be undertaken after successful completion and documentation of these pilot projects. This incremental approach helps minimize technical risks and allows industry participants to build their knowledge and skills in digital construction, automated equipment operation, material manufacturing, and quality control (Hassan et al., 2025).

To sum up, 3D Concrete Printing has a great potential to contribute to the affordable, efficient and sustainable housing development in Pakistan. But it can't be fully automated, push-button construction, as is often believed, if it is to be successfully adopted. Rather, the residential 3D printing process should be seen as a very well-coordinated hybrid construction process that demands careful planning, material qualification, digital design, process monitoring, structural verification, and regulatory compliance. This study has developed a nine-stage implementation methodology that offers an evidence-based framework that brings together these technical and managerial requirements in a coherent construction process. Policymakers, regulators, and construction practitioners can advance the 3D concrete printing revolution in a responsible way, ensuring buildings are safe, perform well, and are of high quality, by implementing stage-gated decision-making, strong quality assurance processes, and localized implementation strategies.

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