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PERFORMANCE INDICATORS FOR BIOMIMICRY-BASED CONSTRUCTION MATERIALS AND THEIR OPERATIONALISATION THROUGH AUGMENTED REALITY: A SYSTEMATIC LITERATURE REVIEW

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ABSTRACT

Biomimicry-based construction materials are nature-inspired materials designed to replicate biological structures, processes, and ecosystem functions to enhance sustainability and building performance. Construction plays a major role in global carbon emissions, and construction materials account for a significant proportion of embodied environmental impacts. Therefore, it is understood that biomimicry-based construction materials have been gaining popularity as replacement materials. Thus, the study highlights the need for addressing the gaps in enhanced effectiveness in early stages of decision-making for the biomimicry-based construction materials. Existing studies predominantly evaluate biomimicry-based materials in isolation, while integrated frameworks capable of operationalising environmental, functional, and aesthetic performance indicators through accessible digital decision-support mechanisms remain limited. Accordingly, this study aims to synthesise multidimensional material performance indicators and examine how minimal Augmented Reality (AR)-based visualisation can support early-stage material selection. Furthermore, the relevant literature retrieved is subjected to qualitative content analysis. Therefore, the study highlights aspects of environmental, functional, and aesthetic-perceptual performance indicators, which have been explored as separate domains. Furthermore, the study highlights the unsatisfactory utilisation of augmented reality for visualising sustainability. Therefore, the study proposes a conceptual approach to deliver enhanced effectiveness for visualising augmented reality-based biomimicry-based construction materials.

Keywords: *Augmented reality; Biomimicry; Construction Materials; Decision-Support Systems; Systematic Literature Review.*

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1. INTRODUCTION

The early-stage selection of construction materials critically influences the sustainability, performance, and lifecycle outcomes of building projects (Ahamed et al., 2022). Biomimicry-based materials, inspired by natural systems, offer significant potential to enhance environmental performance, functional efficiency, and aesthetic quality (Rosario et al., 2023). However, their adoption in practice remains limited, primarily due to fragmented evidence, inaccessible performance data, and the complexity of comparing multiple material attributes during the design phase (Nielsen et al., 2016). Existing studies frequently focus on isolated technical properties, such as embodied Carbon reduction or thermal performance, without integrating these into holistic decision-making frameworks that consider functional, aesthetic, and sustainability dimensions concurrently (Iroegbu & Ray, 2021; Mumcu & Korkmaz, 2025). Moreover, digital tools, including AR, have been applied in construction mainly for visualisation, assembly guidance, or training, rather than as a lightweight decision-support mechanism for material selection (Berryman, 2012). This highlights a critical gap: there is currently no structured approach to operationalise multidimensional performance indicators for biomimicry-based materials in a stakeholder-accessible format that supports early-stage decision-making (Han et al., 2018).

To address this gap, this study adopts a Systematic Literature Review (SLR) methodology, recognised for its rigor in synthesising prior knowledge and identifying conceptual, methodological, and empirical gaps (Briner & Denyer, 2012.; Siddaway et al., 2024). The SLR enables a transparent and reproducible mapping of the interdisciplinary evidence base, encompassing materials science, sustainability assessment, and digital visualisation (Zari & Hecht, 2020). The review focuses on identifying key indicators across environmental, functional, and aesthetic-perceptual dimensions and evaluating the extent to which AR and digital decision-support mechanisms have been applied to facilitate informed material selection (Shufrin et al., 2023; Wang et al., 2025). By systematically analysing peer-reviewed studies from 2016 to 2026, the SLR provides a defensible basis for developing a conceptual framework that integrates these performance indicators into a practical, AR-assisted decision-making process.

Accordingly, the study aims to answer the following research question:

How can environmental, functional, and aesthetic performance indicators of biomimicry-based construction materials be operationalized through minimal AR-based visualization to support effective early-stage decision-making among diverse construction stakeholders?

The SLR-driven approach not only identifies the indicators most relevant to biomimicry-based material performance but also reveals critical shortcomings in existing decision-support practices related to operationalisation, stakeholder communication, and technological facilitation. Building upon these findings, the study proposes a conceptual framework that differs from conventional material selection models by integrating sustainability performance indicators with minimal AR-based visualisation to support interactive comparison, stakeholder engagement, and evidence-based decision-making during early design stages (Ngaba et al., 2025). The framework, therefore contributes a novel pathway for bridging the gap between material performance assessment and practical material selection within sustainable construction contexts.

2. RESEARCH METHODOLOGY

This study adopted a SLR approach, widely recognised as a fundamental component of rigorous research, which enables the structured synthesis of prior knowledge while identifying conceptual, methodological, and empirical gaps within an emerging research domain (Petticrew & Roberts, 2006). Systematic reviews are particularly suitable for consolidating fragmented research fields and supporting theory and framework development through transparent and reproducible procedures (Man et al., 2024). According to Briner and Denyer (2012), a systematic review must: (1) follow a clearly defined and structured process; (2) employ a transparent and well-documented methodology; (3) be reproducible and capable of being updated; and (4) synthesize evidence relevant to the core research problem. These principles ensure methodological robustness and reduce selection bias. Snyder (2019), further conceptualised the SLR process into three overarching phases: (i) planning, (ii) conducting, and (iii) reporting, which were later operationalised into a practical seven-step guideline for social science research by Petticrew and Roberts (2006). This study strictly adhered to these established methodological guidelines in conducting the systematic review (Briner & Denyer, 2012). The selected approach ensures that the review process is methodical, transparent, and repeatable, while maintaining a strong alignment between the research aim and the analytical outcomes (Riani et al., 2025). The SLR methodology was adopted as this study seeks to develop a conceptual framework to support biomimicry-based construction material selection using augmented reality-assisted visualisation, which requires the structured integration of multidisciplinary evidence spanning materials science, sustainability assessment, and digital decision-support technologies.

2.1 DATA COLLECTION AND DATA CLEANING

The systematic review began with the primary research question: *How can sustainability and environmental performance information of biomimicry-based construction materials be operationalized through minimal AR-based visualization to support early-stage decision-making among diverse construction stakeholders?*

A comprehensive keyword search string was developed covering four domains: (1) biomimicry and nature-inspired design, (2) construction and building materials, (3) sustainability and environmental performance indicators, and (4) AR-based visualisation and decision-support tools. A pilot review identified alternative keywords and synonyms. Boolean operators (“AND”, “OR”) and wildcards (“*”) were applied to maximise retrieval sensitivity. The final search string was: (("Biomimicry" OR "Bio-inspired" OR "Nature-inspired") AND ("Construction material" OR "Building material" OR "Green building material*") AND ("Sustainability" OR "Embodied carbon" OR "Environmental performance") AND ("Augmented Reality" OR "AR" OR "Minimal AR" OR "Visualization" OR "Decision support")) *

The search was applied to Scopus and Web of Science for their coverage of high-impact literature in construction, sustainability, and digital technology. Inclusion criteria limited results to titles, abstracts, and keywords; publications from 2016 to 2026; peer-reviewed journals, conferences, reviews, and book chapters; and English-language sources. Grey literature was excluded. The review period from 2016 to 2026 was selected to capture the emergence and rapid development of biomimicry-based material innovation and AR-assisted decision-support applications within construction research. Records were exported to CSV, imported into Mendeley, and duplicates removed. Titles, abstracts, and full texts were screened to exclude studies unrelated to biomimicry materials, sustainability, or AR decision-support. Studies without empirical relevance or explicit linkage between biomimicry materials, sustainability, and AR visualisation were excluded, resulting in a focused, methodologically justified dataset suitable for framework development. Backward and forward snowball searching was conducted following the initial database screening stage to identify additional relevant studies from reference lists and citation networks. Duplicate records identified during snowball searching were removed through Mendeley reference management software prior to full-text screening.

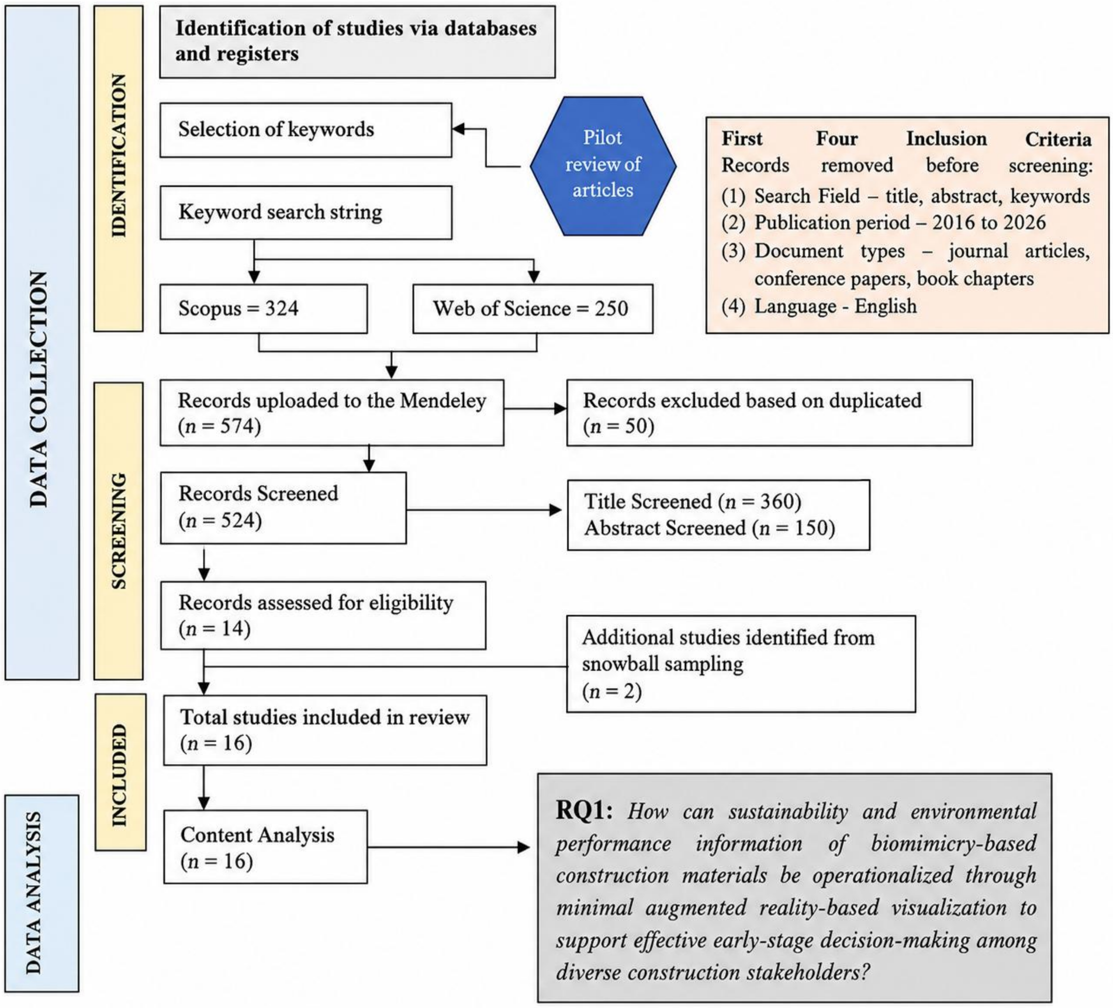

Figure 1: Overview of research methodology

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework guided the literature screening and selection process illustrated in Figure 1.

2.2 DATA ANALYSIS

As the subsequent step, the findings of the selected studies were synthesised using a qualitative content analysis technique (Briner & Denyer, 2012). Content analysis enables the systematic interpretation of textual data through the identification of recurring patterns, themes, and relationships, making it particularly suitable for exploratory and framework-building research (Moher et al., 2007).

The analysis was conducted manually, without the use of qualitative analysis software. Manual analysis allowed deeper interpretive engagement with the studies and facilitated the identification and exclusion of conceptually weak or methodologically limited evidence, thereby prioritising high-quality insights (Toyin et al., 2025). Each study was coded based on key dimensions, including: (i) type of biomimicry-based construction material, (ii) sustainability and environmental performance indicators, decision-support or visualization methods employed, and (iii) the role of augmented or minimal AR in facilitating stakeholder understanding. The synthesised findings were systematically organised and reported in the results section of this study (Börner et al., 2012). An overview of the research methodology and screening process is illustrated using a PRISMA flow diagram, developed in accordance with the PRISMA guidelines to ensure transparency, completeness, and reproducibility (Sohrabi et al., 2021).

The final sample size of 16 studies was considered methodologically appropriate due to the highly focused and interdisciplinary nature of the review topic, which combines biomimicry-based materials, sustainability indicators, and AR-assisted decision-support systems. Similar niche construction management SLR studies have employed focused datasets to support conceptual framework development and thematic synthesis.

3. FINDINGS

3.1 OVERVIEW OF THE INCLUDED STUDIES

The final set included studies comprised of peer-reviewed journal articles, review papers, conference proceedings, and book chapters published between 2016 and 2026, reflecting the growing scholarly interest in biomimicry-based construction materials and sustainability-driven innovation in the built environment (Zari & Hecht, 2020). The reviewed publications were predominantly drawn from journals in materials science, construction engineering, sustainability, biomimetics, and digital construction, highlighting the interdisciplinary nature of the research domain. While a substantial proportion of studies focused on material development and performance optimisation, relatively fewer addressed issues related to material selection, stakeholder decision-making, or communication at the early design stage.

The results of the systematic review revealed 16 publications pertaining to biomimicry-based constructing materials of value for Green building applications. The results of the publications, based on initial research from 2020 to 2022, essentially focused on the assessment of green building performance criteria, which included carbon, biodegradability, and carbon sequestration. As of 2023, the investigations accounted for a wide array of performance criteria, which included thermal resistance, fire safety, durability, and cost. This denotes the fact that stakeholders dealing with green building applications began to understand, from the perspective of biomimicry-based materials, the need to evaluate their effectiveness, both with regard to functionality and the environment. From these scholarly findings, it is ascertainable that biomimicry-based materials, which include bio-cement, mycelium, and algae, had application for green building applications.

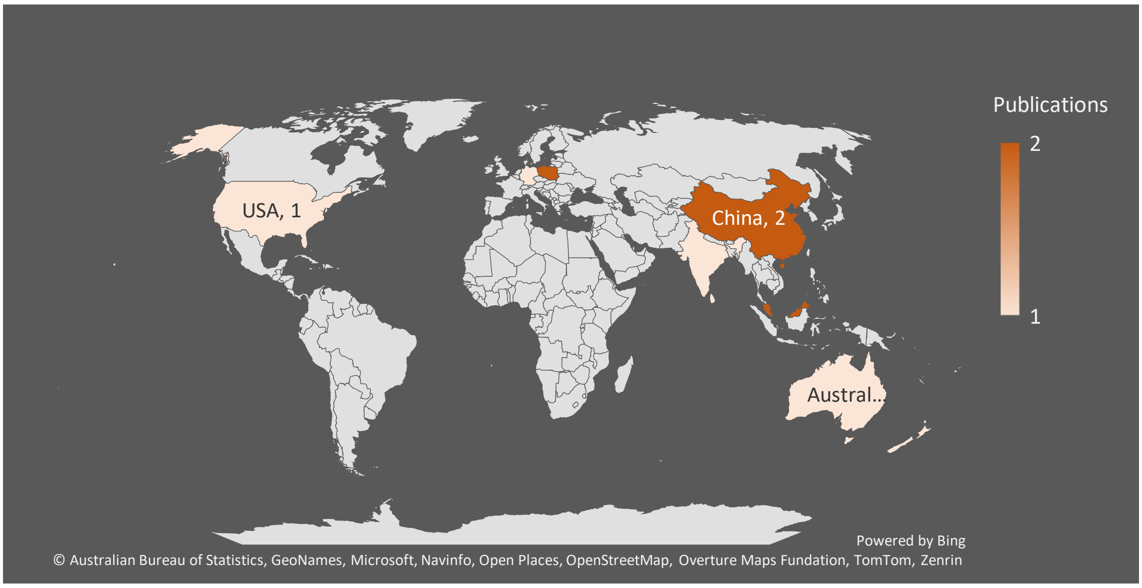

Figure 2: Worldwide distribution map of publications.

From 2024 to 2025, these publications grew exponentially, thus revealing models of research from different parts of the world, including Poland, Germany, China, Malaysia, Sri Lanka, New Zealand, the USA, India, concerning their interest in green building applications as demonstrated in Figure 2.

3.2 BIOMIMICRY-BASED CONSTRUCTION MATERIALS ADDRESSED IN LITERATURE

Analysis of the included studies revealed that biomimicry-based construction materials are primarily investigated within three broad categories. A significant body of research concentrates on bio-cementitious and self-healing materials, including microbially induced calcite precipitation, enzyme-based binders, and biologically enhanced concrete systems (Amran et al., 2022). These studies consistently report improvements in durability, crack-healing capacity, and reductions in embodied carbon when compared to conventional cementitious materials. Another prominent stream of research focuses on biogenic and bio-derived materials such as mycelium composites, algae-based systems, bamboo, cellulose-based materials, and biochar-enhanced composites (Abdelhady et al., 2023). These materials are frequently associated with benefits such as Carbon sequestration, biodegradability, lightweight construction, and improved thermal performance, particularly in non-structural or envelope applications. A smaller yet emerging set of studies explores nature-inspired surface treatments and adaptive material systems that mimic biological processes such as self-cleaning, moisture regulation, and energy optimisation. Despite the demonstrated environmental and functional advantages, the majority of studies examine these materials in isolation, without embedding them within comparative frameworks that support real-world material selection or design decision-making.

3.3 SUSTAINABILITY AND ENVIRONMENTAL PERFORMANCE INDICATORS

The reviewed literature employs a wide range of sustainability and environmental performance indicators to evaluate biomimicry-based construction materials. Embodied carbon and greenhouse gas emission reduction potential emerge as the most frequently reported metrics, particularly in studies comparing bio-based materials to conventional concrete, insulation, or composite systems. Several studies extend beyond embodied carbon to consider lifecycle performance, including durability, maintenance reduction, and end-of-life biodegradability. Thermal performance, energy efficiency, and material efficiency are commonly assessed, especially for envelope-related applications. However, the analysis reveals considerable inconsistency in indicator selection and reporting formats across studies. Sustainability data are predominantly presented in technical, numerical, or tabular forms, often requiring specialist knowledge to interpret. As a result, the potential of these indicators to inform early-stage design decisions among diverse stakeholder groups remains limited.

3.4 DECISION-SUPPORT APPROACHES IN BIOMIMICRY-BASED MATERIAL RESEARCH

Only a limited number of studies explicitly address decision-support mechanisms for biomimicry-based construction materials. Where decision-support is considered, it is typically embedded within advanced engineering models, optimisation algorithms, or artificial intelligence-based assessment tools. While these approaches offer analytical rigor, they often lack accessibility and are unsuitable for rapid, concept-stage material evaluation. Comparative material selection frameworks are rare, and few studies translate sustainability performance data into formats that can support intuitive understanding by architects, clients, or non-technical stakeholders. This indicates a clear disconnect between material innovation research and practical decision-making needs in sustainable building design.

3.5 DIGITAL TECHNOLOGIES AND THE ROLE OF AUGMENTED REALITY

Digital technologies, including building information modelling, artificial intelligence, and simulation-based tools, are addressed in several studies; however, their application is largely oriented toward performance optimisation rather than communication or decision support. Augmented reality is predominantly applied in construction training, assembly guidance, or design visualisation contexts. The review found only limited exploration of AR as a tool for supporting sustainable material selection. Moreover, existing AR applications tend to rely on complex, resource-intensive systems, which limit their suitability for early-stage, low-barrier decision-making. Notably, no study was identified that integrates biomimicry-based material evaluation, sustainability indicators, and minimal or lightweight AR visualisation within a unified decision-support framework.

3.6 SYNTHESIS OF KEY RESEARCH GAPS

The synthesis of findings across the reviewed studies reveals three interrelated gaps. First, there is an operational gap, whereby biomimicry-based materials demonstrate strong sustainability potential but lack structured tools to support systematic comparison and selection during early design stages. Second, communication gaps persist, as sustainability and embodied carbon information are rarely presented in intuitive or visually accessible formats that cater to diverse stakeholder groups. Third, a technological gap is evident, as the potential of minimal augmented reality to function as a lightweight decision-support mechanism for sustainable material selection remains largely unexplored. The reviewed literature collectively demonstrates that while biomimicry-based materials exhibit strong sustainability and functional potential, existing studies remain technologically fragmented and insufficiently operationalised for stakeholder-oriented decision-making. This indicates the absence of lightweight, cognitively accessible frameworks capable of translating multidimensional material performance into comparative design-stage evaluation environments.

Using a case diagram in Figure 3 is a graphical representation to explain the interactions between users (decision-makers / project stakeholders) and the AR-based material selection process.

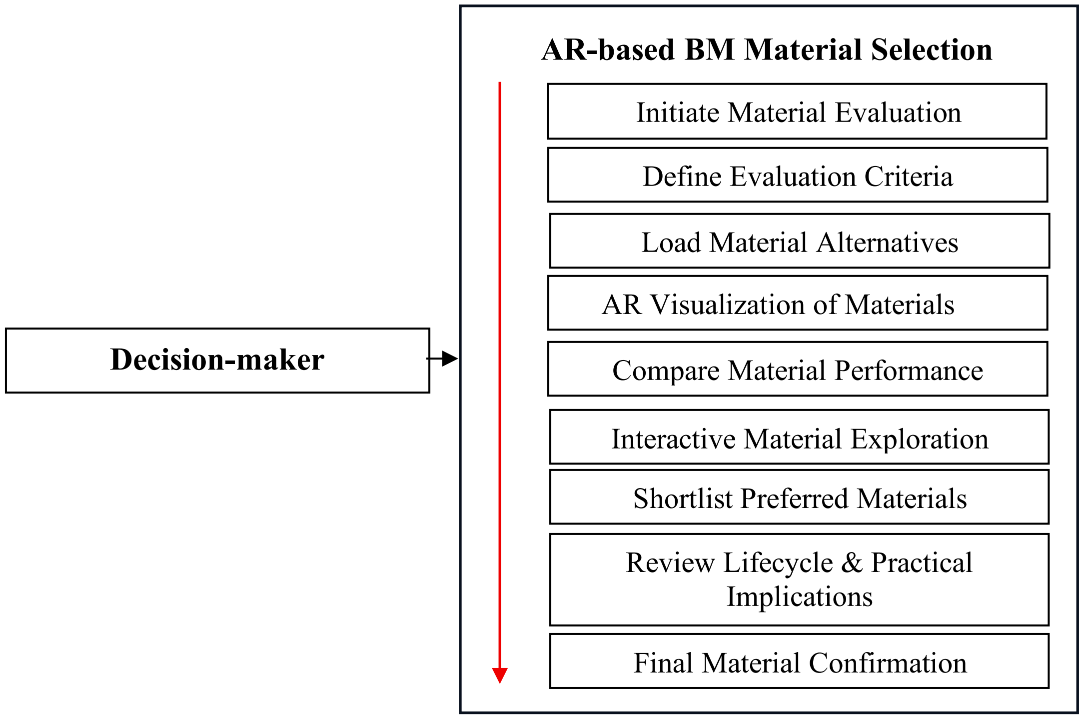

Figure 3: User case diagram for AR-based visualization

First, the user must access the Google account or Microsoft account to the application. The successfully logged-in users can access the database by navigating through primary views and main views. The system validates the user credentials and then allows authorised users to access the specific detailed design and real-time data. Through this application, users can access visualisations of Biomimicry and conventional materials, detailed designs, AR visualization instructions, and generate a detailed report.

3.7 IMPLICATIONS FOR CONCEPTUAL FRAMEWORK DEVELOPMENT

These findings directly informed the development of a conceptual framework to support the effective adoption of biomimicry-based construction materials. By synthesising evidence from materials science, sustainability assessment, and digital visualization research, the framework integrates material attributes, sustainability indicators, stakeholder decision-making needs, and minimal AR-based visualisation mechanisms. This framework addresses the identified gaps and provides a structured basis for enhancing early-stage material decision-making in sustainable building design.

3.8 CONCEPTUAL FRAMEWORK FOR THE MATERIAL SELECTION WITH LIMITED AUGMENTED REALITY BASED ON PERFORMANCE INDICATORS

The conceptual framework outlines the evaluation and selection of biomimicry-based construction materials through an AR-assisted decision-making process. Material assessment serves as the primary input, with AR visualisations aiding stakeholders in informed decision-making (Sparks et al., 2024).

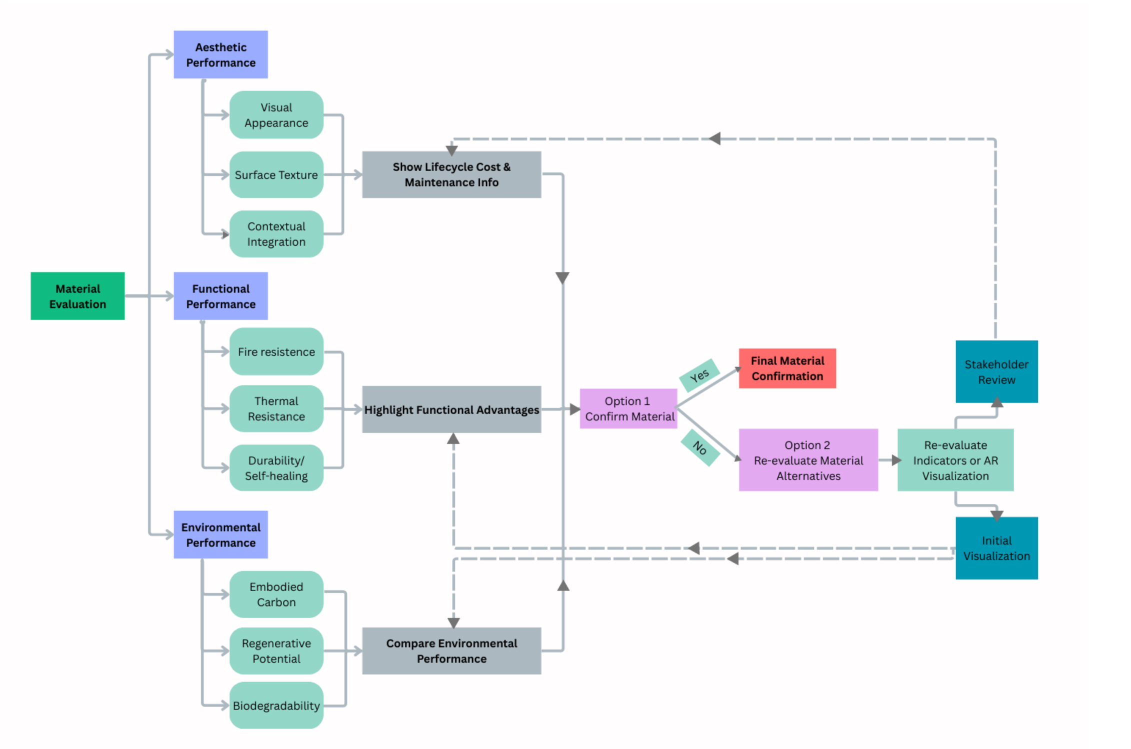

Figure 4: Conceptual framework

Stakeholders actively interact with the AR interface throughout the evaluation process, using visualised information to compare material alternatives and support selection decisions. Material evaluation is structured around three intertwined performance areas: aesthetic, functional, and environmental. Aesthetic performance is assessed via visual appearance, surface texture, and contextual integration, relevant to early design stages. Functional performance considers fire resistance, thermal resistance, and durability or self-healing capacity, reflecting safety, comfort, and long-term usability. Environmental performance is measured through embodied carbon, regenerative potential, and biodegradability, addressing sustainability implications.

These indicators are integrated through AR-mediated analysis, transforming complex performance data into interactive visualisations. AR supports comparative assessment of environmental performance, synthesises functional indicators for trade-off analysis, and links aesthetic and lifecycle factors to maintenance and cost information. Initial AR visualisation acts as a cognitive entry point, helping stakeholders make sense of data before technical review.

The framework introduces two decision pathways: one leading to final material confirmation, and another allowing re-evaluation of alternatives, reflecting real-world iterative behavior. At the decision stage, stakeholders assess the AR-supported comparisons and either confirm a material choice or revisit alternative options for further evaluation. By combining comparison, iteration, and confirmation, it prevents premature decisions and ensures that at least two alternatives are considered. AR functions as more than a visualisation tool; it mediates complex performance and sustainability information for diverse stakeholders.

4. CONCLUSIONS

This study systematically reviewed the literature on biomimicry-based construction materials, their performance indicators, and the potential role of AR in supporting material selection decisions. The review identified that existing research predominantly evaluates biomimicry-based materials based on environmental, functional, or aesthetic performance criteria in isolation, with limited attention given to integrated decision-support approaches. Furthermore, while AR technologies have been increasingly applied within construction, their use has been largely confined to visualisation, training, and assembly-related applications rather than material evaluation and selection.

The findings revealed three key gaps within the current body of knowledge. First, there is an operational gap resulting from the absence of structured approaches for comparing biomimicry-based materials during early-stage design decision-making. Second, a communication gap exists because material performance information is commonly presented in technical formats that may be difficult for diverse stakeholders to interpret. Third, a technological gap was identified, as the application of lightweight AR as a decision-support mechanism for sustainable material selection remains largely unexplored. To address these gaps, the study developed a conceptual framework that integrates environmental, functional, and aesthetic performance indicators within an AR-assisted material selection process. The framework demonstrates how AR can be used to communicate multidimensional material performance information through interactive visualisations that support comparison, stakeholder engagement, and iterative decision-making. By incorporating alternative evaluation and re-evaluation pathways, the framework reflects the iterative nature of real-world material selection processes. The study contributes to the growing body of knowledge on sustainable construction materials by synthesising dispersed evidence across biomimicry, material performance assessment, and digital visualisation research. Practically, the framework provides a foundation for developing accessible digital tools that can support stakeholders in understanding and comparing biomimicry-based material alternatives during the early stages of project development. As the framework has been developed through literature synthesis, future research should focus on its empirical validation through expert evaluation, stakeholder workshops, and prototype implementation. Further studies may also investigate the effectiveness of smartphone-based AR applications in improving stakeholder understanding, decision quality, and adoption of biomimicry-based construction materials within real project environments.

5. RESEARCH CONTRIBUTIONS

This study contributes to the sustainable construction literature by synthesising fragmented knowledge on biomimicry-based construction materials, material performance indicators, and augmented reality-assisted decision-support approaches. The review identifies environmental, functional, and aesthetic performance indicators commonly used to evaluate biomimicry-based materials and highlights the challenges associated with their communication and application during early-stage material selection. Conceptually, the study proposes an integrated framework that brings together these multidimensional performance indicators within an AR-assisted decision-making process. The framework responds to the operational, communication, and technological gaps identified in the literature by illustrating how material performance information can be structured and presented in a more accessible manner for stakeholder evaluation.

From a practical perspective, the framework provides a foundation for the future development of decision-support tools that may assist stakeholders in comparing biomimicry-based and conventional material alternatives during the design stage. By emphasising visualisation and comparative assessment, the framework highlights opportunities to improve the communication of sustainability-related material information. The study contributes to the emerging discussion on the role of AR in sustainable construction by extending its application beyond training and visualisation contexts and exploring its potential as a lightweight decision-support mechanism for material evaluation. As the framework was developed through systematic literature synthesis, its contribution is primarily conceptual. Future research is required to validate the framework through stakeholder evaluation, prototype development, and real-world implementation studies.

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