LivaS INTERNATIONAL JOURNAL ON LIVABLE SPACE
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TOWARD LOW-CARBON TROPICAL BUILDINGS: A SYSTEMATIC REVIEW OF BIO-BASED WASTE MATERIALS FOR THERMAL INSULATION

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ABSTRACT

Aims: This study aims to analyze experimental approaches used to evaluate the thermal insulation performance of bio-based wall materials derived from agro-industrial waste, with a specific focus on Palm Oil Fuel Ash (POFA) and eggshell powder, in the context of sustainable tropical building applications.
Methodology and results: This study employed a **Systematic Literature Review (SLR)** consisting of three primary stages: a comprehensive search across reputable databases (Scopus, ScienceDirect, and Google Scholar), article selection based on predefined inclusion criteria, and thematic analysis of 78 eligible studies. The review focused on experimental methods for evaluating thermal performance, including thermal conductivity (Hot Disk, Guarded Hot Plate), specific heat capacity (DSC), surface reflectance (UV-VIS), and chemical-microstructural analyses (TGA, SEM-EDS, XRD). Findings indicate that POFA and eggshell powder exhibit thermal conductivity values between 0.12–0.25 W/m·K, attributed to microporous structures and high SiO_2 or $CaCO_3$ content. Nonetheless, the integration of these laboratory findings with building energy simulations and the consideration of tropical, specific variables, such as humidity and solar radiation, remains notably limited in existing literature.
Conclusion, significance and impact study: This study identifies critical methodological gaps in current research on bio-based thermal insulation materials and underscores the need for a more integrated evaluation framework. Specifically, it recommends combining laboratory testing with building energy simulation to enhance the validity and applicability of findings. Such an approach is essential for advancing the reliable implementation of agro-industrial bio-waste materials, such as POFA and eggshell powder, in sustainable tropical architecture. The proposed integration not only strengthens the scientific foundation of material

MANUSCRIPT HISTORY

Received
June 19, 2025
Revised
August 8, 2025
Accepted
August 25, 2025

KEYWORDS

- bio-based waste materials,
- thermal insulation
- palm oil fuel ash
- egg shell powder
- tropical building

performance assessment but also contributes to more climate-responsive and low-carbon building design strategies in the Global South.

1. INTRODUCTION

In the pursuit of sustainable architectural practices in tropical regions, the use of bio-based thermal insulation materials has gained significant attention due to their environmental benefits and potential for local resource utilization. Evaluating the thermal performance of these materials, particularly for wall applications, requires an experimental approach that not only adheres to standard testing procedures but is also scalable and relevant to tropical climatic conditions, where high humidity, solar radiation, and temperature fluctuations significantly influence building energy performance [1,2] .

Commonly employed experimental methodologies for thermal characterization include thermal conductivity testing, specific heat capacity measurement, solar reflectance analysis, and microstructural observations. Standard instruments such as the Guarded Hot Plate (ISO 8302), Heat Flow Meter (ASTM C518), and Transient Plane Source (Hot Disk, ISO 22007-2) are widely used, each offering different levels of sensitivity depending on material properties [3,4]. Furthermore, Thermogravimetric Analysis (TGA), Scanning Electron Microscopy with Energy Dispersive Spectroscopy (SEM-EDS), and X-ray Diffraction (XRD) are applied to examine the thermal stability, composition, and phase transformation of material components.

Among the bio-based materials explored, Palm Oil Fuel Ash (POFA) and eggshell powder have been recognized for their promising thermal insulation characteristics. The high silica (SiO_2) content in POFA and calcium carbonate ($CaCO_3$) content in eggshells contribute to the development of porous microstructures, which reduce thermal conductivity by slowing heat transfer [5]. Additionally, the reflective properties of material surfaces, measured via UV-VIS-NIR spectrophotometry, influence solar heat gain [6], while the specific heat capacity (Cp) measured by Differential Scanning Calorimetry (DSC) provides insight into the material's thermal storage behavior [7].

Despite these advancements, current experimental studies often remain limited to laboratory-scale analysis, with insufficient integration into real-world tropical building contexts. For instance, environmental factors such as high humidity, rainfall, and diurnal solar radiation variation are rarely incorporated into the test design [8]. Consequently, the applicability of these materials for actual energy savings in buildings remains underexplored. Integrating laboratory results with building energy simulation tools is therefore essential to predict the

p-ISSN 2580-7552; e-ISSN 2548-7515, Volume10, Number 2, pp 91 – 108, 2025

materials' true impact on thermal comfort and energy efficiency in a realistic and climate-responsive manner [9].

This study aims to critically review the range of experimental approaches applied in evaluating the thermal performance of bio-based insulation materials, with a specific focus on POFA and eggshell powder. It further seeks to identify the extent to which laboratory findings have been translated into building-level performance simulations, highlighting existing methodological gaps and opportunities for improvement. The expected outcome is a clearer understanding of how bio-based materials can be assessed more holistically, thereby contributing to the development of low-carbon, thermally efficient, and climate-adaptive buildings in tropical regions.

2. RESEARCH METHODOLOGY

This study utilized a Systematic Literature Review (SLR) to critically analyze experimental and simulation methods used in assessing bio-based wall materials for thermal insulation in tropical buildings. The SLR approach was chosen for its ability to synthesize existing knowledge, ensure methodological transparency, and reveal trends and gaps across diverse academic disciplines. It provided a rigorous framework for integrating findings from material science, architecture, and environmental engineering. Specifically, the SLR helped map how materials like Palm Oil Fuel Ash (POFA) and eggshell powder have been evaluated, while highlighting inconsistencies and overlooked areas, particularly in linking lab data with building energy simulations for tropical climates.

The review process was conducted in three main stages (as seen in Fig.1): (1) literature search, (2) article selection and screening, and (3) content analysis and thematic classification. In the first stage, a comprehensive search was performed across multiple reputable academic databases—Scopus, ScienceDirect, SpringerLink, and Google Scholar—using a combination of keywords including: *"thermal conductivity," "bio-based materials," "POFA," "eggshell," "tropical buildings," "energy simulation,"* and *"experimental methodology."* To ensure both relevance and recency, the publication timeframe was restricted to 2010–2024.

In the second stage, inclusion and exclusion criteria were applied to filter articles. Studies were included if they: (1) involved experimental testing of bio-based materials, (2) specifically examined POFA and/or eggshell as key material components, (3) measured thermal properties (e.g., conductivity, specific heat, reflectance) or incorporated building energy simulation, and (4) were conducted within a tropical climate context. Articles were excluded if they lacked empirical

p-ISSN 2580-7552; e-ISSN 2548-7515, Volume10, Number 2, pp 91 – 108, 2025

methodology, relied solely on theoretical speculation, or did not provide transparent testing procedures.

By applying this structured SLR process, the study ensures that its analysis is grounded in peer-reviewed, methodologically sound research, thereby strengthening the validity of subsequent evaluations and recommendations for sustainable insulation strategies in tropical architectural practice.

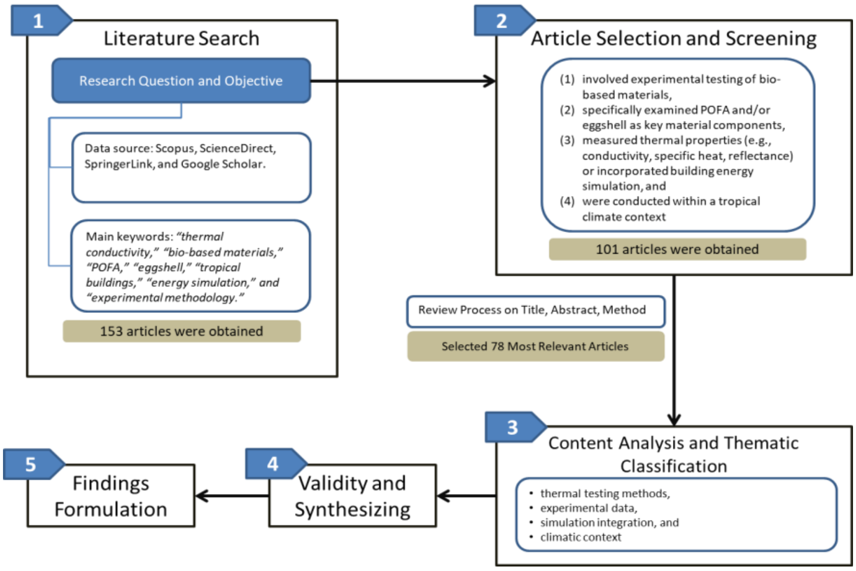

Fig. 1 Systematic Literature Review Workflow.

2.1 Article Selection Process

The article selection process followed a structured procedure to ensure the relevance and quality of the reviewed literature. It began with the formulation of research objectives and questions focused on the experimental evaluation of bio-based insulation materials in tropical architectural contexts. An initial search across multiple academic databases yielded 153 articles, which were then screened based on publication year (2010–2024), accessibility, and thematic relevance, narrowing the dataset to 101 articles.

A more detailed content analysis was conducted to identify studies specifically involving Palm Oil Fuel Ash (POFA) and eggshell powder in relation to thermal insulation in tropical buildings. This resulted in 78 articles deemed eligible for full review. These were then thematically classified according to the authors' disciplinary backgrounds, geographic context, experimental methods, and the integration of laboratory findings with building performance or simulation frameworks. This classification served as the basis for identifying methodological patterns and research gaps in the field.

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2.2 Thematic Analysis

Thematic analysis was conducted across selected studies by examining four key dimensions: thermal testing methods, experimental data, simulation integration, and climatic context. Common testing techniques included Hot Disk (TPS), Guarded Hot Plate, DSC, TGA, UV-VIS-NIR, and SEM-EDS. Reported data focused on thermal conductivity (λ), specific heat capacity (Cp), reflectance, porosity, and microstructural characteristics. Several studies also integrated these results into building energy simulations using tools such as EnergyPlus and DesignBuilder. Attention was given to whether studies addressed tropical climate variables, including high humidity, solar radiation, and natural ventilation, to ensure contextual relevance.

2.3 Validity and Synthesizing

The validity of each thermal testing method was evaluated based on its adherence to recognized international standards, including ISO 8302, ISO 22007-2, and ASTM C518. In addition, test results were assessed for their relevance to thermal performance requirements in tropical buildings. This evaluation formed the basis for a thematic synthesis, which identified methodological trends, gaps in application, and potential for integrating experimental data with building energy simulations. The synthesis provides a foundation for advancing the use of bio-based materials in sustainable and climate-responsive architectural practices.

3. RESULTS AND DISCUSSION

The distribution of data collected in this study can be seen in Figure 2. Of the 78 selected articles, article classification was carried out based on the scientific background of the researchers. The heat map in the FIgure illustrates the distribution of scientific publications related to the utilization of bio-based materials across various disciplines over the past 15 years (2010–2024). The data reveal a dominant contribution from the fields of Civil Engineering and Material Science, particularly in 2020 and 2021, with Civil Engineering recording a peak of 20 publications in 2021 and Material Science reaching 18 in 2020. This indicates a strong research focus on the structural and physical performance of bio-based materials, including their mechanical properties and suitability for construction applications. In contrast, disciplines such as Mechanical Engineering, Environmental Science, and Chemical Engineering contribute more sporadically, reflecting the interdisciplinary nature of bio-based materials research.

p-ISSN 2580-7552; e-ISSN 2548-7515, Volume10, Number 2, pp 91 – 108, 2025

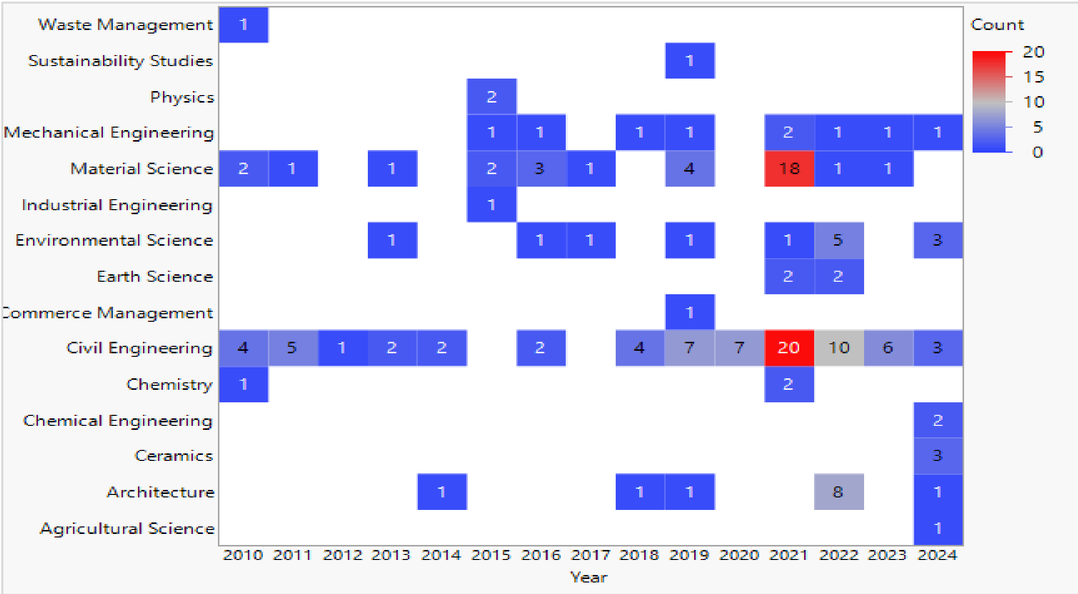

Fig. 2 Heat Maps of Scientific Fields in Bio-based Materials Research over the Last 15 Years.

Notably, the field of Architecture appears only marginally, with publications recorded in 2015 and a modest rise to 8 publications in 2022. This limited representation suggests that architectural research has only recently begun to engage more actively in the discourse on bio-based materials. Given architecture's critical role in integrating material performance with spatial, environmental, and user-oriented design considerations, this gap presents both a challenge and an opportunity. Architectural research can significantly enrich the field by addressing how bio-based materials contribute to passive design strategies, thermal comfort, and sustainable aesthetics—particularly in the context of tropical climates. The observed trend underscores the need for greater interdisciplinary collaboration and highlights the potential for architecture to play a more proactive role in shaping resilient and environmentally responsive building practices using bio-based materials.

Table 1 presents the geographical distribution of research on bio-based waste materials for thermal insulation conducted between 2010 and 2024. The data indicate that Malaysia stands out as the most prominent contributor, with over 45 references, reflecting a sustained and intensive research focus in this area. Other active countries include India, Saudi Arabia, Thailand, and Russia, each contributing multiple studies. These countries appear to have recognized the potential of locally abundant agricultural and industrial by-products—such as palm oil fuel ash (POFA), rice husk, and other biomass residues—as viable thermal insulation materials. In contrast, Indonesia is cited in only one reference, signaling a significant underrepresentation in the global research landscape despite the country's vast availability of bio-based waste. This is particularly noteworthy given Indonesia's rich biomass resources, including palm oil residues, bamboo fibers, coconut husks, and rice husks, all of which are suitable for exploration as sustainable insulation materials.

Table 1 Bio-Based Waste Materials for Thermal Insulation Research by Location (2010–2024)

Location	Distribution	Reference	Location	Distribution	Reference
Bangladesh (1)	1	[10]	Libya	1	[11]
Cameroon	1	[12]	Malaysia	5	[5,10,11,13–60]
Canada	1	[61]	Nigeria	1	[18]
China	1	[62]	Palestine	2	[41,63]
Egypt	2	[62], [64]	Poland	1	[11]
France	1	[25]	Russia	3	[11,36,65]
Indonesia	1	[66]	Saudia	7	[11,36,47,62,63,65,67]
Iraq	3	[41], [22], [68]	South Africa	1	[69]
Jordan	1	[63]	Thailand	2	[70–74]
Lagos	1	[75]	Turkiye	3	[47,65,67]
India	6	[11], [76], [77], [42], [78], [79]	USA	2	[11,67]
			Yemen	3	[36,65,76]

The disparity in publication volume suggests a major research opportunity for Indonesia to expand its contributions, especially within the context of tropical architecture and energy-efficient building design. Given its climatic conditions, Indonesia is well-positioned to develop and test bio-based thermal insulation materials tailored for hot-humid environments. This gap also highlights the need for increased interdisciplinary collaboration and international visibility through scientific publications and partnerships. Indonesia's unique environmental context and resource availability make it a highly relevant, yet underexplored, setting for advancing innovation in sustainable building materials.

2.4 Thermal Performance Characterization

A comprehensive review of thermal testing techniques across the selected studies shows a clear dominance of laboratory-based evaluation methods. Figure 3 presents a summary of thermal and structural testing techniques employed across selected studies investigating bio-based insulation materials. The data clearly reflect a strong preference for laboratory-based characterization methods, underscoring the importance of controlled, precise measurements in evaluating material performance. Among the listed techniques, Thermogravimetric Analysis (TGA) emerges as the most frequently utilized method, appearing in six studies. This highlights the emphasis placed on assessing the thermal stability and decomposition behavior of bio-based composites, particularly those incorporating POFA and eggshell powder.

p-ISSN 2580-7552; e-ISSN 2548-7515, Volume10, Number 2, pp 91 – 108, 2025

Scanning Electron Microscopy (SEM) follows closely with four mentions, indicating the critical role of microstructural examination in explaining the observed insulation properties. Fine and uniform pore distribution—often revealed through SEM—has been repeatedly linked to lower thermal conductivity values, which range between 0.12–0.25 W/m·K, outperforming conventional masonry.

Other common analytical tools include X-Ray Diffraction (XRD) and Fourier Transform Infrared Spectroscopy (FTIR), each employed in three studies, serving to identify crystalline phases and chemical bonding structures. Additionally, X-Ray Fluorescence (XRF) and Field Measurement techniques are applied to examine material composition and validate lab-scale findings in real-world conditions.

While less commonly used, methods like Differential Scanning Calorimetry (DSC), Heat of Hydration testing, and Dilatometry also contribute to understanding heat capacity, thermal expansion, and hydration behavior. Interestingly, simulation software appears in only one instance, suggesting that computational modeling remains underutilized, despite its potential to predict long-term thermal performance in building envelopes.

Overall, the diverse range of methods shown in Figure 3 reflects an increasingly multidisciplinary approach, integrating chemical, thermal, and physical analyses to holistically evaluate bio-based thermal insulation materials. These techniques collectively strengthen the empirical foundation needed to promote wider adoption of such materials in sustainable building design.

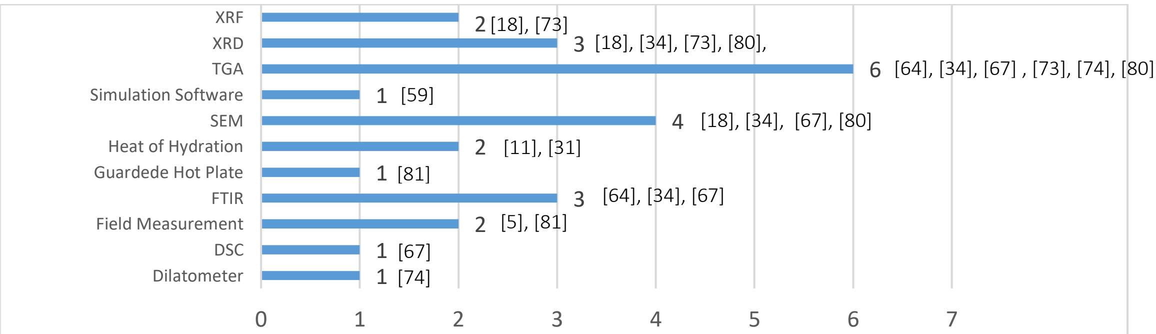

Fig. 3 Thermal Performance Assessment Tools Distribution.

p-ISSN 2580-7552; e-ISSN 2548-7515, Volume10, Number 2, pp 91 – 108, 2025

3. RESULTS AND DISCUSSION

3.1 Distribution of Research Focus by Variable and Method

Analysis of methodological patterns based on dependent variables revealed a clear emphasis on material-level thermal conductivity testing, as shown in Figure 4. While this provides important insights into the intrinsic performance of materials, other important performance indicators-such as operating temperature, thermal mass, and energy demand-remain under-explored. This reflects a methodological gap where the transition from laboratory findings to practical building-level applications remains underdeveloped.

In addition, few studies incorporate simulation-based methods or field testing to contextualise laboratory data in actual building environments. The limited integration of empirical results with simulation frameworks suggests that the real-world application of biobased insulation in tropical buildings remains speculative without further validation.

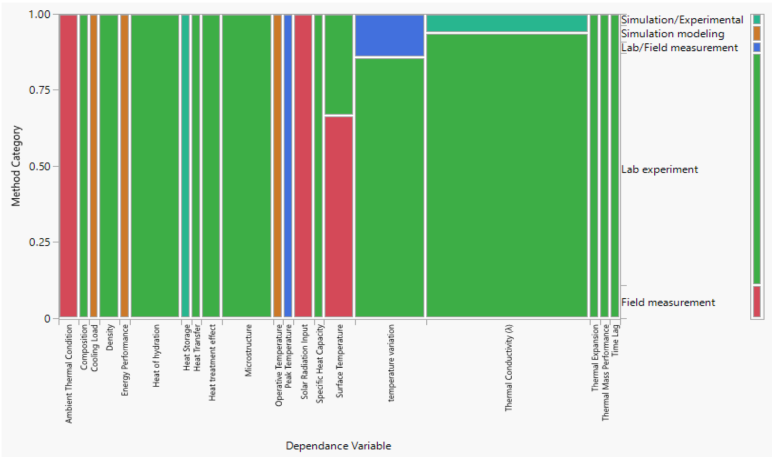

Fig. 4 Correspondance Analysis of Method Categories and Dependent Variables in Bio-Based Thermal Insulation Materials Studies

Despite a wealth of laboratory data on thermal conductivity and microstructure, only a marginal number of studies have translated these findings into simulation-based building energy performance models. This fragmentation limits the practical impact of experimental research in real-world applications. Notably, there is a lack of frameworks that calibrate thermal insulation input values—such as specific heat capacity, reflectance, or time lag—into dynamic simulation tools like EnergyPlus or DesignBuilder, particularly under tropical environmental conditions.

The potential to bridge laboratory-scale data with building-scale energy simulations remains

p-ISSN 2580-7552; e-ISSN 2548-7515, Volume10, Number 2, pp 91 – 108, 2025

underexplored. Such integration is critical to validate how material innovations contribute to operational energy savings and thermal comfort in naturally ventilated tropical structures. Studies incorporating such models were found only after 2019 and remain limited in number and scope (Table 2). Therefore, there is a clear need to promote methodological convergence between material science and performance-driven architectural simulation.

3.2 Temporal Trends in Research Output Focus

The temporal analysis of research output between 2011 and 2024, as detailed in Table 2, reveals a consistent focus on thermal conductivity testing, underscoring its role as the most fundamental parameter in evaluating bio-based insulation materials. This sustained emphasis reflects the need to quantify the heat transfer performance of new materials, especially as they are introduced as alternatives to conventional insulators. Notably, thermal conductivity studies show peak activity in 2021 (5 publications), followed by a steady continuation through 2022–2024, suggesting that material-level investigations remain at the core of scholarly attention.

In contrast, the integration of simulation tools—which are essential for assessing material performance within actual building contexts—appears infrequently, only in the years 2019, 2022, and 2023, each with a single occurrence. This limited uptake points to a lag in methodological expansion toward performance-based modeling, such as energy simulations under various climatic conditions. Similarly, tropical climate-specific studies are highly underrepresented, appearing only in 2019 and 2021, despite the growing relevance of climate-adaptive design in global sustainability discourses.

Further, research on specific heat capacity and microstructure or reflectance analysis—which can enhance understanding of material behavior under dynamic thermal loads—emerged in certain years (notably 2020 and 2021), but without establishing a sustained trend. These sporadic entries reflect a lack of continuity in diversifying research approaches beyond basic thermal resistance measurements.

The temporal trend highlights a methodological plateau: while the scientific community has built a robust foundation in material characterization, it has not significantly evolved toward holistic, system-level analyses. The limited adoption of simulation and climate-contextual approaches suggests a pressing need to recalibrate research priorities. Future efforts should aim to bridge the current gap between laboratory-based findings and real-world energy modeling, particularly within tropical architecture, to fully realize the environmental benefits of

p-ISSN 2580-7552; e-ISSN 2548-7515, Volume10, Number 2, pp 91 – 108, 2025

bio-based thermal insulation materials in sustainable construction practices.

Table 2 Distribution of Research Outputs by Year and Focus Area (2011–2024)

Year	Thermal Conductivity	Simulation Integration	Microstructure/Reflectance	Specific Heat Capacity	Tropical Climate
2011	2	–	–	–	–
2015	3	–	–	–	–
2016	2	–	–	2	–
2019	1	1	1	2	1
2020	3	–	1	5	–
2021	5	–	–	5	1
2022	3	1	–	3	–
2023	3	1	–	3	–
2024	3	–	1	1	–

3.3 Methodological Gaps and Strategic Research Opportunities

The analysis of methodological trends and research gaps in bio-based thermal insulation studies, as synthesized from Figures 2–4 and Tables 1–3, reveals several critical limitations that hinder the practical advancement of the field, especially within tropical contexts. One of the most evident issues is the strong experimental bias toward laboratory-based testing, with most studies focusing narrowly on thermal conductivity and microstructural analysis. While these parameters are foundational, the lack of field validation under actual tropical climate conditions limits the applicability and transferability of results to real-world building scenarios.

Moreover, there is a noticeable absence of studies evaluating broader thermal performance variables such as operative temperature, thermal mass, and energy consumption—factors that are vital for assessing comfort and efficiency in buildings. This highlights a gap between material-level data and its integration into macro-scale performance outcomes.

In addition to methodological constraints, disciplinary fragmentation remains a challenge. Research efforts in material science often proceed independently from architectural design and building simulation, resulting in a disjointed understanding of how bio-based materials perform within complete building systems. This fragmentation prevents the development of holistic, climate-adaptive design strategies. Compounding these issues is the geographical imbalance in research output. Although bio-waste is abundant in tropical countries like Indonesia and other Southeast Asian nations, the majority of relevant studies originate from non-tropical or industrialized regions. This underrepresentation indicates a missed opportunity to conduct

Doi: https://doi.org/10.25105/livas.v10i2.22933

p-ISSN 2580-7552; e-ISSN 2548-7515, Volume10, Number 2, pp 91 – 108, 2025

place-based research that reflects local environmental conditions, cultural practices, and material availability.

Furthermore, simulation and predictive modeling tools—such as Building Information Modeling (BIM), Computational Fluid Dynamics (CFD), and energy simulation software—remain underutilized. Their integration could significantly advance the understanding of how bio-insulated materials perform under dynamic and context-specific building scenarios. Taken together, these gaps underscore the need for a strategic realignment of research priorities. A more transdisciplinary and climate-contextual approach, which combines laboratory testing, digital simulation, and in-situ validation, will not only enhance scientific rigor but also ensure that innovations in bio-based insulation are relevant and impactful for sustainable, low-carbon construction in tropical climates.

Table 3 Mapping Current Issues and Directions in Bio-Insulation Material Studies for Tropical Climates

No	Research Area	Key Insight	Identified Research Gap	Scientific Opportunity
1	Experimental Bias	Lab-based tests dominate the evaluation of thermal conductivity and microstructure	Limited validation under real tropical climate or field simulation conditions	Highlights the need for climate-specific testing that reflects natural ventilation and tropical scenarios
2	Thermal Performance Variables	Operative temperature, energy use, and thermal mass are rarely addressed	Material performance is not directly connected to thermal comfort or energy efficiency	Emphasizes macro-scale evaluation (building level) in future studies
3	Disciplinary Fragmentation	Material characterization is rarely integrated with building performance simulation	Fragmented efforts between material science and architectural design	Opens interdisciplinary research to integrate bio-materials into building design
4	Geographical Scope	Most studies are from non-tropical countries, not from high-waste tropical regions	Climate and socio-cultural needs are not adequately represented	Calls for place-based research that aligns with local waste availability and tropical building demands
5	Methodological Approach	Simulation and modeling (BIM, CFD, EnergyPlus) are underutilized	Predictive digital modeling remains underdeveloped	Opportunity to improve scenario-based simulation for bio-insulated low-carbon design

4. CONCLUSION

This study presents a comprehensive review of experimental methods used to investigate thermal insulation materials derived from biomass waste, focusing on Palm Oil Fuel Ash (POFA) and eggshell powder. The analysis reveals that current research remains largely centered on laboratory-based testing—particularly thermal conductivity—while giving limited attention to how these materials perform within actual building contexts, especially in tropical climates. Identified methodological gaps, such as the lack of field validation, minimal integration with

p-ISSN 2580-7552; e-ISSN 2548-7515, Volume10, Number 2, pp 91 – 108, 2025

building energy simulation, and the underrepresentation of tropical-region studies, highlight the need for a more integrated and context-aware research approach.

These findings carry important implications for the advancement of architectural knowledge, particularly in the realm of climate-responsive and sustainable design. Architecture, as a discipline that operates at the intersection of material science, spatial experience, and environmental performance, stands to benefit significantly from a deeper integration with empirical material studies. By proposing a framework that links laboratory-based thermal data with building energy simulation models, this research opens new pathways for architects to evaluate, specify, and design with bio-based materials not only for their ecological benefits but also for their tangible contributions to thermal comfort, energy efficiency, and carbon reduction.

Furthermore, this study challenges the architectural field to go beyond aesthetics and form, urging a shift toward evidence-based design rooted in material performance and climate adaptability. It calls for transdisciplinary collaboration between architects, engineers, and material scientists to co-develop solutions that are both scientifically rigorous and architecturally meaningful. In doing so, this work contributes to the growing body of architectural research that seeks to align design innovation with sustainability imperatives, positioning bio-based insulation materials as vital components in the decarbonization of the built environment, particularly in tropical regions where the need for contextually adaptive solutions is most urgent.

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