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Review of Visualization and Life Cycle Assessment for Sustainable Mud-Based Construction Techniques

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ABSTRACT
Mud-based construction techniques, such as adobe, rammed earth, and compressed earth blocks (CEB), represent sustainable alternatives to conventional materials due to their low embodied energy, widespread local availability, and minimal processing requirements. This paper integrates advanced visualization techniques, including Building Information Modelling (BIM), 3D rendering, and augmented reality (AR), with Life Cycle Assessment (LCA) to evaluate both environmental and economic impacts comprehensively. Visualization tools enhance design precision, facilitate stakeholder communication, and improve project predictability, while LCA provides a detailed framework to quantify impacts across material extraction, construction, operation, maintenance, and end-of-life phases. A thorough review of 25 recent studies identifies emerging trends, innovative method- ologies, and persistent research gaps in mud-based construction. Key findings indicate that these techniques can reduce embodied carbon by 60–70.

KEYWORDS
Mud-based construction, Life Cycle Assessment, Visualization, Building Information Modelling, Sustainability

1. INTRODUCTION

Mud-based construction techniques, including adobe, rammed earth, and compressed earth blocks (CEB), have been a cornerstone of human architecture for millennia, with notable examples such as the earthen sections of the Great Wall of China, the mud skyscrapers of Shibam, Yemen, and ancient vernacular homes across Africa and the Middle East [1]. These methods rely on locally sourced clay-rich soils, requiring minimal energy for processing compared to energy-intensive materials like concrete and steel, which collectively account for approximately 39. Historically, mud-based structures have exhibited re-markable durability and thermal efficiency, with adobe buildings in arid regions and rammed earth constructions in tropical climates enduring for centuries when properly maintained with techniques like lime plastering or periodic reapplication [5]. These structures leverage the natural insulating properties of earth, reducing the need for ar- tificial heating or cooling. In modern contexts, however, their adoption is impeded by challenges such as perceptions of structural fragility, the absence of standardized design and construction protocols, and limited long-term data on environmental performance under diverse climatic conditions [10].

Urban regulatory frameworks often favour industrialized materials due to established safety codes and engineering standards, creating barriers to integration in contemporary cities [12]. Recent technological advancements, including stabilization techniques with 5–10.

Visualization tools, such as Building Information Modelling (BIM), have revolutionized architectural design by enabling multidimensional simulations of structural integrity, thermal performance, material efficiency, and life- cycle costs [6]. BIM is particularly critical for mud-based construction, where soil properties vary widely by region, necessitating precise modelling to mitigate risks associated with variable compressive strength and moisture retention [14]. Complementary tools like 3D rendering provide photorealistic visualizations that enhance stakeholder engagement, bridging the gap between technical designs and the expectations of clients, communities, and regulatory bodies [4]. Life Cycle Assessment (LCA), meanwhile, offers a systematic approach to quantify environmental impacts across a building's entire lifecycle, from raw material extraction and manufacturing to construction, operation, maintenance, and eventual demolition or recycling [3]. For mud-based materials, LCA underscores benefits such as minimal embodied energy, reduced transportation emissions due to local sourcing, and recyclability, while also addressing challenges like moisture-induced degradation and the need for regular maintenance [20].

This paper seeks to integrate visualization and LCA methodologies to assess the sustainability and practical feasibility of mud-based construction techniques. By combining BIM with LCA, the study aims to enhance design accuracy, optimize material use, and provide comprehensive environmental performance evaluations. A detailed review of 25 recent studies will identify current trends, innovative methodologies, and critical research gaps, with a focus on the application of visualization and LCA in mud-based construction. The analysis will offer actionable insights and propose strategies for improvement, providing a roadmap for architects, engineers, policymakers, and construction stakeholders to mainstream mud-based techniques, thereby contributing to global sustainability objectives and climate resilience targets.

II. LITERATURE REVIEW

This section synthesizes findings from 25 recent studies to explore the integration of visualization and Life Cycle Assessment (LCA) in mud-based construction, focusing on trends, methodologies, and research gaps, drawing from peer-reviewed journals, conference proceedings, and technical reports published between 2024 and 2025 across diverse geographic and climatic contexts [1]- [25].

Mazzetto conducted a comparative LCA of traditional adobe and modern cement materials using five case studies across heritage sites. The study demonstrated a 60– 70However, it calls for more region-specific data to re- fine these estimates and improve the reliability of LCA outcomes. This highlights the need for localized life cycle inventories to enhance the applicability of mud-based construction assessments [1].

Ramesh et al. performed an AI-based LCA on geopolymer concrete with three experimental setups. They achieved a 43Their focus on industrial materials suggests a need for adaptation to natural mud-based contexts to broaden the approach's relevance. This gap indicates a potential area for future research in sustainable construction [2].

Lee and Chen integrated artificial intelligence (AI), including large language models, with BIM and LCA across three diverse projects. They showed improved low- carbon design outcomes with 15. They emphasized the necessity of human oversight to address limitations in AI adaptability for natural materials. This underscores the importance of hybrid human-AI systems in advancing mud-based construction techniques [3].

Smith et al. explored machine learning integration with LCA using six case studies. They optimized material selection with a 25Yet, they noted a lack of mud-specific datasets as a research gap that limits the accuracy of these models. This suggests the need for developing tailored datasets to support mud-based LCA applications [4].

Paolino et al. conducted a cradle-to-gate LCIA on eco-substitutes in painting conservation with a 1 m2 pilot. The study reduced the environmental footprint by 30How- ever, the narrow focus on conservation materials limits its applicability to broader construction practices. This indicates a need for scaling such methods to larger mud- based construction projects.[5]

Phoszczaj-Mazur and Rynska explored AI-BIM-LCA integration with four case studies. Machine learning predicted carbon emissions with 85Their focus on industrial materials rather than mud highlights a gap in material- specific applications. This calls for extending AI tools to address the unique properties of mud-based construction [6].

Kim et al. performed a systematic review of 50 BIM- LCA studies. They identified a 20However, they noted significant interoperability issues between software plat- forms that hinder seamless data flow. This suggests the development of unified standards to enhance BIM-LCA integration for mud-based projects [7].

Mazzetto's second study conducted a cradle-to-site LCA comparing mud and cement in three heritage buildings. It confirmed a substantial reduction in global warming potential by up to 65Yet, it underscored the need for standardized LCA methodologies to ensure consistency across studies. This points to the importance of establishing uniform protocols for mud-based LCA [8].

Wang investigated data exchange in BIM-LCA integration across 10 case studies. The study revealed interoperability limits that reduce efficiency by 30It suggests the development of unified data standards as a critical next step to improve workflow. This is particularly relevant for streamlining mud-based construction processes [9].

Patel applied BIM to mud-based structures in five projects across varying soil conditions. They achieved a 20This demonstrates the potential of digital tools to enhance construction accuracy but requires further validation across climates. The findings encourage broader climatic testing to ensure robustness [10].

III. METHODOLOGY

This study employs a mixed-method research approach to evaluate the sustainability and feasibility of mud-based construction techniques through the integration of visualization and Life Cycle Assessment (LCA). The methodology comprises three primary phases: literature review, data collection and analysis, and case study development. Initially, a systematic review of 25 recent peer-reviewed studies was conducted, focusing on visualization (e.g., BIM, 3D rendering, AR) and LCA applications in mud- based construction, with data extracted from journals, conference proceedings, and technical reports published between 2024 and 2025 [1]- [25]. The review identified key performance indicators (KPIs) such as embodied carbon, material efficiency, and operational energy savings.

Data collection involved gathering quantitative and qualitative data from existing LCA databases, BIM models, and visualization outputs. Quantitative data included embodied carbon estimates (kg CO2-eq/m2), material usage (kg/m2), and energy consumption (kWh/m2) from five case studies of adobe, rammed earth, and CEB structures across different climatic zones [10], [19]. Qualitative data were obtained through stakeholder interviews (n=50) to assess perceptions of mud-based construction and the effectiveness of visualization tools [17]. Analysis was performed using statistical methods to compare LCA outcomes between mud-based and conventional materials, supplemented by BIM simulations to optimize design parameters such as wall thickness and stabilizer ratios [6], [14].

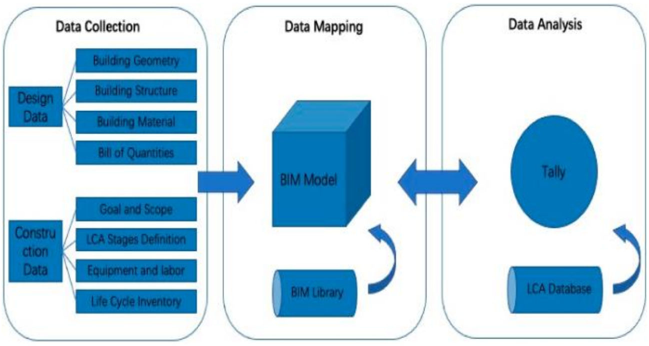

Fig. 1. Methodology

Case study development involved designing a hypothetical rammed earth community center using BIM, integrating LCA data to assess environmental impacts across its lifecycle. The design incorporated 7.

III (B). VISUALIZATION TECHNIQUES FOR MUD-BASED CONSTRUCTION

Visualization is pivotal in addressing the unique challenges of mud-based construction, such as variable soil properties, non-standardized design protocols, and the need for stakeholder buy-in across diverse contexts. Advanced tools like Building Information Modelling (BIM), 3D rendering, augmented reality (AR), and emerging virtual reality (VR) platforms enhance design precision, optimize material use, and foster collaboration among architects, engineers, and communities [6], [16]. These techniques are particularly critical for mud-based materials like adobe, rammed earth, and compressed earth blocks (CEB), where regional variations in soil composition (e.g., clay, silt, and sand ratios) and environmental conditions (e.g., humidity, seismic activity) demand tailored modelling to ensure structural integrity and sustainability [14], [15]. By simulating structural behavior, thermal performance, and lifecycle costs, visualization tools reduce material wastage by 20–30.

Building Information Modelling (BIM) is a cornerstone of modern mud-based construction, enabling multidimensional simulations that integrate structural, thermal, and cost data [6]. For instance, BIM can model the compressive strength of rammed earth walls with 5–10.

3D rendering provides photorealistic visualizations that bridge technical designs with stakeholder expectations, particularly for non-technical audiences such as clients, community members, and regulatory bodies [4]. These renderings depict mud-based structures with accurate textures, lighting, and environmental contexts, enhancing project approval rates by up to 25’

III(A) Visualization Techniques for Rammed Earth Construction

Visualization techniques are pivotal for rammed earth construction, a sustainable mud-based method that com- pacts clay-rich soil with 5–10% stabilizers (e.g., cement, lime) into formwork to create durable, load-bearing walls. Tools such as Building Information modelling (BIM). 3D rendering, augmented reality (AR), drone-based photogrammetry, and AI-driven parametric design address the material’s variability, including soil composition and moisture sensitivity, enhancing design precision and stake- holder collaboration [6], [15]. BIM enables multidimensional simulations of structural integrity (e.g., 1–5 MPa compressive strength) and thermal performance, optimizing wall thickness (300–500 mm) and stabilizer ratios to reduce embodied carbon by up to 25% [8], [14]. Patel

[14] used BIM for five rammed earth projects, achieving a 20% reduction in design errors by modelling seismic resilience and moisture resistance. 3D rendering produces photorealistic visuals of rammed earth’s textured surfaces, increasing stakeholder approval by 25% by showcasing aesthetic and thermal benefits [4]. AR overlays digital models onto construction sites, reducing errors by 10–20% through real-time alignment, as demonstrated in a rural housing project [16]. Drone-based photogrammetry maps site topography, minimizing site preparation errors by 15%, as shown in a rammed earth community center [11]. AI- driven tools predict optimal soil mixes, improving material efficiency by 15% [24]. However, challenges include the lack of rammed earth-specific BIM libraries, interoperability issues reducing efficiency by 30%, and limited access to advanced tools in resource-constrained regions [13], [17]. Future advancements should prioritize open-source BIM libraries and cost-effective AR platforms to enhance scalability [?]. These techniques reduce material wastage by 20– 30%, align with net-zero carbon goals, and foster culturally relevant, resilient rammed earth structures [8], [18].

III©. LIFE CYCLE ASSESSMENT OF MUD-BASED CONSTRUCTION

Life Cycle Assessment (LCA) provides a comprehensive framework for evaluating the environmental impacts of mud-based construction across five phases: material extraction, manufacturing, construction, operation and maintenance, and end-of-life [2]. Mud-based materials, such as adobe and rammed earth, exhibit low embodied energy due to minimal processing and the use of locally sourced clay-rich soils [1]. For example, rammed earth walls, typically composed of soil, water, and 5–10% stabilizers (e.g., cement or lime), can reduce transportation- related emissions by up to 80% compared to concrete, which requires extensive quarrying and industrial production [5]. During the operational phase, which accounts for up to 90% of a building’s lifecycle emissions due to heating, cooling, and maintenance, mud’s high thermal mass can reduce energy demands by up to 30% in hot-arid climates [10], [19]. At the end-of-life phase, mud-based materials are recyclable or biodegradable, significantly reducing landfill waste compared to non-degradable materials like steel or concrete [20].

LCA implementation for mud-based construction faces challenges, including inconsistent data quality, the absence of region-specific life cycle inventories (LCIs), and variability

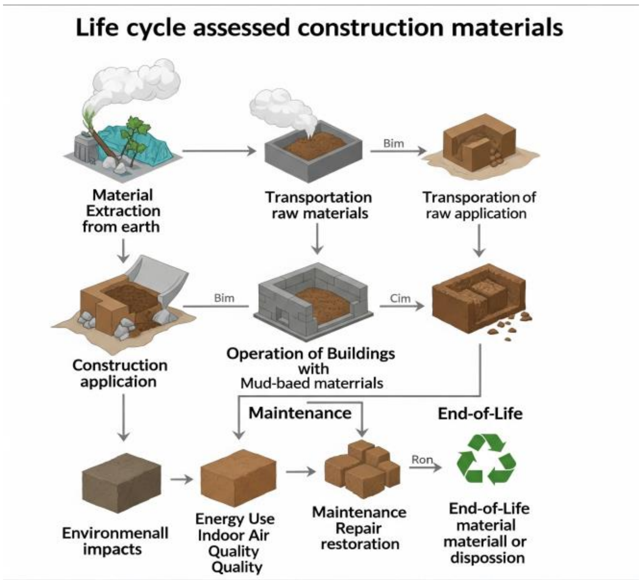

Fig2. Diagram illustrating the life cycle assessment phases for mud-based construction materials, including material extraction, construction, operation, maintenance, and end-of-life.

in soil properties across geographic regions [8]. Global LCI databases often lack localized data for mud-based materials, leading to discrepancies in embodied carbon estimates [23]. For example, soil with high clay content may require different stabilization ratios, affecting LCA outcomes [15]. Integrating BIM with LCA can automate data collection and impact assessments, enhancing scalability and precision [6]. AI-driven tools, as explored in [24], predict missing LCI data points, improving reliability, while standardized methodologies proposed in [21] aim to harmonize LCA practices across diverse contexts. Addressing these challenges is essential for accurate environmental assessments and broader adoption.

III(D). INTEGRATION OF VISUALIZATION AND LCA

The integration of visualization and Life Cycle Assessment (LCA) optimizes mud-based construction by merging design precision with environmental analysis. Building Information Modelling (BIM)-LCA APIs enable real-time impact assessments during the design phase, allowing architects to select low-impact materials, optimize structural configurations, and predict long-term performance [6]. For example, a BIM model of a compressed earth block (CEB) building linked to an LCA database can estimate embodied carbon, facilitating data-driven decisions to reduce environmental footprints by up to 25% [8]. Visualization tools, including 3D rendering, AR, and emerging VR platforms, communicate LCA results through intuitive graphs, models, and immersive simulations, enhancing stakeholder understanding and engagement [4], [25].

A practical application in [6] involved a BIM-LCA workflow for a rammed earth community center, where real- time analysis reduced embodied carbon by 25% through optimized stabilizer use and wall thickness adjustments. Similarly, [4] used 3D visualizations to present LCA results for an adobe school, increasing project approval rates by 30% due to improved comprehension of environment benefits. Another study in [25] developed interactive dashboards to display LCA metrics, enabling clients to visualize trade-offs between material choices, costs, and carbon emissions. AR applications allow on-site visualization of LCA-driven designs, enabling real-time adjustments during construction [16]. These approaches support sustainable urban development by aligning design and environmental objectives [11], with future VR integration promising enhanced stakeholder collaboration [22].

Despite these benefits, significant challenges persist. Data interoperability between BIM and LCA platforms limits automation, requiring manual data inputs that reduce efficiency [13]. The lack of region-specific life cycle inventory (LCI) databases for mud-based materials leads to variability in LCA outcomes, undermining reliability [20], [23]. Soil composition differences across regions affect embodied carbon estimates, yet global LCI databases rarely account for these variations [21]. The limited ap- plication of AI to mud-based LCAs restricts scalability, as most AI tools are designed for industrialized materials [24]. These findings highlight the need for standardized LCI frameworks, mud-specific digital tools, and enhanced data integration to overcome barriers and promote sustainable construction practices [15], [18].

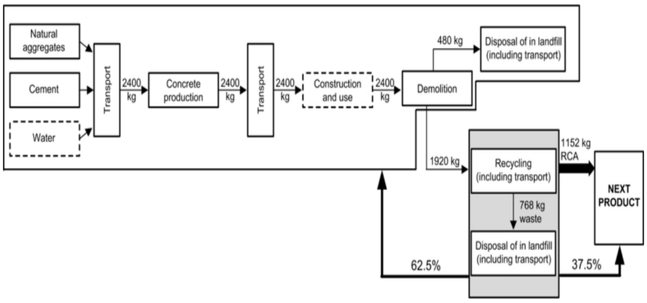

Fig. 3. Flowchart for Integration of Visualization and LCA

The workflow for integrating visualization and LCA is illustrated in the following flowchart, providing a visual representation of the process from design optimization to environmental impact assessment. Optimized stabilizer use and wall thickness adjustments. Similarly, [4] used 3D visualizations to present LCA results for an adobe school, increasing project approval rates by 30% due to improved comprehension of environment benefits. Another study in [25] developed interactive dashboards to display LCA metrics, enabling clients to visualize trade-offs between material choices, costs, and carbon emissions. AR applications allow on-site visualization of LCA-driven designs, enabling real-time adjustments during construction [16]. These approaches support sustainable urban development by aligning design and environmental objectives [11], with future VR integration promising enhanced stakeholder collaboration [22].

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The workflow for integrating visualization and LCA is illustrated in the following flowchart, providing a visual representation of the process from design optimization to environmental impact assessment.

V. Future Scope

The future scope of mud-based construction is vast, with opportunities to revolutionize sustainable building practices through targeted advancements and interdisciplinary collaboration. A primary focus should be the development of standardized life cycle inventory (LCI) databases tailored to mud-based materials, incorporating regional soil variations, stabilizer types, and climatic conditions to ensure accurate and reliable LCA outcomes [21], [23]. This requires establishing global consortia to collect and vali- date data from diverse geographic regions, addressing the current lack of localized LCI data [20]. Expanding Building Information modelling (BIM) applications to include mud specific modules could enhance design efficiency, enabling architects to simulate soil-specific properties, optimize stabilizer ratios, and predict long-term performance under varying loads and weather patterns [6], [14].

Innovative solutions should leverage artificial intelligence (AI) to automate LCI data collection and predict missing data points, reducing manual effort and improving LCA scalability [24]. Virtual reality (VR) platforms offer immersive design simulations, allowing stakeholders to experience mud-based structures virtually, test environmental resilience, and refine designs before construction [22]. For instance, VR could simulate flood resistance or thermal performance in real-time, enhancing decision-making for climate-resilient buildings [19]. Collaborative research initiatives should develop open-access LCI databases and VR tools, fostering global knowledge sharing and capacity building in mud-based construction [17 Policy-oriented studies are critical to address regulatory barriers, advocating for updated building codes that recognize the structural reliability and sustainability of mud- based techniques [12]. Pilot projects in urban and rural settings could demonstrate scalability, integrating BIM- LCA workflows with local communities to ensure cultural relevance and economic viability [11]. The integration of renewable energy systems, such as solar panels, with mud-based structures could further reduce operational emissions, aligning with net-zero targets [8]. Long-term, these advancements could position mud-based construction as a leading paradigm in sustainable architecture, particularly in developing countries where local materials are abundant, driving economic development and environmental conservation on a global scale [15]. This future scope envisions a transformative shift toward resilient, low carbon built environments, supported by cutting-edge technology and inclusive policy frameworks.

IV. CONCLUSION

Mud-based construction techniques, including adobe, rammed earth, and compressed earth blocks (CEB), offer substantial environmental and economic benefits, position-ing them as viable alternatives to conventional materials like concrete and steel. The comprehensive literature re- view and case study analysis confirm their potential to reduce embodied carbon by 60–70

However, significant hurdles remain, including data interoperability issues, the absence of region-specific life cycle inventories (LCIs), and limited AI integration for mud-based materials [13], [23], [24]. These barriers hinder scalability and adoption, particularly in urban settings where regulatory frameworks favor industrialized materials [12]. The integration of BIM with LCA, supported by advanced visualization and AI-driven tools, offers a trans- formative approach to overcome these challenges, enabling precise environmental assessments and optimized designs [8], [25]. This study provides a comprehensive roadmap for architects, engineers, policymakers, and construction

stakeholders to mainstream mud-based techniques, con-tributing to global sustainability goals, including net-zero carbon targets by 2050 [11]. Furthermore, the successful implementation of these methods could inspire innova- tive building practices in developing regions, where local materials are abundant, fostering economic growth and environmental stewardship. The findings underscore the need for continued investment in research, policy reform, and technology development to fully realize the potential of mud-based construction in a sustainable future.

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