Journal of Building Material Science
https://journals.bilpubgroup.com/index.php/jbms

ARTICLE

Physicochemical and Thermomechanical Performance of Eco-Friendly Unfired Clay-Biopolymer Composite Bricks

Rachid Et-Tanteny [1], Imad Manssouri [2], Aboubakr Bouayad [3], Houssame Limami [4], Amine Azzouzi [2], Bouchta El Amrani [1], Karim El Khadiri [1]*

[1] *Laboratory of Computer Science and Interdisciplinary Physics (LIPI), ENS-Fez, Sidi Mohamed Ben Abdellah University, Fez P.O. Box 5206, Morocco*

[2] *Team of Innovative Research and Applied Physics, Faculty of Sciences, Moulay Ismail University, Meknes P.O. Box 11201, Morocco*

[3] *Laboratory of Engineering Sciences and Professions, ENSAM, Moulay Ismaïl University, Meknes P.O. Box 15290, Morocco*

[4] *Laboratory of Sustainable Energy Materials, Al Akhawayn University, Ifrane P.O. Box 104, Morocco*

ABSTRACT

The rapid growth of the global population, coupled with increasing pollution levels, highlights the urgent need for sustainable and eco-friendly construction materials, such as unfired clay bricks. However, their widespread adoption remains limited due to certain performance drawbacks, particularly in thermal insulation, a critical factor in addressing climate change challenges. In this study, a plant-based waste-derived biopolymer was incorporated into unfired clay bricks to enhance their physicochemical and thermomechanical properties. The biopolymer was added at six different weight fractions (0%, 1%, 3%, 7%, 15%, and 20%) to systematically evaluate its impact on bulk density, porosity, capillary water absorption, thermal conductivity, specific heat capacity, and compressive strength. The results revealed a gradual decrease in porosity as the biopolymer content increased, leading to a 41% improvement in thermal conductivity at 20 wt%. However, the optimal balance between thermal efficiency and compressive strength was achieved at 7 wt%

*CORRESPONDING AUTHOR:
Rachid Et-Tanteny, Laboratory of Computer Science and Interdisciplinary Physics (LIPI), ENS-Fez, Sidi Mohamed Ben Abdellah University, Fez P.O. Box 5206, Morocco; Email: rachid.ettanteny@usmba.ac.ma

ARTICLE INFO
Received:26 May 2025 | Revised: 12 August 2025 | Accepted: 2 September 2025 | Published Online: 18 September 2025
DOI: https://doi.org/10.30564/jbms.v7i3.7994

CITATION
Et-Tanteny, R., Manssouri, I., Bouayad, A., et al., 2025. Physicochemical and Thermomechanical Performance of Eco-Friendly Unfired Clay-Biopolymer Composite Bricks. Journal of Building Material Science. 7(3): 166–182. DOI: https://doi.org/10.30564/jbms.v7i3.7994

biopolymer; this result has been verified through a combination of experimental methods and modeling. Additionally, TRNSYS simulations confirmed the enhanced thermal performance, demonstrating a 9.74% increase in time lag and a 16% reduction in decrement factor, both of which contribute to optimizing building energy efficiency. Overall, this approach not only helps reduce environmental pollution but also enhances insulation capacity while lowering heating and cooling demands, thereby improving overall building performance. Biopolymer-reinforced unfired clay bricks thus represent a promising solution for advancing a low-carbon and sustainable construction industry, aligning with the United Nations Sustainable Development Goals (SDGs) for climate change mitigation and responsible resource management.

Keywords: Clay–Polymer Composites; Sustainable Construction Materials; Climate Change Adaptation; Waste-Derived Additives; Circular Economy Strategies; Low-Carbon Building Technologies

1. Introduction

Faced with the urgent realities of climate change, the ecological transition of the building sector has become a necessity rather than an option. Given its high energy demand, the construction industry represents a significant contributor to global energy consumption [1], making its transformation a priority. Population growth only exacerbates this challenge, particularly in countries like Morocco, where the pressure on resources is intensifying [2]. In response, stakeholders in the Moroccan construction sector are increasingly embracing strategies aimed at delivering high-energy-efficiency buildings. National policy reflects this shift, with Morocco committing to a 20% reduction in building-related energy consumption by 2030 through the adoption of sustainable construction practices [3]. In this framework, the valorization of agricultural by-products emerges as a promising pathway to both reduce the carbon footprint of buildings and meet energy efficiency targets. As highlighted by recent work from Sileshi et al. [4], the global burden of organic residues, originating from agriculture, fisheries, and forestry, poses a pressing environmental challenge. Their data-driven assessment revealed that the open burning of such materials is a major contributor to atmospheric pollution and climate forcing, with 2019 alone witnessing the combustion of nearly 458 Mt of residues, releasing an estimated 1.2 Mt of CH_4 and 32,000 t of N_2O. In the Moroccan context, the study of Belmakki et al. [5] provided an essential baseline for the identification and characterization of domestic organic waste streams, underpinning future valorization policies. They estimated an annual generation of roughly 60 Mt of organic waste nationwide, dominated (≈ 92%) by agricultural residues. Although part of this biomass is integrated into local markets as soil amendments or other agricultural inputs, a considerable share remains untapped, ultimately relegated to landfilling or open burning, thereby representing both an environmental liability and a missed resource recovery opportunity.

However, a growing body of research has demonstrated the potential of incorporating various forms of organic waste, such as rice husk ash [6], millet husk residues [7], Typha fibers [8], agricultural biowaste [9], and sawdust fibers [10], into brick manufacturing. These bio-based additives have been shown to significantly influence key physicochemical and thermomechanical properties, including compressive strength, thermal conductivity, bulk density, and porosity. In addition to their technical benefits, these solutions address critical environmental concerns and contribute to broader public health priorities. In fact, in many regions, inadequate waste management results in substantial quantities of organic residues remaining untreated or being disposed of unsafely, creating conditions that foster respiratory illnesses and waterborne diseases, as studied by Mayasari et al. [11] and Chari et al. [12]. By integrating such waste materials into clay brick formulations, it becomes possible to not only reduce environmental burdens through waste valorization but also enhance the thermal insulation performance of masonry products, contributing to more sustainable construction practices [13].

Pea shell waste is a readily available by-product of the agro-food industry. It represents a renewable and eco-friendly resource with diverse potential for valorisation. It is rich in plant fibres and bioactive compounds, and contains significant amounts of protein, fibre, calcium, iron, potassium, and magnesium. When used in agriculture, these components can enhance soil structure and fertility [14]. Their potential extends far beyond agricultural applications. They have been investigated as feedstock for sustainable bioprocesses, such as bio-hydrogen and polyhydroxybutyrate production [15], as well as in environmental remediation, demonstrating effectiveness in removing pollutants like methylene blue from wastewater [16]. Given their abundance and renewability, pea shells represent a promising raw material for developing functional, nutrient-rich, and eco-conscious products. In the construction sector, their valorization offers a promising approach to reducing environmental impacts by enabling the production of low-energy, cost-effective building materials. Transforming this lignocellulosic biomass into a construction additive is a twofold strategy. First, it diverts organic waste from landfills, which is beneficial for the environment. Second, it decreases reliance on virgin resources, thereby contributing to a more sustainable and circular economy [17]. Previous research has consistently shown that the incorporation of organic waste into unfired clay bricks induces notable changes in their physicochemical and thermomechanical behavior. Belkharchouche and Chaker [18] observed that incorporating 1–2% olive pomace decreases compressive strength but enhances thermal performance, reflecting a trade-off between structural and insulation properties. Limami et al. [19] demonstrated that introducing Typha fibers significantly increases porosity, from 1.14% to 14.95% at a 20% incorporation rate, while reducing compressive strength from 6.16 MPa to 3.67 MPa. This weakening effect was attributed to the formation of flocculant particles and the concomitant reduction in silica content, both of which adversely influence the brick matrix's cohesion.

This study explores the incorporation of recycled pea shell powder as an eco-efficient additive in unfired clay bricks, offering a low-carbon alternative to conventional fired masonry. By eliminating energy-intensive firing, the approach not only curtails greenhouse gas emissions but also reduces the depletion of natural raw materials. The investigation encompasses a detailed assessment of the clay-biopolymer composite's physicochemical and thermomechanical properties, highlighting its self-reinforcing potential derived from the natural fibrous network of the pea shells. Particular attention is given to optimizing mixing protocols to prevent clay migration and swelling, thereby avoiding the need for costly chemical stabilizers. This valorization strategy addresses two pressing challenges: diverting agro-industrial wastes from landfills and mitigating the environmental footprint of traditional brick production [20]. In consideration of the anticipated escalation in global temperatures and the projected alterations in precipitation patterns, which are indicative of a warming climate, as indicated by Ona et al. [21], developing thermally efficient and climate-resilient building materials has become a priority. Overall, this study reveals that incorporating recycled pea shell powder into unfired clay bricks significantly enhances their thermal insulation capacity, thereby reducing heating and cooling energy requirements while preserving satisfactory thermomechanical performance. Combined with thermal performance simulations, the results confirm the material's ability to improve overall building energy efficiency. This innovation not only valorizes agricultural residues but also supports climate-resilient construction by lowering operational energy demand and minimizing environmental impact. In alignment with the United Nations Sustainable Development Goals (SDG), specifically SDG 12 on responsible consumption and production, and SDG 13 on climate action. This study presents a viable, scalable, and cost-effective pathway for advancing sustainable, low-carbon building practices.

2. Materials and Methods

2.1. Materials

The clay used in this study was sourced from the Bensmim locality in the Ifrane region of Morocco. After refinement and sieving, the resulting clay powder was characterized structurally and compositionally using X-ray diffraction (XRD) and X-ray fluorescence (XRF) analyses. For XRD analysis, the powdered specimen was mounted in the diffractometer sample chamber and irradiated using a Cu-Kα source ($\lambda = 1.5406$ Å) with a standard Bragg-Brentano geometry configuration incorporating 1° divergence slits. Moreover, the chemical composition was determined by XRF spectroscopy using a SPECTRO X-ray fluorescence spectrometer. The analysis was performed on homogenized powdered samples to ensure representative bulk composition measurements. **Figure 1** shows the XRD pattern of the clay, which revealed the presence of several crystalline phases, including quartz (SiO_2), illite, calcite, dolomite, and muscovite. The presence of illite and muscovite indicates that the clay is non-swelling illitic, with minimal muscovite content [22]. This was further confirmed by the observed weak swelling behavior upon hydration, which supports the classification of the clay as non-expansive [23]. Furthermore, the XRF results in **Table 1** confirm that quartz (SiO_2) is the most abundant oxide, accounting for about 59.6% of the total composition. The presence of significant amounts of aluminum oxide (Al_2O_3) and potassium oxide (K_2O) confirms the illitic nature of the sample and indicates a well-developed clay matrix as revealed by XRD patterns. These findings underscore the material's potential as a promising candidate for functional applications in sustainable construction.

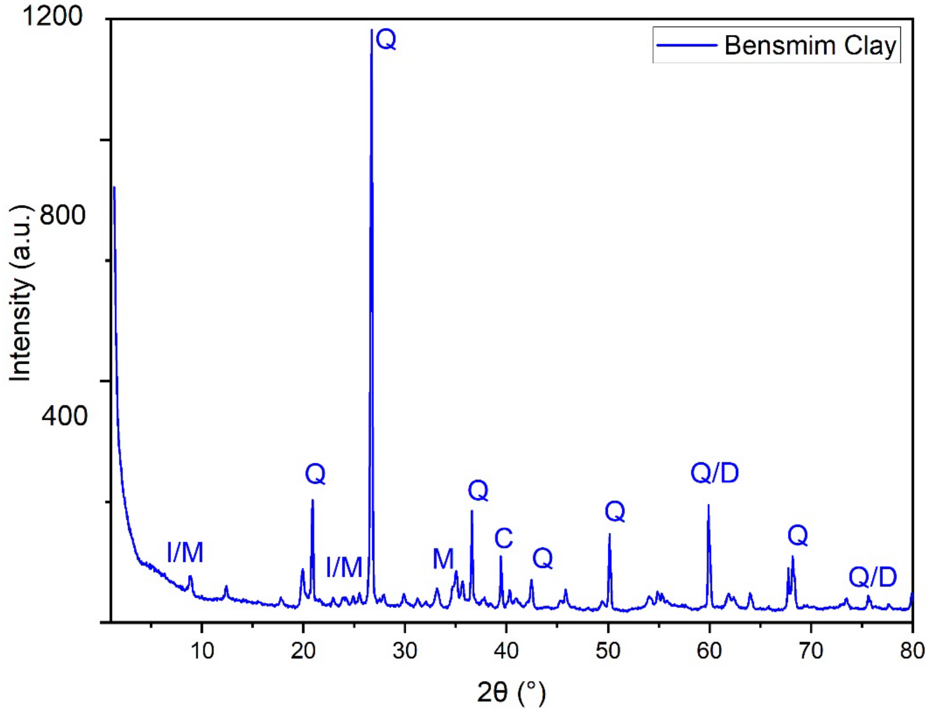

Figure 1. XRD pattern of Bensmim clay: (Q) is quartz; (I) is illite; (M) is muscovite; (C) is calcite; and (D) is dolomite.

Table 1. XRF analysis of chemical composition in the Bensmim clay sample.

Chemical Element	SiO_2	AL_2O_3	Fe_2O_3	CaO	MgO	K_2O	TiO_2	P_2O_5	Loss on Ignition
(%)	59.6	22.4	6.69	0.08	0.97	2.53	0.83	0.46	5.34

The second material is the pea shells waste as a biopolymer, sourced from a local vegetable market in Meknes, as an organic additive. To eliminate moisture, the shells were sun-dried for 10 days before processing. After drying, they were ground into a fine powder using an electric grinder and sieved to a uniform particle size of 315µm (**Figure 2**). Chemical analysis revealed that the processed shells consisted primarily of cellulose (29.5%), hemicellulose (38.1%), lignin (28.5%), and ash (3.9%), as reported by Li et al. [24]. The high polysaccharide content, particularly cellulose and hemicellulose, underscores the material's suitability for sustainable construction applications. Given its renewable nature and composition, pea shell waste demonstrates significant potential as a raw material for developing eco-friendly building products, aligning with circular economy principles in waste valorization.

(**a**) (**b**) (**c**) (**d**)

Figure 2. Biopolymer powder preparation from pea shell waste: (**a**) Collection and sun-drying; (**b**) Grinding; (**c**) Sieving; and (**d**) final powdered product.

2.2. Fabrication of Clay-Biopolymer Composite Bricks

To prepare a mineral-enriched soil, organic matter, plant roots, and clay impurities were carefully removed from the field-collected material. The raw soil was then ground using an electric grinder and sieved to a particle size of 200 µm. The purified clay was blended with pea shell biopolymer additives at different weight fractions (0, 1, 3, 7, 15, and 20 wt%) to fabricate brick specimens with varied compositions. Homogenization of the clay–biopolymer mixture was carried out using a CONTROLS automatic electric stirrer operated at 100 rpm for 7 min, ensuring uniform dispersion of the waste particles within the clay matrix, a crucial step for achieving consistent composition and structural homogeneity. The mixture was then conditioned to its optimum moisture content (OMC) of 16% [22], in accordance with Moroccan standard NM 13.1.044-2005 (equivalent to ASTM D698). Finally, the prepared blend was molded into prismatic specimens measuring 160 mm × 40 mm × 40 mm, in accordance with ASTM C216 specifications.

To improve compaction and eliminate air voids, the molds were placed on an impact table and subjected to controlled vibrations, which ensured uniform distribution of the clay paste and minimized structural defects in the final bricks. After molding, the specimens were cured under controlled laboratory conditions (20 ± 3 °C) for 28 days to allow gradual drying (**Figure 3**). Subsequently, oven-drying was carried out using a stepwise heating protocol: the temperature was first set at 30 °C, then increased at a rate of 1.5 °C/h over 24 h until reaching 100 °C. Drying was maintained until a constant mass was obtained, confirming complete removal of moisture. This controlled drying stage is essential, as residual water may negatively influence the physicochemical and thermomechanical properties of the bricks, potentially compromising measurement accuracy due to microstructural degradation [25]. Once dried, the brick specimens were polished and prepared for subsequent experimental characterization tests.

(**a**) (**b**) (**c**)

Figure 3. Preparation of clay-biopolymer composite bricks: (**a**) Powdered clay-biopolymer composite; (**b**) Mold (dimensions: 160 mm × 40 mm × 40 mm); and (**c**) Molded clay-biopolymer composites.

2.3. Test Procedures

Following the preparation stage, the clay–biopolymer bricks were subjected to experimental characterization in accordance with Moroccan building material standards. Porosity was determined in accordance with NM ISO 10545-3 (2000), which applies to porous construction materials, and ASTM C20-00, which quantifies the percentage of voids within the brick microstructure. Bulk density was evaluated in accordance with the standard specified in EN 772-16, which is specifically applicable to solid bricks. Capillary water absorption coefficient was measured by means of immersion testing, in accordance with the standard NM EN 772-11 for the assessment of capillarity in construction materials. Compressive strength was determined using a Controls compression machine (**Figure 4**). Tests were performed at a controlled loading rate of 0.15 MPa/s (±0.0008 MPa) until specimen failure, as prescribed by NM EN 772-1 (2015). Thermal performance was assessed using a heat flow meter operating in two configurations: transient mode to determine specific heat capacity and steady-state mode to evaluate thermal conductivity (**Figure 5**). All thermal tests were conducted according to the standard NM EN 1745 (2015), which is equivalent to ASTM C1470. To ensure the reliability of the statistical results, three replicate tests were performed for each specimen, and the mean value was considered the representative result. This comprehensive experimental protocol ensured an accurate assessment of the physicochemical, mechanical, and thermal properties of the developed bricks.

Figure 4. Compressive strength analysis of unfired clay-biopolymer bricks.

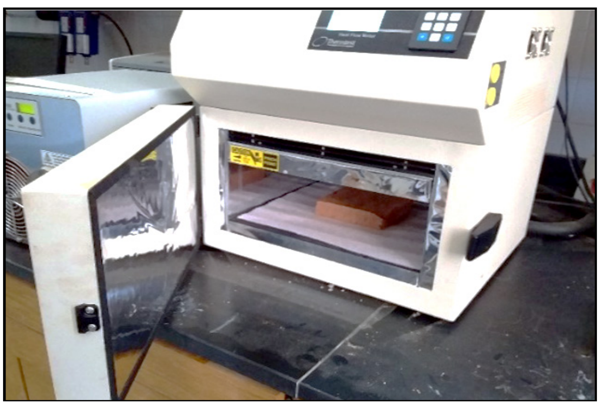

Figure 5. Thermal property analysis of clay-biopolymer bricks.

3. Results and Discussion

3.1. Bulk Density Test

Table 2 presents the bulk density values of the unfired clay bricks incorporating varying proportions of biopolymer powder. The data indicate a clear inverse correlation between bulk density and the amount of biopolymer additive: as the biopolymer content increases, the bricks become progressively lighter. Specifically, the highest density measured was 1.24 g/cm³ at 1 wt% addition, while the lowest bulk density, 0.85 g/cm³, was observed at 20 wt%. This reduction in density is primarily attributed to the lower intrinsic density of the biopolymer material compared to natural clay. These biopolymers are rich in organic constituents such as cellulose, hemicellulose, and lignin [14], all of which possess lower densities than clay minerals. Their inclusion reduces the overall mass of the composite material. In addition to their low density, these organic components interfere with the tight packing of clay particles during mixing and compaction. The fibrous nature of the biopolymer disrupts the homogeneous structure of the clay matrix, increasing porosity and reducing internal cohesion.

Table 2. Bulk density of clay-biopolymer brick samples.

Samples	Bulk Density ρ (g/cm^3)				Coefficient of Variation*		
	Trial 1	Trial 2	Trial 3	Mean Value	Trial 1	Trial 2	Trial 3
Clay + Additive 0%	1.23	1.24	1.26	**1.24**	0.81	0.81	1.61
Clay + Additive 1%	1.21	1.20	1.22	**1.21**	0.00	0.83	1.82
Clay + Additive 3%	1.18	1. 15	1.16	**1.16**	1.72	0.86	0.00
Clay + Additive 7%	1.14	1.13	1.14	**1.13**	0.88	0.00	0.88
Clay + Additive 15%	0.94	0.95	0.97	**0.95**	1.05	0.00	2.10
Clay + Additive 20%	0.84	0.85	0.85	**0.85**	1.17	0.00	0.00

Note: *Coefficient of variation (%) = 100 × $|\rho_{trial} - \rho_{mean}| / \rho_{mean}$.

As a result, the final bricks are not only lighter but also more porous, which contributes to easier handling and transportation, an aspect particularly relevant to SDG 9 (Industry, Innovation, and Infrastructure), which promotes resilient infrastructure and sustainable industrialization. Additionally, according to standard classifications, materials with bulk densities below 1.75 g/cm³ qualify as lightweight bricks. All the fabricated compositions in this study meet that criterion. These observations are consistent with previous findings. For instance, Jannat et al. [26] recorded a 30% reduction with 10% of sawdust inclusion.

3.2. Porosity Test

As shown in **Table 3**, there is a clear inverse relationship between biopolymer content and porosity in unfired clay bricks, highlighting the significant role of biopolymers in tailoring pore structure. Bricks incorporating 20 wt% biopolymer exhibited markedly lower porosity (4.1%), whereas those containing only 1 wt% reached a higher porosity level (7.6%), resulting in a 48% reduction compared to the reference brick. This unexpected trend stems from the biopolymer's organic makeup, where cellulose and hemicellulose form fibrous networks that intertwine with the SiO_2-rich clay matrix, boosting particle bonding and reducing voids [27]. Additionally, wet processing and optimized mold vibration ensured uniform dispersion and improved compaction. The use of finely powdered biomass-based additives further contributed to minimizing air entrapment, resulting in denser products [28].

Table 3. Porosity of clay-biopolymer brick samples.

Samples	Porosity ϕ (%)				Coefficient of Variation*		
	Trial 1	Trial 2	Trial 3	Mean Value	Trial 1	Trial 2	Trial 3
Clay + Additive 0%	7.79	7.90	7.83	**7.88**	1.42	0.25	0.63
Clay + Additive 1%	7.45	7.61	7.75	**7.60**	1.97	0.13	1.97
Clay + Additive 3%	6.13	6.10	6.07	**6.10**	0.49	0.00	0.49
Clay + Additive 7%	5.65	5.63	5.64	**5.64**	0.17	0.18	0.00
Clay + Additive 15%	4.66	4.61	4.68	**4.65**	0.21	0.86	0.64
Clay + Additive 20%	4.10	4.07	4.13	**4.10**	0.00	0.73	0.73

Note: *Coefficient of variation (%) = 100 × $|\phi_{trial} - \phi_{mean}| / \phi_{mean}$.

In a related investigation, Djenabou et al. [29] found that unfired bricks reinforced with straw displayed a 6% reduction in porosity compared to conventional bricks, with a 10% straw content yielding the most favorable results. These findings support the proposed mechanism whereby cellulose/hemicellulose components interact with clay particles through hydrogen bonding and physical pore-filling effects, effectively restricting pore volume [30]. Comparable results were reported by El-Sayed et al. [31], who studied the development of lightweight concrete incorporating cement kiln dust (CKD) and liquefied polystyrene foam (LPS). Their work demonstrated that a 30% LPS–CKD blend achieved a substantial 51.3% reduction in porosity, largely attributed to the efficient void-filling action of the liquefied polymer. Collectively, such studies highlight the ability of both lignocellulosic and synthetic polymer additives to regulate porosity, indicating a synergistic effect between organic and inorganic phases [32].

3.3. Capillary Water Absorption Coefficient Test

The capillary water absorption (CWA) behavior of clay-biopolymer brick specimens was quantitatively assessed using standardized immersion testing. While recent advances like Kabir et al.'s [33] AI-driven smart sensor system offer automated sorptivity measurement with remarkable precision for cementitious materials, our study employed conventional immersion methods due to sample size limitations. As systematically documented in **Table 4**, results revealed a pronounced correlation between biopolymer additive content and CWA. Control specimens (0 wt% additive) displayed characteristic CWA of 0.73 $kg/m^2.min^{0.5}$, whereas biopolymer-modified formulations showed significantly enhanced water resistance, demonstrating the effectiveness of these additives in modifying CWA behavior. Notably, the 20 wt% additive formulation reduced CWA by 71%, yielding the lowest recorded coefficient of 0.21 $kg/m^2.min^{0.5}$. This optimal performance correlates directly with the brick's minimized porosity, suggesting that the biopolymer additive induces microstructural modifications that effectively limit capillary pore connectivity. The significantly improved hydrophobic properties of biopolymer-modified bricks present compelling advantages for construction applications, particularly in regions with variable climatic conditions [34]. However, the improved water resistance comes with an inherent trade-off in materials: introducing biopolymer additives reduces the brick's bulk density from a reference value of 1.24 g/cm^3 to 0.85 g/cm^3 at the 20 wt% loading level (discussed in section 3.1). This density reduction stems from the primary factor of the lower density of the organic filler compared to the clay matrix. While such microstructural evolution is beneficial for water resistance, it necessitates careful consideration in structural applications where mechanical performance is paramount. Moreover, biopolymer powder improves the performance of unfired clay bricks due to its unique physicochemical properties [30]. With its high water absorption (5.89 ± 0.29 mL/g) and retention (4.21 ± 0.04 g/mL) capacities, it stabilizes moisture in the clay matrix, thereby reducing crack formation during drying. Its swelling capacity (7.12 ± 0.15 mL/g) fills voids, thereby decreasing porosity and CWA, a finding similar that of straw additives [29]. The fibrous cellulose structure prevents water infiltration. These properties enhance the durability of bricks by minimizing erosion, cracking, and moisture damage. The use of clay-biopolymer composites in weather-resistant construction is optimal [35], and further testing of these materials is recommended for future studies.

Table 4. CWA of clay-biopolymer brick samples.

Samples	CWA ($Kg/m^2.min^{0.5}$)				Coefficient of Variation*		
	Trial 1	Trial 2	Trial 3	Mean Value	Trial 1	Trial 2	Trial 3
Clay + Additive 0%	0.65	0.79	0.76	**0.73**	10.95	8.21	4.10
Clay + Additive 1%	0.60	0.69	0.74	**0.67**	10.44	2.98	10.44
Clay + Additive 3%	0.36	0.44	0.64	**0.48**	25.00	8.33	33.33
Clay + Additive 7%	0.42	0.24	0.28	**0.35**	20.00	31.42	20.00
Clay + Additive 15%	0.37	0.31	0.24	**0.30**	23.33	3.33	20.00
Clay + Additive 20%	0.20	0.24	0.21	**0.21**	4.76	14.28	0.00

Note: *Coefficient of variation (%) = $100 \times | CWA_{trial} - CWA_{mean}| / CWA_{mean}$.

3.4. Compressive Strength Test

Table 5 indicates that the compressive strength of the brick samples decreases with increasing biopolymer content. The reference sample exhibits a compressive strength of 9.6 MPa, whereas the brick containing 20 wt% biopolymer shows a reduced strength of 7.79 MPa, representing a decline of approximately 15%. The light organic compounds contained in powdered biomass, such as cellulose, hemicellulose, and lignin, act as weakening agents within the clay matrix. They disrupt the bonds between clay particles, decreasing the internal cohesion of the structure and making it more susceptible to compression. Additionally, reducing the clay content and increasing the biopolymer dosage disrupts the clay particle arrangement, reducing the minerals' crystallinity and the bricks' cohesion. Additionally, the biopolymer, acting as a dispersed phase, creates interfaces with the clay matrix. This disrupts the continuity of the solid phase, reducing the compaction and compressive strength of the bricks. Similar studies, such as those by AlShuhail et al. [36], found a significant decrease in the compressive strength of bricks reinforced with date palm fibers, from 4.5 MPa to 2.2 MPa at a 3% content.

Table 5. Compressive strength of clay-biopolymer brick samples.

Samples	Compressive Strength σ (MPa)				Coefficient of Variation*		
	Trial 1	Trial 2	Trial 3	Mean Value	Trial 1	Trial 2	Trial 3
Clay + Additive 0%	9.41	9.65	9.44	**9.50**	0.94	1.57	0.63
Clay + Additive 1%	9.13	9.20	9.21	**9.18**	0.54	0.21	0.32
Clay + Additive 3%	8.92	8.81	9.01	**8.91**	0.11	1.12	1.12
Clay + Additive 7%	8.84	8.74	8.88	**8.82**	0.22	0.56	0.68
Clay + Additive 15%	8.37	8.39	8.50	**8.42**	0.59	0.35	0.95
Clay + Additive 20%	7.75	7.98	7.64	**7.79**	0.51	2.43	1.92

Note: *Coefficient of variation (%) = $100 \times |\sigma_{trial} - \sigma_{mean}| / \sigma_{mean}$.

Overall, the utilization of pea shell waste additives confers numerous benefits; however, their incorporation into unfired clay bricks typically leads to a reduction in compressive strength [37]. A comprehensive investigation into the size of these additives could facilitate the determination of an optimal size that would minimize the negative effects [38]. Furthermore, a recent study by Abdelkader et al. [39] demonstrated that the addition of lime significantly enhances the mechanical performance of unfired bricks, particularly their compressive strength. Lime's role as a natural binder contributes to enhanced internal cohesion, reduced cracking, and increased structural durability, while concurrently reducing maintenance requirements.

3.5. Thermal Properties Test

As shown in **Table 6**, incorporating biopolymers into brick samples significantly enhances their thermal performance. Specifically, thermal conductivity decreases by 41%, from 0.45 W/m.K for the reference sample to 0.26 W/m.K at 20 wt% (**Table 6**). Concurrently, specific heat capacity increases by 18%, from 0.77 kJ/kg.K for the reference sample to 0.91 kJ/kg.K at 20 wt% (**Table 7**). These improvements can be attributed to the biopolymer's organic composition, which exhibits superior insulating properties compared to pure clay. By forming a thermal barrier within the clay matrix, the biopolymer effectively reduces heat transfer. This enhanced insulation is particularly advantageous in extreme climates, improving indoor comfort while lowering energy consumption. These findings are consistent with previous research: Lertwattanaruk et al. [40] observed a 36% increase in specific heat capacity with 6% rice husk additives, while a study confirms that higher additive contents further reduce thermal conductivity and increase heat capacity [41].

Table 6. Thermal performance of clay-biopolymer brick samples: Thermal conductivity.

Samples	Thermal Conductivity λ (W/m.K)				Coefficient of Variation*		
	Trial 1	Trial 2	Trial 3	Mean Value	Trial 1	Trial 2	Trial 3
Clay + Additive 0%	0.44	0.45	0.45	0.45	2.22	0	0
Clay + Additive 1%	0.42	0.42	0.43	0.42	0	0	2.38
Clay + Additive 3%	0.39	0.39	0.38	0.39	0	0	2.56
Clay + Additive 7%	0.35	0.35	0.37	0.35	0	0	5.71
Clay + Additive 15%	0.31	0.30	0.30	0.30	3.33	0	0
Clay + Additive 20%	0.26	0.25	0.27	0.26	0	3.84	3.84

Note: *Coefficient of variation (%) = 100 × | λ_{trial} - λ_{mean}| / λ_{mean}.

Table 7. Thermal performance of clay-biopolymer brick samples: Specific heat capacity.

Samples	Specific Heat Capacity Cp (kJ/kg.K)				Coefficient of Variation*		
	Trial 1	Trial 2	Trial 3	Mean value	Trial 1	Trial 2	Trial 3
Clay + Additive 0%	0.78	0.77	0.78	**0.77**	1.29	0.00	1.29
Clay + Additive 1%	0.79	0.79	0.80	**0.79**	0.00	0.00	1.26
Clay + Additive 3%	0.82	0.81	0.82	**0.82**	0.00	1.22	0.00
Clay + Additive 7%	0.86	0.85	0.84	**0.85**	1.17	0.00	1.17
Clay + Additive 15%	0.89	0.89	0.9	**0.89**	0.00	0.00	0.01
Clay + Additive 20%	0.92	0.91	0.91	**0.91**	1.09	0.00	0.00

Note: *Coefficient of variation (%) = 100 × | Cp_{trial} - Cp_{mean}| / Cp_{mean}.

The developed clay-biopolymer composite bricks outperform conventional bricks in thermal efficiency, contributing to energy savings and improved occupant well-being. Moreover, the unfired brick production method aligns with circular economy principles, offering both economic and environmental benefits. Its lower energy requirement supports SDG 7 (Affordable and Clean Energy), reduces production costs, and promotes sustainable industrial growth through eco-friendly construction solutions.

3.6. Thermomechanical Performance: Analysis and Modeling

The thermomechanical performance of unfired clay-biopolymer bricks indicates a clear trade-off between thermal and mechanical properties. Bricks exhibiting enhanced thermal insulation, characterized by lower thermal conductivity and higher specific heat capacity, tend to show a slight reduction in compressive strength. This phenomenon can be attributed to the composite nature of the material, wherein the incorporation of biopolymer enhances insulation efficiency but concurrently threatens structural cohesion. **Figure 6** illustrates the correlation between the thermal properties (thermal conductivity and specific heat capacity) of clay-biopolymer composite bricks and their compressive strength as a function of wt% biopolymer. Each property was modeled with a high correlation coefficient, revealing distinct trends. The experimental findings and their corresponding models demonstrated a nearly linear relationship between thermal conductivity (λ) and compressive strength (σ). Conversely, as the biopolymer content increased, the σ increased while the λ decreased, as indicated by their modeling with good respective correlation coefficients (R^2 = 0.936 and R^2 = 0.964). Conversely, the specific heat capacity (Cp) exhibited dualistic behavior, with its best-fit modeling following either an allometric model (exponent = 0.047) or a linear function. Both of these models yielded high correlation coefficients (R^2 = 0.979 and R^2 = 0.944, respectively). In principle, the models predict an optimal biopolymer content ranging from 6.41 wt% (minimum) to 8.25 wt% (maximum), with an average predicted value of 7.33 wt%. This theoretical average closely matches the experimentally determined optimum of 7 wt%, thereby confirming the substantial agreement between the models and experimental results. The findings of the present study demonstrate that the optimal amount of biopolymer is 7 wt%. Consequently, the clay-biopolymer composite bricks demonstrated a compressive strength of σ = 8.81 MPa. Furthermore, the bricks demonstrated favorable thermal properties, characterized by a thermal conductivity (λ) of 0.36 W/m.K and a specific heat capacity (Cp) of 0.84 kJ/kg.K. These results align with a previous study on polyethylene glycol (PEG 6000)-modified unfired clay bricks, where 7% by weight of PEG 6000 was also identified as the optimal percentage for producing high-performance bricks [25]. However, Soliman et al. [42] reported that fired clay bricks with a 7% eggshell additive, processed at 1100°C, exhibited enhanced thermal insulation and durability, including a 57.5% higher compressive strength and 52.7% porosity. However, the high-temperature firing process used by other manufacturers is energy-intensive and emits CO_2. In contrast, our unfired brick method provides a more eco-friendly alternative, with lower energy consumption and reduced environmental impact. Despite these advantages, challenges related to waste management persist, particularly in Africa. Edomah et al. [43] underscore the importance of cultivating technical competencies in sustainable waste management. In this context, our study proposes a simple yet innovative approach to producing unfired clay bricks by reusing organic waste. This approach contributes to waste valorization and sustainable construction.

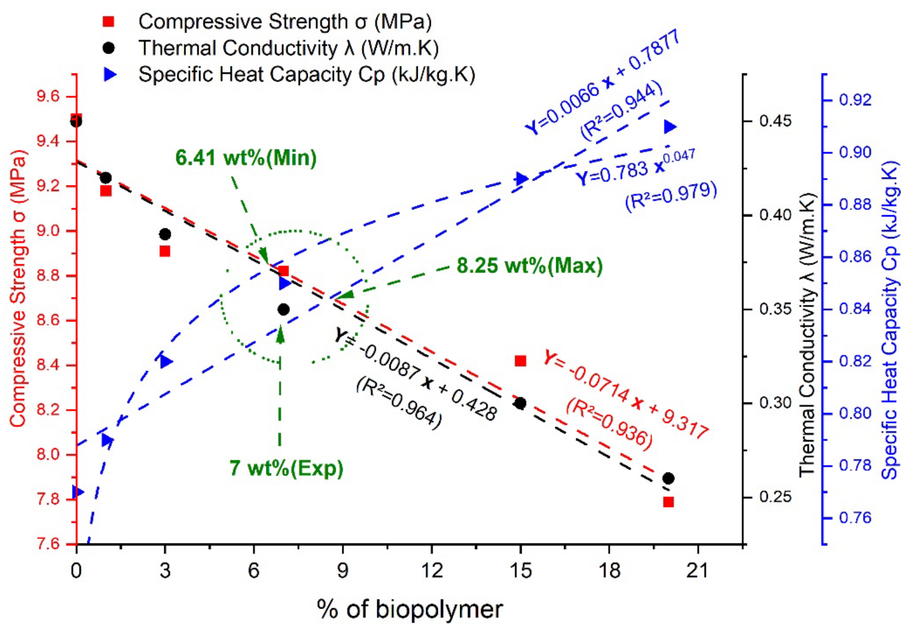

Figure 6. Correlation between thermal properties and compressive strength of clay-biopolymer composite bricks.

3.7. Simulation of Thermal Insulation Parameters

To assess the thermal insulation performance of clay-biopolymer composite construction materials incorporating pea shell waste, a thermal simulation was conducted using TRNSYS software. This simulation relied on thermal conductivity, specific heat capacity, and bulk density values that had been previously measured for the brick samples. The simulation was conducted in a single-story reference room measuring (6 m × 5 m × 3 m), with exterior walls 0.30 m thick. The selected study location, Meknes city (Morocco), boasts a Mediterranean climate with continental influences, making it a suitable representative case for testing building materials under contrasting seasonal conditions. The summers are typically hot and dry, with average temperatures between 25 and 35 °C and peaks up to 40 °C, while the winters are mild and humid, ranging from 5 to 15 °C. The region receives an annual average of 600 mm of precipitation, primarily concentrated between October and April. The region also experiences strong solar radiation and significant diurnal temperature fluctuations, which have a considerable impact on thermal comfort and energy demand. These climatic parameters were incorporated into the TRNSYS model as boundary conditions, providing a realistic framework for evaluating the thermal performance of clay–biopolymer bricks in energy-efficient building design. The objective of the simulation was to determine the time lag and decrement factor. This assessment evaluated the delay in heat transfer through the designed brick and its impact on maintaining indoor comfort. This, in turn, influenced heating and cooling requirements under two scenarios. In the first scenario, the room was constructed using conventional unfired clay bricks without additives, while in the second, unfired clay bricks containing 7 wt% biopolymer were utilized. By comparing these scenarios, the methodology enabled quantification of the pea shell waste additive's effect on the building's thermal inertia.

Figure 7 presents a comparison of the simulation results, highlighting the differences in time lag and decrement factor between the optimal formulation at 7 wt% of additive and the reference. In fact, the simulation results show an improvement in the thermal performance of the clay-biopolymer composite wall, with a 9.74% increase in time lag from 8.11 to 8.90 h and a 16% decrease in the decrement factor from 0.30 to 0.25. These improvements are attributed to the extended thermal path within the composite material, due to increased thermal resistance. In this context, Toure et al.'s [44] calculations showed that the temperature inside the cell has a time lag of about 6 h compared to the outside temperature, with a decrement factor of 0.4. In another study, the results of Shaik et al. [45] showed that fly ash bricks, whether used alone or in combination with other materials, exhibit a higher thermal damping capacity than the other materials studied. Their results in a decrement factor of 0.401 for homogeneous bricks and 0.342 for composite walls, as well as a time lag of 8.159 and 9.199 h, respectively. The results of our study are promising. Using pea shell waste as an eco-friendly additive helps achieve environmental goals, making it a valuable advancement in modern construction practices. This finding aligns with studies on other eco-friendly additives, including hemp wool [46] and vegetal fiber additives [47].

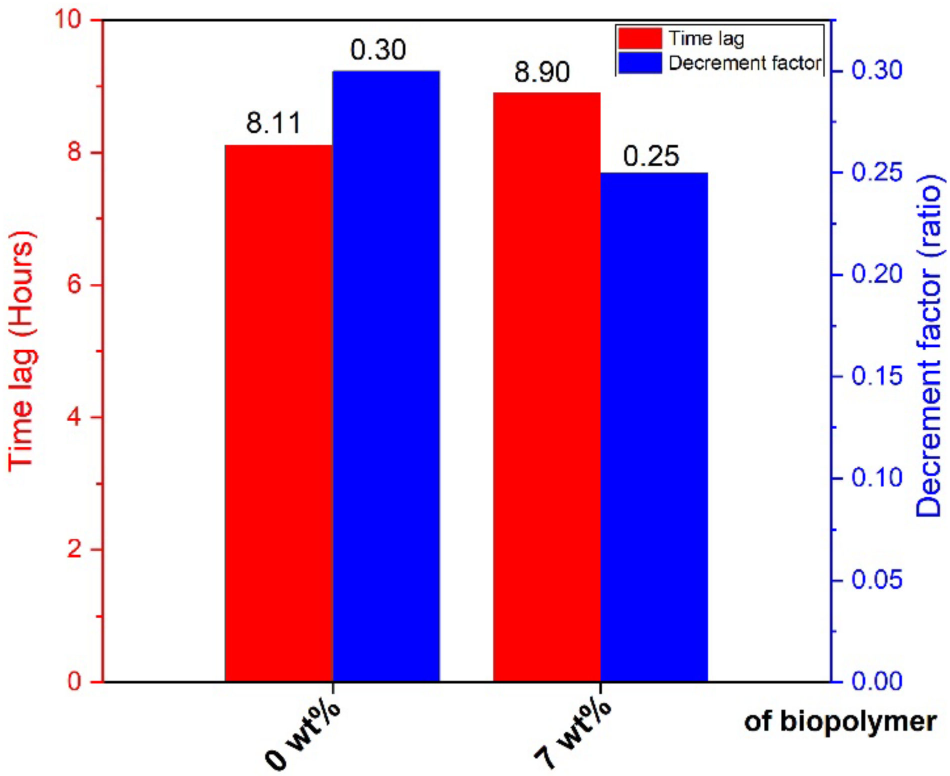

Figure 7. Simulation results comparing the time lag and decrement factor between the optimized biopolymer content brick (7 wt%) and the reference brick.

The power required to lower the temperature of a 6 m × 5 m × 3 m (90 m³) room by 10 °C in 0.8 h (Time lag difference = 8.90–8.11 ≈ 0.8 h) can be estimated from the heat balance. The mass of air to be cooled/heated is m = 106.56 kg, calculated using a density of 1.184 kg/m³. Considering the specific heat capacity of air ($c_p \approx 1005$ J/kg.K) and a temperature variation of Δ□ = 10 °C, the amount of heat to be extracted is approximately 1071 kJ = 0.2975 kWh. To achieve this cooling (heating) in 0.8 h, the required cooling capacity (P) is around P = 0.372 kW, calculated by the following equation:

$$P = \frac{m.C_p.\Delta T}{t} \quad (1)$$

Assuming a coefficient of performance (COP) of 3, the actual electrical power consumed by the air conditioner is approximately P_{elect} = 0.124 kWh over this period. In our case, the duration of 0.8 h represents an energy-saving opportunity. To estimate the annual energy consumption of a 9000 BTU/h domestic air conditioner in Morocco, for example, we can make realistic assumptions: an average usage of 0.8 h/day over 6 months, 3 months in summer and 3 months in winter, totaling 180 days/year, with a typical electricity consumption of 1.8 kW and a COP of 3. In this case, daily consumption reaches P_{day} = 1.8 kW × 0.8 h × 3 / 3 = 1.44 kWh, which leads to an annual consumption of P_{annual} = 1.44 kWh/day × 180 days = 259.2 kWh. Taking into account the Moroccan national electricity tariff of 1.5 MAD/kWh, the annual operating cost of the device will be reduced by 388.8 MAD/year per room of volume of 90m^3.

Overall, the novelty of our study lies in the composite material employed and the promising results obtained. Notably, its manufacturing process requires no heat treatment, which makes it both environmentally friendly and energy-efficient by reducing air conditioning demand. This approach aligns with the SDGs goals, particularly SDGs 12, 11, and 13, related to responsible production and clean energy.

4. Conclusion

This study investigates the sustainable use of a biopolymer derived from pea shell waste as an eco-friendly additive in unfired clay bricks, examining its impact on the material's physicochemical and thermomechanical properties. The results show that adding this recycled biopolymer greatly improves the performance of the building material, offering a promising solution for low-carbon construction materials.

- **Porosity Modifications:** The biopolymer reduces brick porosity from 7.88 wt% (reference sample) to 4.1% at a 20% biopolymer content, reaching a reduction of 48 %. This reduction is attributed to the biopolymer's fine particle size, which fills interstitial voids in the clay matrix and minimizes pore formation. This microstructural densification improves durability by limiting water infiltration and enhancing resistance to environmental degradation.
- **Mechanical Properties:** A 15% reduction in compressive strength was observed with increasing biopolymer to 20 wt%. This decrease primarily results from reduced silica content, which weakens the clay's crystalline structure. While higher biopolymer concentrations (20 wt%) significantly compromise mechanical integrity, an optimal dosage of 7 wt% maintains structural stability while enhancing other functional properties.
- **Thermal Performance Enhancement:** The natural insulating properties of the biopolymer resulted in a 41% reduction in thermal conductivity at 20 wt%, leading to a significant enhancement in thermal insulation. This improvement makes the clay–biopolymer composite bricks highly suitable for energy-efficient construction, as they effectively limit heat transfer and contribute to reducing heating (cooling) energy demand.
- **Optimal Composition and Modeling Validation:** The 7 wt% biopolymer formulation was identified as the optimal composition, as it simultaneously reduced porosity and CWA while maintaining sufficient compressive strength (σ = 8.81 MPa, λ=0.36 W/m.K, and Cp=0.84 kJ/kg.K), a result confirmed by both experimental measurements and numerical modeling.
- **Thermal Simulation:** TRNSYS thermal simulations confirmed notable improvements in thermal performance, showing a 9.74% increase in thermal time lag, from 8.11 h for the reference bricks to 8.90 h for the clay-biopolymer bricks, and a 16% reduction in decrement factor, decreasing from 0.30 to 0.25. The results reveal enhanced thermal inertia in the clay-biopolymer composite, leading to superior indoor thermal regulation and decreased energy consumption. Crucially, this thermal performance improvement was attained while maintaining structural stability, positioning these bricks as a promising material for sustainable building applications.
- **Environmental and Sustainable Development Im-**

plications: Integrating organic waste into construction materials aligns with circular economy principles by reducing landfill dependency and lowering the carbon footprint of brick production. Replacing conventional, energy-intensive fired bricks with unfired, biopolymer-modified clay bricks supports:

- SDG 11 (Sustainable Cities) by enabling energy-efficient building solutions.
- SDG 12 (Responsible Consumption and Production) by promoting waste valorization.
- SDG 13 (Climate Action) by reducing greenhouse gas emissions.

- **Future Perspectives:** Future work should optimize clay-biopolymer synergy, evaluate weathering durability, and verify scalability, complemented by Life-cycle assessment (LCA) and seismic tests to benchmark environmental and structural performance against conventional bricks.

This study demonstrates that pea shell biopolymer-modified unfired clay bricks represent a sustainable, thermally efficient alternative to conventional construction materials. By achieving an optimal balance between mechanical properties, thermal insulation performance, and environmental advantages, this innovation makes dual contributions: advancing green building practices and supporting progress toward global sustainability objectives.

Author Contributions

Methodology, I.M. and H.L.; validation, I.M. and A.B.; formal analysis, R.E.-T.; investigation, A.A.; writing—original draft preparation, R.E.-T.; writing—review and editing, H.L. and B.E.A.; supervision, K.E.K. All authors have read and agreed to the published version of the manuscript.

Funding

This work received no external funding.

Institutional Review Board Statement

This study involves no human/animal testing. We investigate materials with scientific rigor and ethical integrity.

Informed Consent Statement

Not applicable.

Data Availability Statement

The authors agree to share their research data upon request.

Conflicts of Interest

The authors declare that there is no conflict of interest.

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