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A REVIEW OF EXPERIMENTAL METHODS IN BUILDING WALL THERMAL INSULATION: PHYSICAL, DIGITAL, AND HYBRID APPROACHES

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ABSTRACT

The implementation of thermal insulation within the walls of building constitutes a pivotal strategy aimed at mitigating cooling loads and augmenting energy efficiency, particularly in tropical climate conditions. In the preceding decade, scholars have progressively utilized both empirical and computational methodologies to evaluate the efficacy of insulation under diverse environmental and material parameters.

Aims: This study undertakes a comprehensive review of methodological frameworks in the domain of thermal insulation research for building walls conducted between 2020 and 2024, with an emphasis on hybrid experimental design that integrate physical measurements with digital simulations to yield more accurate, dependable, and contextually pertinent data.

Methodology and results: A systematic literature review (SLR) encompassing 52 scholarly articles was performed, categorizing the studies into four distinct classifications: field studies, laboratory-based investigations, digital methodologies (e.g., EnergyPlus, TRISCO, ABAQUS), and hybrid methodologies. Among these, digital experimentation emerged as the most predominant methodology, with EnergyPlus identified as the most frequently utilized instrument. Research employing hybrid methodologies demonstrated enhanced analytical rigor through cross-validation, versatile scenario exploration, and comprehensive thermal performance assessment.

Conclusion, significance, and impact study: Combining empirical data with digital experimentation significantly improves the precision and contextual relevance of thermal insulation evaluation. Hybrid methodologies facilitate the simulation of prolonged or extreme conditions that are often impractical to physically assess. Calibrated digital instruments such as EnergyPlus, TRISCO,

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ABAQUS, Delphin, and COMSOL are particularly effective. Especially for tropical climates, hybrid methodologies offer a robust framework for improving the design, applicability, and performance of building insulation systems.

1. INTRODUCTION

Studies have shown that wall thermal insulation significantly reduces the cooling energy requirements of buildings, especially in tropical regions. Studies have demonstrated that applying thermal insulation can decrease air conditioning energy consumption by up to 75% [1] and reduce the surface temperature of brick walls by 23% [2]. These results emphasize the importance of selecting appropriate insulation materials and design strategies to improve the thermal performance in hot climates.

Over the past decade, research in this field has employed two main categories of methodological approaches: physical experiments conducted in laboratories or the field and digital experiments using building energy modeling tools. Physical experiments provide direct empirical data under real or controlled environmental conditions and offer measurements such as thermal conductivity, U-value, and wall materials durability [3],[4],[5]. However, these methods are often limited by high cost, longer time, and technical constraints.

In contrast, digital experimentation carried out using software such as EnergyPlus, TRISCO, ABAQUS, Delphin, and COMSOL enables the efficient exploration of a wide range of design alternatives, insulation materials, and environmental conditions [6],[7]. These tools support thermal simulations, hygrothermal analyses, and structural modeling without the need for physical prototypes. However, digital models depend heavily on input parameters and assumptions. When not calibrated against physical data, their outputs may lack contextual accuracy. For example, Al-Tamimi et al. found that energy performance predictions were significantly more accurate when Building Information Modeling (BIM) was complemented with empirical data from physical tests. This demonstrates that assumptions made during the simulation can heavily influence outcomes [8]. Similarly, Zakiah demonstrated the effectiveness of simulation-based analysis for evaluating energy consumption and payback periods in various glazing strategies applied in tropical buildings, reinforcing the relevance of digital experimentation in supporting energy-efficient design decisions [9].

Acknowledging the limitations of each approach, researchers have increasingly adopted hybrid experimentation, combining empirical measurements with digital modeling. This integration enables model validation, confirmation of observed behaviors, rapid preliminary scenario testing, and performance projection under extreme or long-term conditions. These combinations are especially useful when physical replication is impractical or too costly.

Although there are review papers on wall insulation, most focus on performance evaluation or material innovations. This review provides a novel perspective by examining the hybridization of experimental methodologies applied in wall insulation research. By systematically analyzing studies from 2020 to 2024, this review identifies trends, tools, sequences, and rationales behind experimental designs, filling a gap in the current literature.

In the Indonesian research context, studies of thermal insulation have predominantly relied on digital experimentation without integrating empirical data from field or laboratory measurements. This reliance on simulation without local empirical inputs poses a methodological limitation, as it may misrepresent construction practices, materials, and climate conditions. The study aims to support the development of insulation research methodologies that are technically robust and well-calibrated to the environmental and construction realities of tropical regions such as Indonesia.

Therefore, this paper reviews studies from 2020 to 2024 that apply physical, digital, or hybrid experimental approaches in wall thermal insulation research. Specifically, it investigates: (1) the most common experimental approach in insulation research; (2) the most frequently measured variables across these approaches; and (3) the relationship between the reasons for choosing hybrid experimentation and the sequence of physical and digital experiments. By mapping and comparing these strategies, this study will provide stronger and more climate-responsive insights into research practices, particularly in tropical regions where empirical validation is limited yet necessary.

2. RESEARCH METHODOLOGY

This study used a systematic literature review (SLR) to explore and synthesize empirical research on thermal insulation in building walls, focusing on physical and digital experimental approaches. The SLR framework was selected because of its structured and replicable process, which supports the comprehensive mapping of methodological diversity, experimental techniques, and thematic patterns across studies published between 2020 and 2024.

Given the increasing volume of insulation-related studies utilizing various experimental setups and simulation tools, the SLR method was considered appropriate. Unlike narrative reviews, SLRs provide a replicable procedure for objectively classifying, evaluating, and

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comparing research designs and outcomes. It also enables identifying knowledge gaps, assessing synergy between physical and digital experimentation, and evaluating methodological robustness across different climate zones and material contexts. This structured approach facilitates transparent reporting and reproducibility, both of which are crucial for advancing evidence-based practice in building science [10].

In this study, 67 articles were initially retrieved from reputable, Scopus-indexed databases using predefined keywords. After applying inclusion and exclusion criteria, 52 articles were retained for further analysis. These articles were categorized into three main methodological approaches: physical experimentation (field or laboratory), digital experimentation (using tools such as EnergyPlus, TRISCO, ABAQUS, COMSOL, and Delphin), and hybrid approaches combining both. Hybrid studies were emphasized due to their ability to provide cross-validation, scenario extension, and greater analytical depth. Each article was examined based on its objectives, experimental and digital techniques, measured variables, and how physical data were functionally integrated into the digital analyses. Figure 1 illustrates the filtering and classification process.

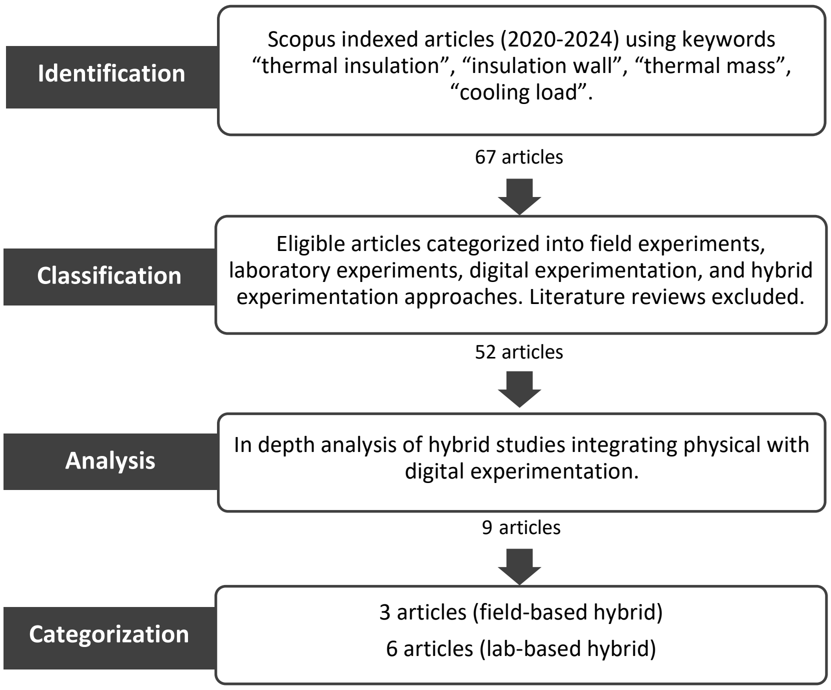

Fig. 1 Systematic Literature Review (SLR) Process of Thermal Insulation Studies.

Next, we identified the relationship between the reasons for choosing hybrid experiments in the nine articles, and the order in which the experiments were conducted. The goal of this

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analysis is to understand how motivations for using hybrid experiments relate to the order in which physical and digital methods are applied. The researchers quantified the reasons given into categories and analyzed the distribution of these reasons based on the order in which the experiments were conducted. This approach revealed the relationship between the reasons for choosing a method and the order of the experiments, as well as the factors that influenced the decision to determine the order of the physical and the digital experiments.

3. RESULTS AND DISCUSSION

Research on thermal insulation for building walls has used different methodological approaches to evaluate the effectiveness of various insulation strategies. Of the 52 articles analyzed in this review (see Table 1), four main approaches were identified: field-based physical experiments, laboratory-based physical experiments, digital experimentation using simulation software, and hybrid experimentation integrating both physical and digital methods.

Digital experimentation, employed in 46% of the studies (24 articles), was the most dominant approach. This reflects a growing reliance on simulation tools due to their efficiency, cost-effectiveness, and ability to model a wide range of thermal conditions without the logistical constraints of physical testing. However, the widespread use of digital experimentation raises concerns about contextual accuracy, particularly in tropical climates, where standardized input parameters may not accurately represent local environmental or construction realities.

Though less prevalent, field experiments (12 articles) and hybrid approaches (nine articles) offer the advantage of grounding results in real or semi-real conditions. The relatively low number of hybrid studies indicates a potential methodological gap, as hybrid methods offer a balanced approach that leverages the control and scalability of simulations while maintaining empirical grounding.

Table 1 Percentage of wall thermal insulation research methods in 2020-2024

Method	Percentage	Reference
Field experiment	23%	[5], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21]
Lab experiment	14%	[3], [22], [23], [24], [25], [26], [27]
Digital experiment	46%	[2], [28], [29], [30], [31], [32], [33], [34], [35], [36], [37], [38], [39], [40], [41], [42], [43], [44], [45], [46], [47], [48], [49], [50]
Hybrid	17%	[51], [52], [53], [54], [55], [56], [57], [58], [59]

The digital experimentation tools used in the reviewed studies included EnergyPlus, TRISCO, COMSOL, ABAQUS, and Delphin (see Figure 2). EnergyPlus was the most widely used tool (10 articles). Developed by the U.S. Department of Energy, EnergyPlus is commonly used to model energy consumption related to HVAC systems, lighting, and building envelope configurations. In hybrid experiments, EnergyPlus enables researchers to predict energy demand and thermal comfort levels based on physical measurements [7].

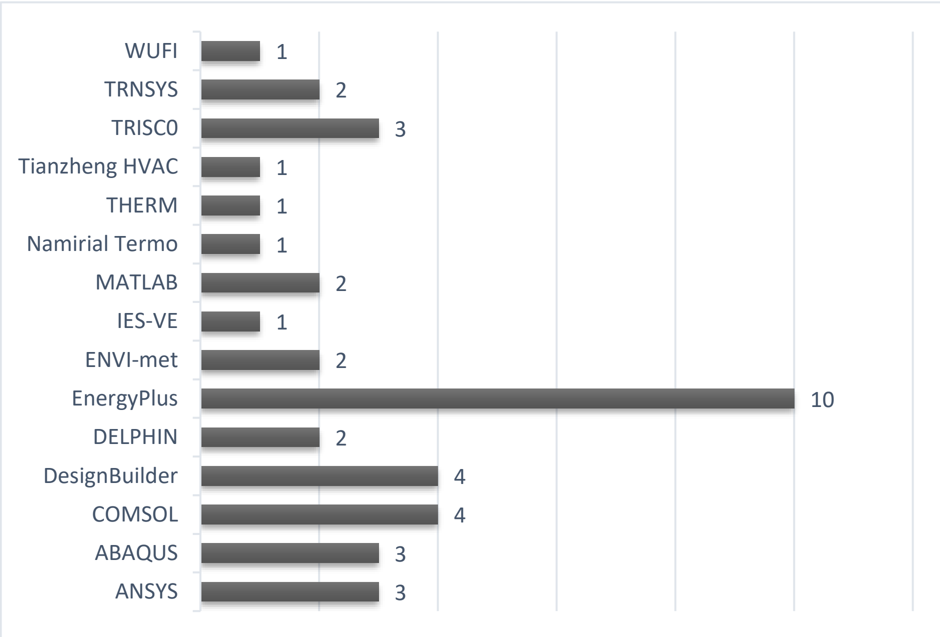

Fig. 2 Digital simulation software in wall insulation research

3.1 Hybrid Experimentation Using EnergyPlus

To better understand the application of hybrid experimentation in wall insulation research, this section highlights selected studies combining physical testing and digital experimentation. Each study incorporates empirical measurements such as temperature profiles, U-values, and material behavior into digital experiments to achieve specific goals. These objectives include validating digital models with real-world data, confirming observed thermal phenomena, conducting preliminary cost-efficient assessments, and analyzing scenarios that cannot be replicated through physical testing. Table 2 through 4 summarize representative studies, categorized by the primary digital tools used. Each table includes a discussion of the rationale behind the methodological combination.

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Table 2 Wall insulation article experimental approach with EnergyPlus simulation

Title	Method	Measured Variable
Impact of insulation and wall thickness in compressed earth buildings in hot and dry tropical [57]	1. Field experiment	Outdoor air temperature, relative humidity, wind speed and direction, solar radiation, Indoor air temperature, wall/roof/floor surface temperature, natural ventilation conditions, building configuration (orientation, dimensions, openings)
	2. EnergyPlus 9.0.1	Material conductivity, density, and specific heat (glass wool, straw + lime), effect of wall thickness, daily temperature amplitude, decrement factor, energy efficiency
Insulation performance evaluation of stone-finished exterior insulation systems with insulation frames for green remodeling of concrete exterior walls [60]	1. Physibel Trisco 14.0w	U-factor (thermal bridging effect), heat loss, lowest inside surface temperature, temperature difference ratio (condensation risk indicator)
	2. Lab experiment (mock-up)	U-factor of mock-up (verification of simulation results), thermal bridging effect physically
	3. DesignBuilder v6 + EnergyPlus v8.9.0	Annual energy consumption for heating and cooling

Neya et al. combined field measurements from compressed earth buildings in a dry tropical region with EnergyPlus simulations. This combination was used to validate simulation results against real climate conditions, and to test variations in wall thickness and insulation materials that would be too laborious and costly to assess physically [57]. Meanwhile, Choi and Song used a laboratory mock-up and multiple simulation tools (TRISCO, DesignBuilder, and EnergyPlus) to evaluate U-values and annual energy consumption. Digital experimentation confirmed thermal bridge effects detected in the lab and projected long-term energy performance under different insulation configurations. This enables scenario testing beyond the constraints of physical models [60]. These hybrid studies demonstrate the importance of empirical data in improving the realism and accuracy of simulation outputs.

3.2 Hybrid Experimentation Using TRISCO

A similar hybrid approach was employed in studies utilizing TRISCO, a digital tool designed for steady-state thermal analysis and the evaluation of thermal bridges. Krause et al. combined

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field measurements of surface temperatures at construction joints with TRISCO's numerical modelling to assess two-dimensional temperature distribution and quantify linear thermal transmittance [59]. This combination aimed to validate the spatial thermal patterns simulated by TRISCO against real-world thermal behavior at construction joints.

Table 3 Wall insulation article experimental approach with TRISCO simulation

Title	Method	Measured Variable
The impact of internal insulation on heat transport through the wall: case study [59]	1. Field experiment	Indoor and outdoor air temperature, surface temperature inside the wall at the joint area.
	2. TRISCO	2D temperature distribution in the joint area (wall, ceiling, window), heat flux (Φ), thermal power (W), linear thermal transmission coefficient (W/m-K), linear thermal coupling coefficient (W/m-K), U-value (Us, Uf, Ug) of building elements (wall, window frame, glass), inner surface temperature factor fRsi(2D), visual and digital temperature distribution, thermal conductivity (λ).
Analysis of thermal properties of materials used to insulate external walls [54]	1. Lab experiment	Thermal conductivity (λ), heat flux, temperature difference between plates, thickness and sample area, macroscopic structure of material surface, storage conditions (control, indoor, outdoor), change in λ value.
	2. TRISCO	U-value of wall, temperature factor of inner surface, minimum temperature of inner surface, linear heat transmittance coefficient, total heat flow through 2D joint, length of envelope element, U-value of each part of envelope, temperature distribution in wall, boundary condition of outer and inner temperature, heat transfer resistance of inner and outer sides

Meanwhile, Pomada et al. conducted laboratory experiments to measure the performance of insulation materials under varying storage conditions. They then applied these data to calibrate TRISCO models for evaluating the overall thermal resistance of walls [54]. In both cases, digital experimentation extended the analysis beyond the constraints of physical testing, particularly in identifying localized heat flow anomalies difficult to capture through measurements alone.

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3.3 Hybrid Experimentation Using ABAQUS

A comparable hybrid methodology was adopted in studies involving ABAQUS, a digital tool used for advanced thermal, mechanical, and hygrothermal modeling. As shown in Table 4, three studies combined laboratory-scale physical experiments with ABAQUS digital experimentation to investigate material behavior under conditions such as moisture ingress, weathering cycles, and shear loading.

Table 4 Wall insulation article experimental approach with ABAQUS simulation

Title	Method	Measured Variable
Hygrothermal performance of micro inhomogeneous insulation materials - EPS-based wall panel [61]	1. DesignBuilder	Indoor and outdoor temperature (°C), Relative humidity (%RH), Moisture load (PPM), Solar radiation, natural ventilation, building orientation, space zones, building dimensions, and materials.
	2. ABAQUS	Water vapor concentration (PPM), water vapor diffusion coefficient, water vapor resistance factor (μ), open porosity, specific heat capacity, mass density, EPS bead distribution, exposure duration (1 day)
	3. Lab Experiment	Material microstructure (SEM), chemical element distribution (EDX/EDAX), visual moisture accumulation at the boundary between materials.
Weathering resistance of novel sustainable prefabricated thermal insulation wall [53]	1. Lab Experiment	Panel and cube dimensions, material composition and thickness, temperature and duration of test cycles (Thermal-Rain, Thermal-Cold, Freeze-Thaw), cracking, peeling, voids, calcification, tile adhesion strength (pull-off test), strain.
	2. ABAQUS	Surface temperature distribution simulation, thermal stress simulation due to temperature change.
Shear behavior of FRP connectors in precast sandwich insulation wall panels [51]	1. Lab experiment	7-, 14-, and 28-day concrete compressive strength, elastic modulus of concrete, shear testing of FRP connectors, damage modes, load-displacement curves.
	2. ABAQUS	Numerical modeling based on experimental data, parametric analysis of connector spacing, anchor depth, and insulation thickness.

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We used empirical data (including microstructural characteristics (via SEM), compressive strength, and pull-off resistance) to inform and calibrate the digital models. This combination made it possible to stimulate complex physical phenomena that are difficult to capture experimentally with high fidelity, such as internal stress distribution and degradation over time. In these studies, digital experimentation was used not only to validate laboratory findings but also to analyze long-term or extreme environmental conditions that would be impractical to replicate through physical testing alone.

3.4 Hybrid Experimentation Using Other Simulation Tools

Other forms of hybrid experimentation were applied in studies involving Delphin and COMSOL Multiphysics, both of which support complex Multiphysics modeling. Keskküla et al. integrated field data, specifically temperature and humidity measurements, into Delphin to simulate the long-term hygrothermal behavior of reed-board-insulated walls under real climatic conditions [58]. This integration assessed the risk of condensation and moisture accumulation, which would require an extended period to observe through physical testing alone.

Similarly, Malz et al. combined laboratory experiments with digital modeling in COMSOL to examine transient heat transfer and airflow in insulating materials with reflective air gaps [52]. In both cases, digital experimentation was used not only for validation but also to project thermal-moisture dynamics that are difficult to track in real time. These studies demonstrate how hybrid approaches enable the in-depth analysis of coupled processes, such as simultaneous heat and vapor transport, that are critical in assessing insulation performance in humid or variable environments.

Table 5 Wall insulation articles of experimental approach with other simulations

Title	Method	Measured Variable
Hygrothermal analysis of masonry wall with reed boards as interior insulation system [58]	1. Field experiment	Temperature at multiple points between the original wall and insulation, interior and exterior temperature, relative humidity, measurement position (370 mm and 1500 mm from the floor), with measurement intervals every 1 hour.
	2. HAM Delphin 5.9	Input temperature and humidity data from experiments and weather stations, wall and insulation material properties (thermal conductivity, heat capacity, vapor permeability), and 6-year long-term weather

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		data. Simulation outputs are 6-year wall temperature and humidity, condensation risk, mold growth risk index (VTT mold index), wall drying potential, and changes in relative humidity and temperature inside the wall under different conditions (e.g., with/without vapor retarder and heating cable).
On the development of a building insulation using air layers with highly reflective interfaces [52]	1. Lab experiment	Indoor and outdoor air temperature, wall surface temperature and insulation layer, heat flux density (W/m²), relative humidity (%), time to steady state.
	2. COMSOL Multiphysics	Multiphysics Temperature distribution within the wall and insulation layers (°C), Heat flux density through layers and surfaces (W/m²), Air flow velocity within layers (m/s), Heat radiation emission between surfaces (W/m²), Simulation duration (seconds/minute) for transient simulation according to the duration of the experiment.

3.5 Synthesis of Experiment Sequences and Rationales

Figure 3 summarizes a comparative analysis of the simulation tools. EnergyPlus is suitable for macro-level energy consumption modeling, while TRISCO excels in 2D steady-state thermal bridging analysis. ABAQUS is superior for detailed material stress and degradation modeling. Delphin is ideal for heat-moisture interaction analysis, particularly in humid climates. COMSOL offers Multiphysics modeling for transient and complex conditions.

Each software has strengths that align with specific research questions; however, none is universally optimal. Consequently, hybrid experimentation, which combines physical measurements with simulation, provides a more holistic and validated understanding of insulation performance. This integrative strategy is particularly valuable in contexts where simulation inputs require empirical calibration to accurately reflect real-world conditions.

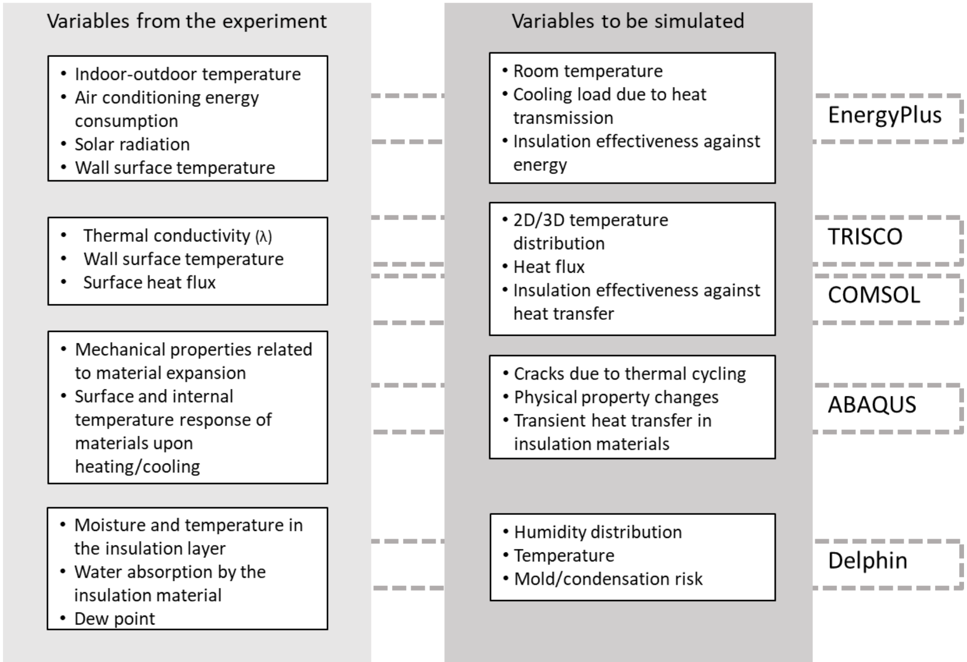

Fig. 3 Mapping of variables from the physical and digital experiment variables

To learn more about hybrid experiments, it is helpful to examine the relationship between the order of experiments and the reasons for choosing this approach. This relationship shows how the order of experiments can affect the entire research process, and how different motivations can lead to different strategies for combining physical and digital experiments. Figure 4 illustrates this relationship, providing a clearer understanding of how the specific reasons for using hybrid experimentation align with the sequence of methods used.

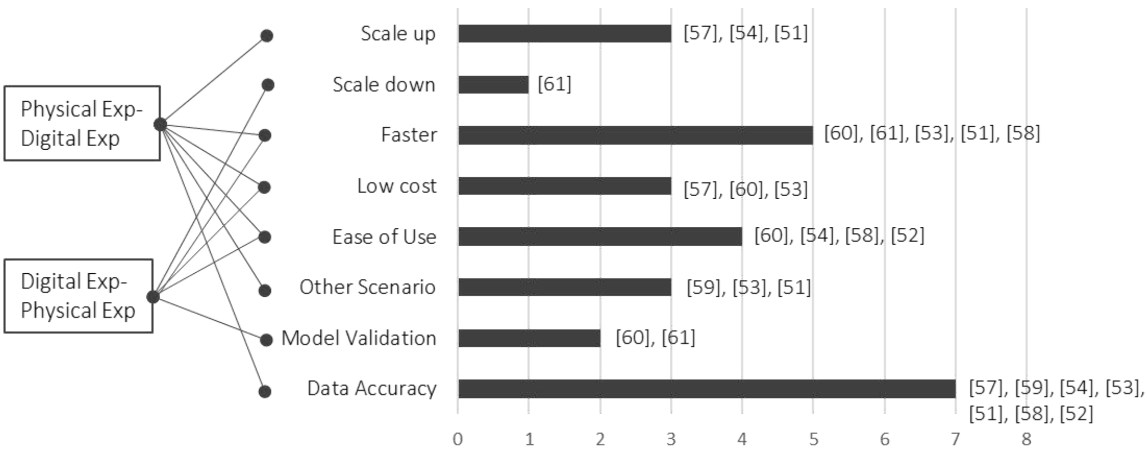

Fig. 4 Relationship between the hybrid sequence and the rationale of method application

Studies using the hybrid experimentation approach revealed an interesting relationship between the reasons for choosing the two approaches and the order in which the experiments

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were conducted. Researchers who prioritize reasons such as scaling up, testing other scenarios, and ensuring data accuracy tend to conduct physical experiments first, followed by digital experiments. This suggests that physical experiments are used to obtain real data and validate simulation results, before moving on to digital experiments, which are more likely to test different scenarios and confirm data accuracy.

Conversely, the need for model validation and downscaling is more evident in studies where digital experiments are conducted first, followed by physical experiments. These studies utilize digital experiments to validate the initial model and adjust the simulation scale, before conducting physical experiments to ensure that the simulation results match the real conditions. Meanwhile, reasons such as faster processing, lower cost, and ease of use did not show a specific relationship with the order of experimentation. Rather, these reasons were related to the practical advantages of both experimentation approaches.

These findings provide valuable methodological insights for tropical regions such as Indonesia, where high humidity, intense sunlight, and the need for cooling pose unique challenges to building designs. Digital experimentation tools like EnergyPlus are ideal for evaluating the overall energy performance of buildings with various insulation strategies suited to tropical conditions. Meanwhile, Delphin is essential for modeling the long-term interaction between heat and moisture, which is particularly important in humid climates. However, the accuracy and relevance of these models depend heavily on empirical calibration, which requires data on real materials and environmental conditions. The reviewed study illustrates that hybrid experimentation, including validation, scenario testing, and scale-up modeling, has advantages in developing insulation solutions that are not only technically sound but also climate-responsive and suitable for real-world applications.

4. CONCLUSION

This review emphasizes the importance of combining physical and digital experimentation in studies on building wall thermal insulation. Of the 52 reviewed studies, the most commonly used approach was digital experimentation (46%), followed by field (23%), laboratory (14%), and hybrid (17%) approaches. Although the hybrid approach remains underutilized, it provides a balanced methodological framework by combining empirical grounding with scalable simulation modeling. These approaches allow researchers to validate numerical outputs, confirm observed thermal behavior, conduct cost-effective preliminary assessments, and simulate long-term or extreme conditions that are impractical to test physically.

This study reviews digital platforms that contribute distinct analytical strengths. EnergyPlus is ideal for macro-scale energy modeling, TRISCO is ideal for steady-state thermal bridge detection, ABAQUS is ideal for complex material degradation and mechanical stress simulation, Delphin is ideal for hygrothermal performance analysis, and COMSOL is ideal for advanced Multiphysics modeling. These tools are most effective when calibrated with empirical data such as temperature profiles, U-values, material properties, and moisture dynamics, collected through laboratory or field-based testing.

Due to the variety of insulation challenges in different climates and construction contexts, particularly in humid and hot tropical regions like Indonesia, researchers are encouraged to adopt hybrid experimentation as a core methodological strategy. This is especially important in local settings where thermal comfort heavily depends on effective cooling strategies, building envelope design, and material selection under high humidity, solar radiation, and fluctuating ambient conditions. Hybrid approaches offer a more accurate and adaptable framework for evaluating insulation technologies that reflect the specific characteristics of tropical buildings, including lightweight structures, natural ventilation, and intermittent air conditioning use.

This review reveals an important insight: the relationship between the reasons for choosing hybrid experimentation and the sequence in which physical and digital experiments are conducted. Research that prioritizes scaling up, testing other scenarios, and ensuring data accuracy begins with physical experiments followed by digital simulations. This order allows for the validation of physical data and the testing of various scenarios in digital models. Conversely, studies focused on model validation and scaling down tend to reverse this sequence. First, digital experimentation is conducted to refine the model and adjust the simulation scale. Then, physical validation is performed to ensure consistency with real-world conditions. Other reasons, such as faster execution, lower cost, and ease of use, do not show a specific connection to the sequence of methods, but highlight the general advantages of combining both approaches.

However, this review has several limitations. First, the publication range is limited to 2020–2024, which may not capture all relevant studies. Second, most of the reviewed studies were conducted in regions with diverse climatic conditions, without focusing on a single climate zone. Future research should target regions with consistent climatic characteristics and clearly define the purpose of hybrid approaches (e.g., validation, prediction, or thermal performance exploration). This will allow future findings to be applied more effectively to building design practices suited to those specific contexts.

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