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Thermo-Economic Optimization and Life Cycle Analysis of Bio-Limestone Bricks Enriched with Eggshells for Buildings

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Abstract

Tunisia is confronted with dual challenges in its energy transition and the management of organic waste, where eggshells constitute a significant yet underutilized resource, with an annual production approximating 50,000 tons. This study presents an integrated thermo-economic and environmental assessment of bio-limestone bricks incorporating eggshell waste, addressing critical gaps in sustainable construction research. The primary objectives are to present the thermophysical properties of these innovative bricks, evaluate their energy performance at the building scale through dynamic simulation, and quantify their economic viability and environmental benefits. Using dynamic thermal simulation with TRNSYS software validated by analytical solutions for a building in a Mediterranean climate. The methodology combines energy modeling with detailed economic analysis and life cycle assessment to provide a holistic evaluation framework. Key findings reveal that bricks with 20% eggshell content reduce cooling loads by 50.9% (2648 W vs. 5400 W for conventional bricks), achieve annual energy savings of 81.5 TND with a favorable 1.23-year payback period, and reduce CO_2 emissions by 51%. The originality of this work lies in a complete energy and economic simulation and a simplified environmental assessment for building materials enriched with eggshells, providing both waste recovery strategies and energy efficiency of buildings in hot climates.

Keywords: Bio-Limestone Brick; Eggshells; Energy Efficiency; Life Cycle Analysis.

1. Introduction

Sustainable construction has become a global imperative in response to the interconnected challenges of climate change, resource depletion, and waste management. The building sector, responsible for approximately 40% of global energy-related CO_2 emissions and 50% of raw material extraction, lies at the heart of this challenge [1]. This reality is particularly acute in Mediterranean regions such as Tunisia, where growing summer cooling demands exacerbate energy consumption and associated emissions. In this context, transitioning toward a circular economy in construction has emerged as an essential solution, transforming waste into resources while simultaneously reducing the sector's environmental footprint. This transition aligns with Tunisia's national commitments, particularly the National Circular Economy Strategy (2025–2035) and the Nationally Determined Contributions (NDCs), which aim for a 45% reduction in carbon emissions by 2030, identifying the building sector as a priority lever for action. However, current public policies and incentives focus primarily on the energy efficiency of equipment and systems, without specifically targeting the valorization of local waste in construction materials. Therefore, the objective of this study is to generate robust

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technical, economic, and environmental data to serve as a scientific basis for the design of future policy incentives. These instruments could include tax credits, sustainable public procurement mechanisms, or aid for circular innovation, specifically aimed at accelerating the deployment of sustainable, low-carbon construction solutions that integrate local resources.

Among the agro-industrial waste streams generated in large quantities in Tunisia, eggshells represent a remarkable yet largely untapped valorization opportunity. With an annual production estimated at several tens of thousands of tons, these organic residues are mostly landfilled, incurring management costs and negative environmental impacts. Nevertheless, their exceptional chemical composition containing over 95% calcium carbonate ($CaCO_3$) and their naturally porous microstructure make them a bio-based analogue to limestone, opening promising avenues for integration into sustainable construction materials [2, 3].

Recent international research (2019–2025) has demonstrated the multifunctional nature of eggshell powder (ESP) across diverse construction matrices. In fired clay ceramics, ESP plays a triple role: a pore-forming agent through thermal decomposition of $CaCO_3$, a mineral flux via CaO formation, and a bio-filler that modifies microstructure. The work of Tangboriboon et al. [4] systematically analyzed the impact of particle size and incorporation rate on brick properties, while Ngayakamo et al. [5] highlighted mechanisms underlying improvements in physical-thermal-mechanical properties. Vigneron & Holanda [6] further demonstrated synergistic effects when combining ESP with granite waste, optimizing both mechanical and thermal performance in clay bricks. Innovative applications extend to bi-layered ceramic tiles, where Yirijor [7] utilized ESP as an intrinsic pore-forming agent, and to laterite-based systems, as studied by Zhang et al. [8].

In the field of cementitious materials, ESP has been extensively investigated as a partial replacement for cement or limestone. Research by Mushtaq et al. [9] elucidated its influence on cement hydration and microstructure, revealing its role as a micro-filler and nucleation site for hydrates. Chong et al. [10] quantified its impact on concrete properties, establishing optimal substitution ranges. A significant advancement comes from Kumar et al. [11], who demonstrated ESP's technical viability as a sustainable alternative to limestone in composite cement production, reducing the carbon footprint associated with quarrying. Practical applications are increasingly demonstrated, such as in the production of compliant paver blocks [12]. Furthermore, hybrid systems combining ESP with other industrial by-products such as rice hull ash [13] or sawdust ash [14] show promise for maximizing cement reduction while maintaining performance, as also highlighted in recent reviews by Jannat et a. [15]. Beyond traditional fired or cement-bound systems, ESP finds application in low-energy and alternative construction materials. Consoli et al. [16] incorporated ESP with walnut shells in unburnt clay blocks (adobe), improving cohesion and reducing drying shrinkage. Thermochemical conversion of eggshells yields reactive lime, demonstrated by Gomez-Vazquez et al. [17] for soil stabilization and by Martínez Schulte et al. [18] for various construction applications, offering a bio-sourced alternative to conventional lime. Furthermore, research is evolving toward functional composite materials for specific low-carbon building components, as explored in Soliman et al. [19].

However, despite these advances in material characterization and application, significant research gaps persist. First, most studies focus on laboratory-scale properties, with limited attention to system-level performance at the building scale. Although work such as that by Nakkeeran et al. [20] explored green building development using modified bricks. Fantucci et al. [21] evaluated bio-brick masonry systems. Studies combining dynamic energy simulation with rigorous thermo-economic optimization are a well-established methodology in energy system analysis. While environmental assessment through life cycle assessment (LCA) is recognized as essential, as demonstrated by Arduin et al. [22], and studies of bio-bricks in Tariq et al. [23] and Othman et al. [24] have provided valuable information, their integration into detailed thermo-energy and economic analyses within a coherent framework is notably lacking. The specific Mediterranean and Tunisian context presents unique climatic and socio-economic conditions, often overlooked in generic studies, despite the predominance of cooling energy needs in these regions.

This study aims to address these critical gaps by proposing an integrated and holistic assessment framework for bio-limestone bricks enriched with Tunisian eggshells. The originality of this work lies in the systematic coupling of three complementary dimensions: (1) validated dynamic thermal modeling of building performance under Tunisian climate using TRNSYS software; (2) a detailed thermo-economic analysis incorporating energy savings, cost evaluation, and return on investment calculation, applying principles akin to those used in building energy and (3) a streamlined environmental assessment quantifying operational CO_2 emission reductions, thereby contributing to a more comprehensive life cycle perspective.

More specifically, this research pursues four main objectives:

- Characterize the impact of incremental eggshell incorporation (0% to 20%) on the thermophysical properties of bio-limestone bricks.
- Dynamically simulate the energy performance of a typical Tunisian residence using these innovative bricks, quantifying reductions in cooling load and energy consumption.
- Conduct a rigorous thermo-economic analysis to evaluate the profitability of the initial investment through annual savings and payback period.

- Assess the environmental benefits by calculating avoided CO_2 emissions, integrating energy, economic, and environmental metrics into a unified evaluation.

By combining validated energy simulation, rigorous economic analysis, and quantitative environmental evaluation, this study provides a comprehensive methodological framework for assessing sustainable, waste-valorized construction materials. The results aim to deliver concrete, reliable, and multi-criteria data to policymakers, construction industry stakeholders, and researchers in Tunisia and similar climatic regions, thereby promoting the adoption of truly circular, high-performance, and economically viable building solutions within an accelerated energy and environmental transition.

2. Material and Methods

This is a building (Figure 1) with an imposed or free indoor air temperature, depending on the case. This building is subject to real and variable weather conditions.

2.1. Description of the Building

2.1.1. Revit Architectural Software

The Surface area: S = 100 m² (Figure 1) is as follows:

Figure 1. Revit Architectural plan in 3D

2.1.2. Simulation of TRNSYS 2018 Software

The simulated building corresponds to a residence with a floor area of 100 m², located in a climatic zone in Tunisia. The exterior walls were defined with a thickness of 20 cm (Figure 2), and the thermo-physical properties of the material were specified based on values extracted from the literature for enriched Bio-limestone Brick.

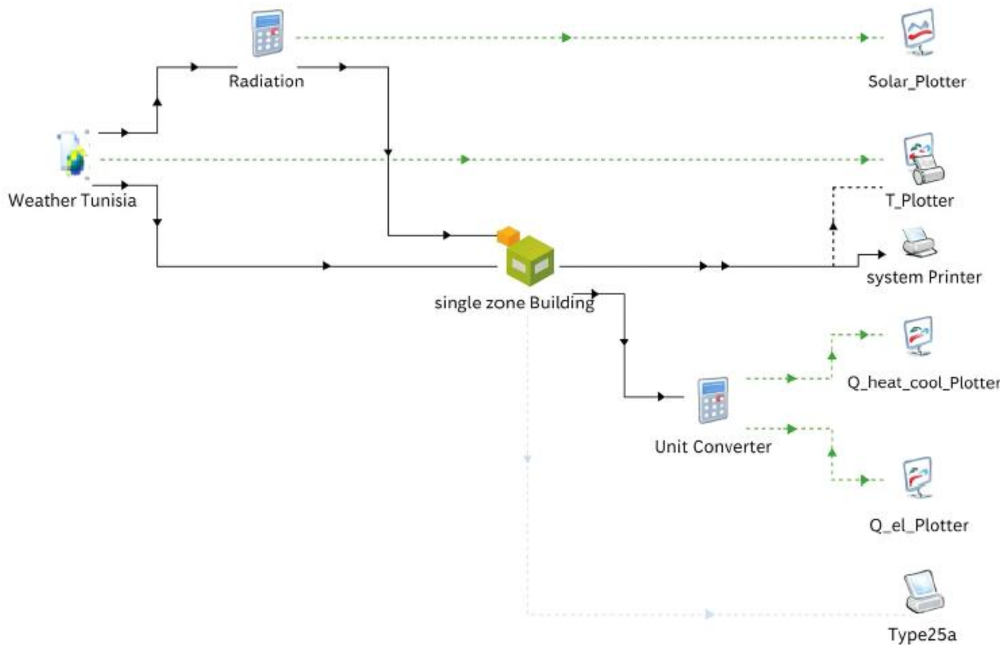

Figure 2. Simulation of the project

2.2. Material Characteristics

2.2.1. Summary Table Comparing the Properties of Different Bricks

The thermo-physical properties of the standard and innovative bricks, which serve as critical inputs for the simulation, are detailed in Table 1. These properties, including thermal conductivity (λ), specific heat capacity (Cp), and density (ρ), were derived from experimental characterization for varying eggshell content (0% to 20%). The geometric configuration of the simulated building's walls, comprising external cladding, the brick layer, and internal cladding, is illustrated in Figure 3. Similarly, the composition of the roof and ceiling layers is presented in Figure 4.

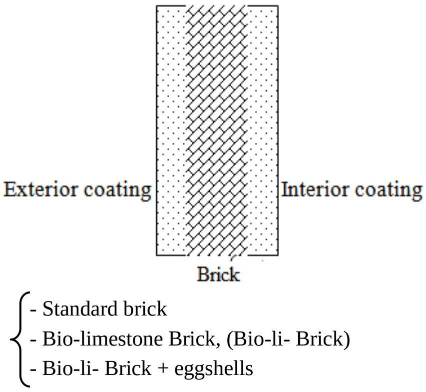

Figure 3. Vertical walls

Figure 4 shows a roof and ceiling structure. It is composed of two main layers: concrete and insulation.

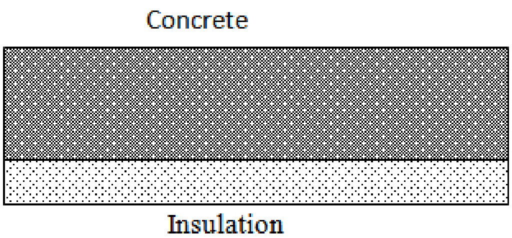

Figure 4. Roof and Ceiling

Table 1. Thermo-physical characteristics of the building walls

Materials	% Eggshells	λ (KJ /h.m.k)	Cp (KJ/kg·K)	ρ (kg/m³)	Thickness (cm)
Exterior Interior coating	-	1.26	1	1700	1.5
Concrete	-	6.12	0.8	2400	15
Insulation	-	0.14	1.38	40	5
Standard brick	-	3.16	0.87	1800	20
Bio-limestone brick (Bio-li-Brick)	0%	1.98	0.85	1650	20
	5 %	1.8	0.830	1550	20
	10 %	1.51	0.80	1450	20
	15 %	1.29	0.78	1370	20
	20 %	1.11	0.76	1300	20

3. Mathematical Formulation

3.1. Assumptions

- One-dimensional heat transfer is assumed
- Thermal bridges and contact resistances between layers are neglected
- The solar radiation incident on the exterior wall surface is assumed to be uniform, including both direct and diffuse components.

- The indoor air temperature is considered uniform throughout the interior space.
- The solar flux includes the direct and the diffuse
- The thermo-physical properties of all materials are assumed to be constant, as shown in Table 1
- The convective surface resistances are set at:
  - 0.1 m² K/W for the exterior surface,
  - 0.16 m² K/W for the interior surface
- The average solar absorption coefficients are:
  - 0.2 for the interior surface (smooth and light-colored),
  - 0.35 for the exterior surface (rough and light-colored), according to data reported by Zhu & Chang [25].

3.2. Thermal Analysis

The total heat balance *P* in summer is given by the following formula:

$$P_i(t) = Ci\,\frac{dT_i(t)}{dt} = \underbrace{P_{sur,i}(t) + P_{inf,i}(t) + P_{ven,i}(t)}_{Q_i(t)} + \underbrace{P_{app,i}(t)}_{\text{Internal gains}} + \underbrace{P_{app,s}(t)}_{\text{Solar gains}} + \underbrace{P(t)}_{\text{Cooling (or heating) power}} \tag{1}$$

The heat losses $Q_i(t)$ consist of three main components of (Equation 1), as detailed in Tables 2 to 4.

Table 2. Decomposition of terms of Heat losses $Q_i(t)$

Termes	Formulation		Variables
$P_{sur,i}(t)$: Convective flow exchanged with all interior surfaces [KJ/h]	$\sum_i U_{surf,i} Ai \left(T_i(t) - T_{surf,i}(t)\right)$	(2)	**$U_{surf,i}$:** Total heat transfer coefficient of the wall (convection and conduction) [KJ/h. m².k] **Ai:**Surface [m²] **$T_i(t)$**:Indoor air temperature of the building [°C]
$P_{inf,i}(t)$: Exchanges by infiltration (gains or losses) [KJ/h]	$\rho\ cp\ V_{inf}\ (T_i(t) - T_{out}(t))$	(3)	ρ: air density (1.2 Kg/m3] Cp: Heat capacity of air (1.005[KJ/kg.k]) V_{inf}: air infiltration rate [m^3/h]
$P_{ven,i}(t)$: The exchanges by ventilation coming from a heating or cooling system [KJ/h]	$\rho\ cp\ V_{vent}\ (T_i(t) - T_{out}(t))$	(4)	**V_{vent}:** air ventilation rate [m^3/h]

Table 3. The decomposition of the thermal gains' terms of Equation 1

Termes	Formulation		Variables
$P_{app,i}(t)$: internal gains [KJ/h]	$p_{Ocp} + p_{eqp} + p_{lig}$	(5)	p_{Ocp}: Internal convective gain occupant p_{eqp}: Internal convective gain equipment p_{lig}: Internal convective gain lighting
$P_{app,s}(t)$: Contributions through opaque surfaces (walls) [KJ/h]	$\alpha\, G_{sol} Ai\, \Delta t$	(6)	α: absorption coefficient of the wall receiving the radiation G_{sol}: solar radiation factor

- Where the temperature is imposed: we calculate the cooling load P(t) required to maintain the constant set-point temperature T_i= 25 °C, $\frac{dT_i(t)}{dt} = 0$.
- Where the air temperature is free, the cooling load P(t) =0, we express the indoor air temperature of the building $T_i(t)$: $P_i(t) = Ci\,\frac{dT_i(t)}{dt}$.

3.3. Analytical Solution:

$$T_i(t) = T_{out}(t) + \left(T_{i,o} - T_{out}(t)\right) e^{-\frac{t}{\tau}} + \frac{1}{Ci}\int_{u=0}^{u=t} \left(P_{app,i}(u) + P_{app,s}(u)\right) e^{-\frac{t-u}{\tau}}\, du \tag{8}$$

Table 4. Decomposes the terms of Equation 8

Termes	Description	Formulation
Ci [KJ/K]	Effective heat capacity of the surface	$(\rho\ cp\ V_i)$ Vi = Volume of the surface [m^3]
$T_{out}(t)$ [°C]	Outdoor temperature	File input variable (Weather Tunisia)
$T_{i,o}$[°C]	Initial interior temperature at t=0	Initial condition
$\tau = \frac{Ci}{\rho\ cp\ (V_{inf}+V_{vent})+U_{surf,i}Ai}$ [h]	Thermal time constant	Thermal time constant

3.4. Economic Analysis

3.4.1. Annual Cooling Energy Consumption

The annual energy consumption for cooling is calculated as follows:

$$E = \frac{P(t)}{3600} \times t \tag{9}$$

where, E: Annual energy consumption (kWh); P: Cooling power (KJ/h) of Equation 1; t: Annual cooling duration: 500 hours per day (reasonable value for Mediterranean climate, adjustable in TRNSYS model).

The annual cooling duration of 500 hours is derived from the dynamic simulation results under typical residential use. The economic payback remains highly attractive (well under 2 years) across a realistic range of operating hours, as the annual savings scale linearly with this duration while the key performance indicator—the 51% reduction in peak cooling load—remains constant

3.4.2. Annual Electricity Cost

The corresponding annual electricity cost is calculated as:

$$C = E \times C_u \tag{10}$$

where, C: Annual electricity cost (TND); C_u: Unit electricity cost (TND/kWh), taken here as 0.213 TND/kWh [26].

3.5. Payback Period (Return on Investment)

The payback period is calculated as:

$$ROI = \frac{C_s}{\Delta c} \tag{11}$$

where, ROI: Payback period in years; C_s: Additional initial investment cost of the modified brick (TND); Δc: Annual savings (TND/year).

3.6. Environmental Impact

3.6.1. Annual CO_2 Emissions

$$ECO_2 = E \times EF_{CO2} \tag{12}$$

where, ECO_2 : Annual CO_2 emissions (kg); EF_{CO_2}: Emission factor for the Tunisian environment is 0.709 $kgCO_2$/kWh according to ANME reports and STEG reports [26].

3.6.2. Percentage of CO_2 Emissions

$$ECO_2(\%) = \frac{E_{CO2,S}-E_{CO2,m}}{E_{CO2,S}} \tag{13}$$

where, $E_{CO2,S}$: CO_2 emissions from the standard brick (kg); $E_{CO_2,S}$ = 750 × 0.70 = 531.75 kg/an.

4. Results and Discussion

4.1. Weather Conditions Results

Figure 5 illustrates the annual variation of outdoor temperature in Tunisia, revealing a clear cyclical trend. Temperature peaks are observed during summer months, reaching maximum values of around 42°C**,** reflecting the region's typical seasonal dynamics.

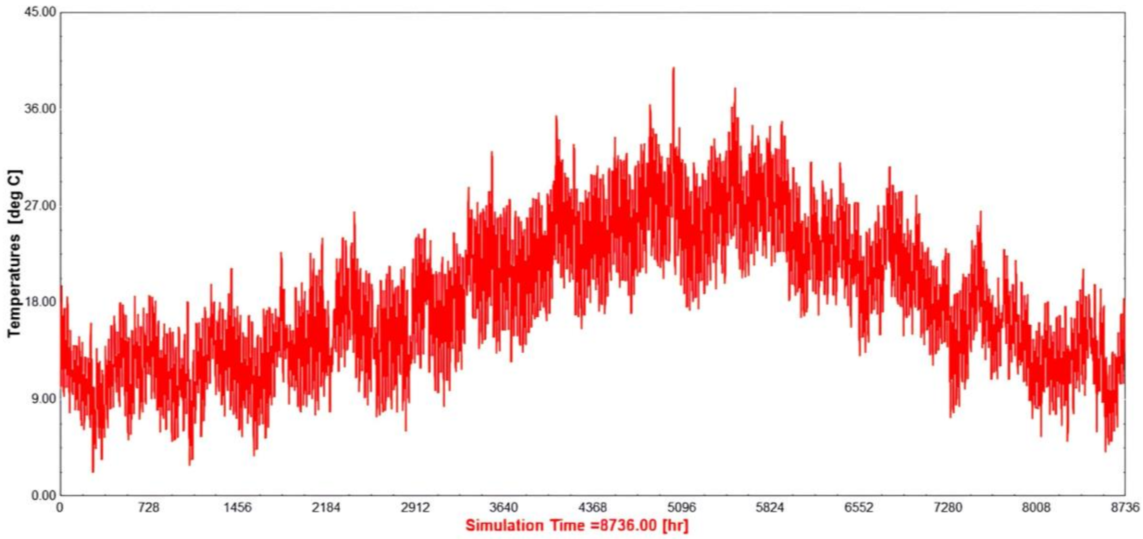

Figure 5. Annual evolution of the outside temperature of Tunisia

4.2. Validation of the Model

Figure 6 compares the indoor temperature simulated by TRNSYS (Ti TRNSYS) with the analytical solution (Ti analytical) and the outdoor temperature (Tout) in July. The curves of (Ti TRNSYS) and (Ti analytical) superpose almost perfectly, confirming the accuracy of the numerical model for a building with standard brick walls. The slight decrease in indoor temperatures suggests a high thermal inertia, typical of materials such as brick, which dampens rapid fluctuations. This consistency between simulation and analytical model validates the use of TRNSYS for thermal studies of buildings.

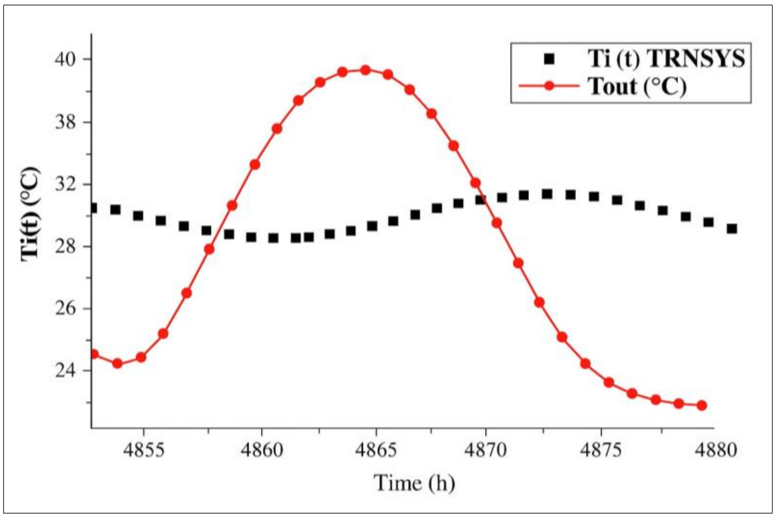

Figure 6. Comparison of simulated (TRNSYS) and analytical indoor temperatures for a standard brick-walled building in July

Table 5 presents a comparison between (Ti TRNSYS) and (Ti analytical) over a similar range to Figure 6. The results show excellent agreement between the two methods, with very low absolute errors (≤ 0.0183°C) and relative errors not exceeding 0.06%, which confirms the accuracy of the TRNSYS model in simulating the thermal behavior of the building. These results validate the reliability of TRNSYS for modeling heat transfer in standard brick constructions, with negligible error margins for practical applications.

Absolute errors (°C) = | Ti (t)TRNSYS-Ti (t)analytical |

Relative errors (%) = | (Ti (t)TRNSYS-Ti (t)analytical)/(Ti (t)TRNSYS) | *100%

Table 5. Comparison of TRNSYS and analytical indoor temperatures with error calculation for a brick-walled building

Time (h)	T_i (t) TRNSYS (°C)	T_i (t) Analytical (°C)	Absolute errors (°C)	Relative errors (%)
4853	32.7478	32.7478	0.0000	0.00%
4854	32.5206	32.5389	0.0183	0.06%
4855	32.2830	32.3012	0.0182	0.06%
4856	32.0518	32.0695	0.0177	0.06%
4857	31.8433	31.8604	0.0171	0.05%
4858	31.6838	31.7003	0.0165	0.05%
4859	31.5914	31.6073	0.0159	0.05%
4860	31.5715	31.5869	0.0154	0.05%
4861	31.6241	31.6390	0.0149	0.05%
4862	31.7411	31.7555	0.0144	0.05%
4863	31.9107	31.9246	0.0139	0.04%
4864	32.1235	32.1369	0.0134	0.04%
4865	32.3694	32.3823	0.0129	0.04%
4866	32.6334	32.6458	0.0124	0.04%
4867	32.8995	32.9115	0.0120	0.04%
4868	33.1536	33.1651	0.0115	0.03%
4869	33.3784	33.3895	0.0111	0.03%
4870	33.5466	33.5572	0.0106	0.03%
4871	33.6390	33.6493	0.0103	0.03%
4872	33.6552	33.6651	0.0099	0.03%
4873	33.6020	33.6115	0.0095	0.03%
4874	33.4866	33.4958	0.0092	0.03%
4875	33.3152	33.3240	0.0088	0.03%
4876	33.0962	33.1047	0.0085	0.03%
4877	32.8371	32.8453	0.0082	0.02%
4878	32.5488	32.5567	0.0079	0.02%
4879	32.2515	32.2591	0.0076	0.02%
4880	31.9627	31.9701	0.0074	0.02%

The close agreement between TRNSYS simulations and analytical solutions (Figure 6, Table 6) validates the reliability of the thermal model employed in this study. The maximum relative error of 0.06% is well within accepted thresholds for building energy simulation, ensuring that subsequent performance comparisons are both robust and scientifically sound. This validation is critical, as it supports the transferability of the findings to other building typologies and climatic zones beyond Tunisia. It also provides a trustworthy foundation for policymakers, architects, and engineers to adopt these results in the development of energy codes, thermal regulations, and sustainable building design guidelines.

4.3. Case Where the Air Temperature Is Free

Based on model validation (Figure 6, Table 5). Figure 7 illustrates the evolution of the interior wall surface temperature over time for different types of bricks, compared to the outdoor ambient temperature. The ambient temperature follows a typical diurnal cycle, peaking around noon and decreasing at night. The standard brick closely follows outdoor temperature variations, displaying a pronounced peak. This indicates high thermal transmission and poor insulation, leading to rapid and significant heat transfer into the building. In contrast, all **Bio-**limestone based Brick, including those enriched with egg shell waste (5 to 20%)**,** exhibit a much flatter temperature curve. These materials more effectively dampen thermal variations, resulting in lower internal temperature peak**s** and delayed thermal response. Among them, the Bio-limestone Brick with 20% eggshells shows the lowest peak temperature, demonstrating superior thermal insulation and phase shift. This confirms that the incorporation of eggshell waste improves thermal inertia, making interiors more stable and reducing cooling needs.

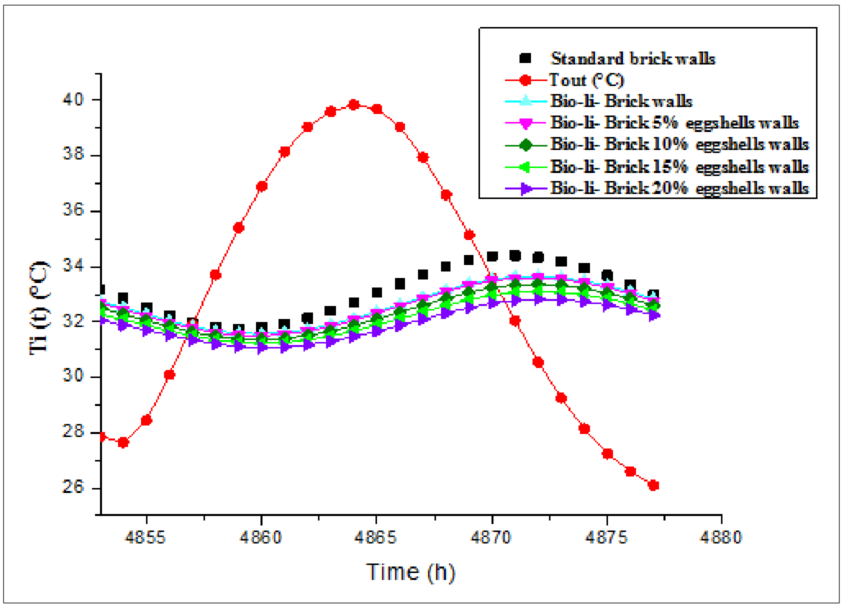

Figure 7. Evolution of indoor air temperature during July

4.4. Case Where the Interior Air Temperature of Building is Imposed

4.4.1. Evolution of Cooling Power for Standard Brick

Figure 8 presents the cooling power required to maintain thermal comfort in a building constructed with standard brick. The trend likely shows high energy consumption, reflecting the limitations of this brick in terms of thermal insulation. Fluctuations could be linked to outdoor temperature variations or the material's intrinsic properties.

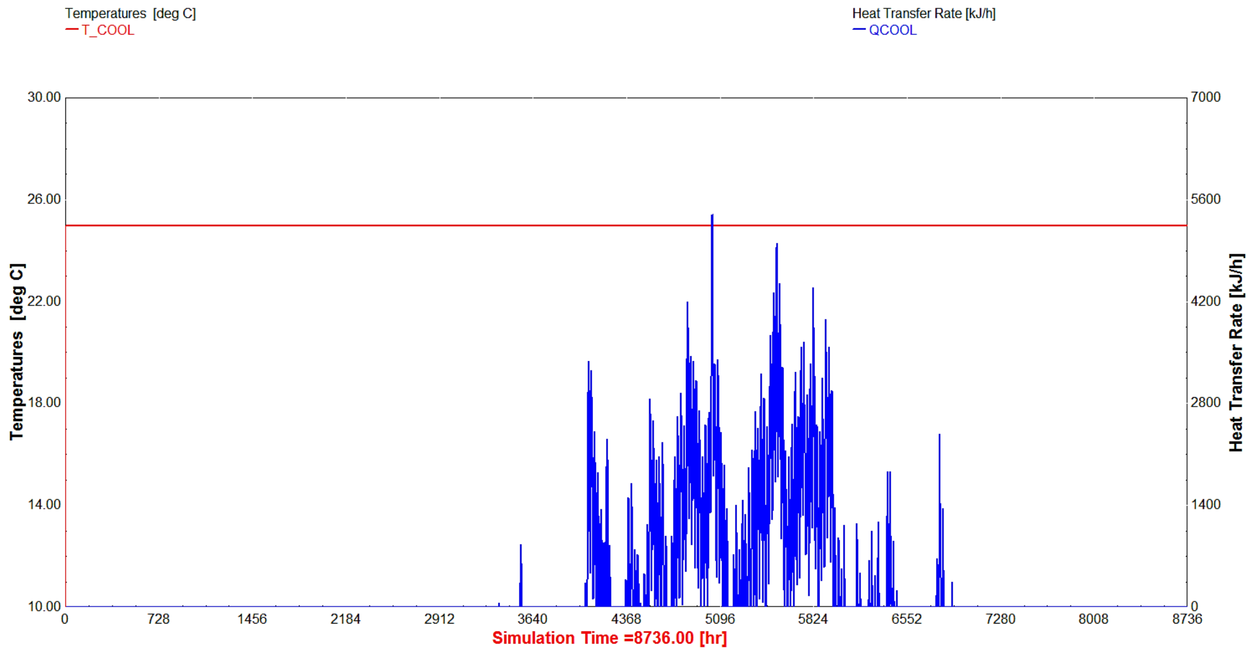

Figure 8. Evolution of Cooling Power for standard brick

4.4.2. Evolution of Cooling Power for Bio-limestone Brick

Figure 9 illustrates the cooling power required to maintain thermal comfort in a building constructed with Bio-limestone Brick. This figure shows the performance of Bio-limestone brick, which appear to offer better thermal insulation than standard brick, as evidenced by generally lower cooling power. This improvement could be due to the porous structure or natural properties of the Bio-limestone material.

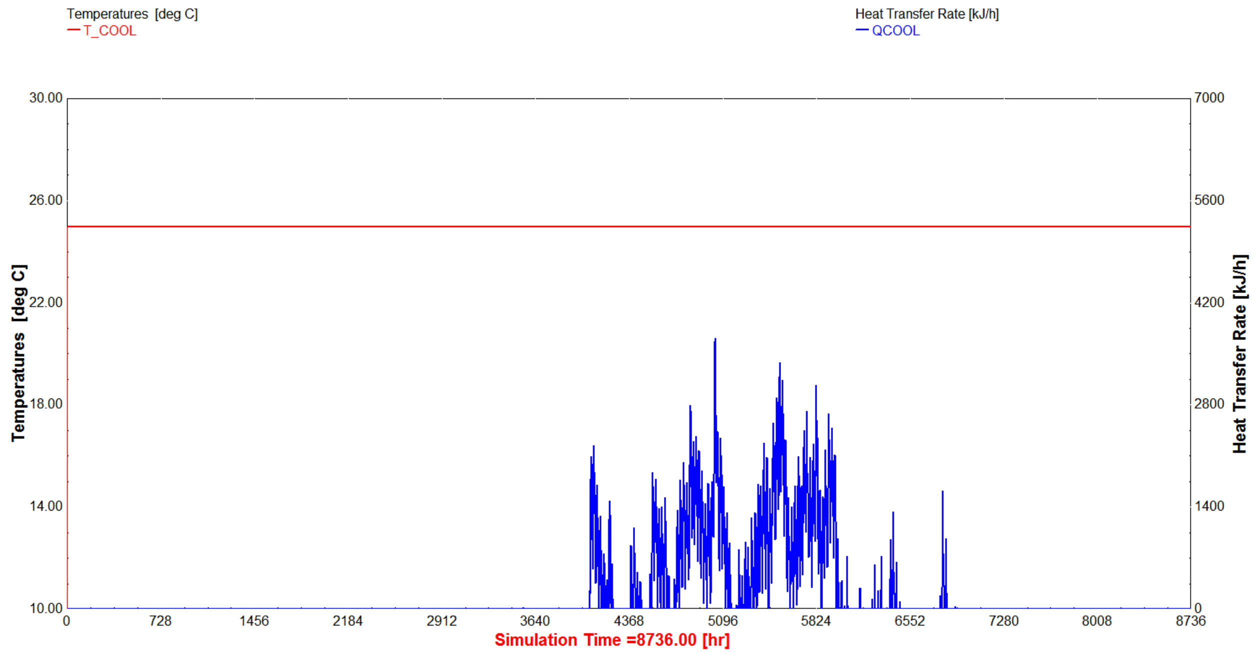

Figure 9. Evolution of Cooling Power for Bio-Limestone Brick

Figure 10 illustrates the cooling power required to maintain thermal comfort in a building constructed with Bio-limestone Brick containing 5% Eggshells. This figure shows a slight reduction in cooling power, suggesting that eggshells could improve the insulating properties of the material. This curve presents that the addition of 5% eggshells appears to slightly improve the thermal efficiency of the Bio-Limestone Brick.

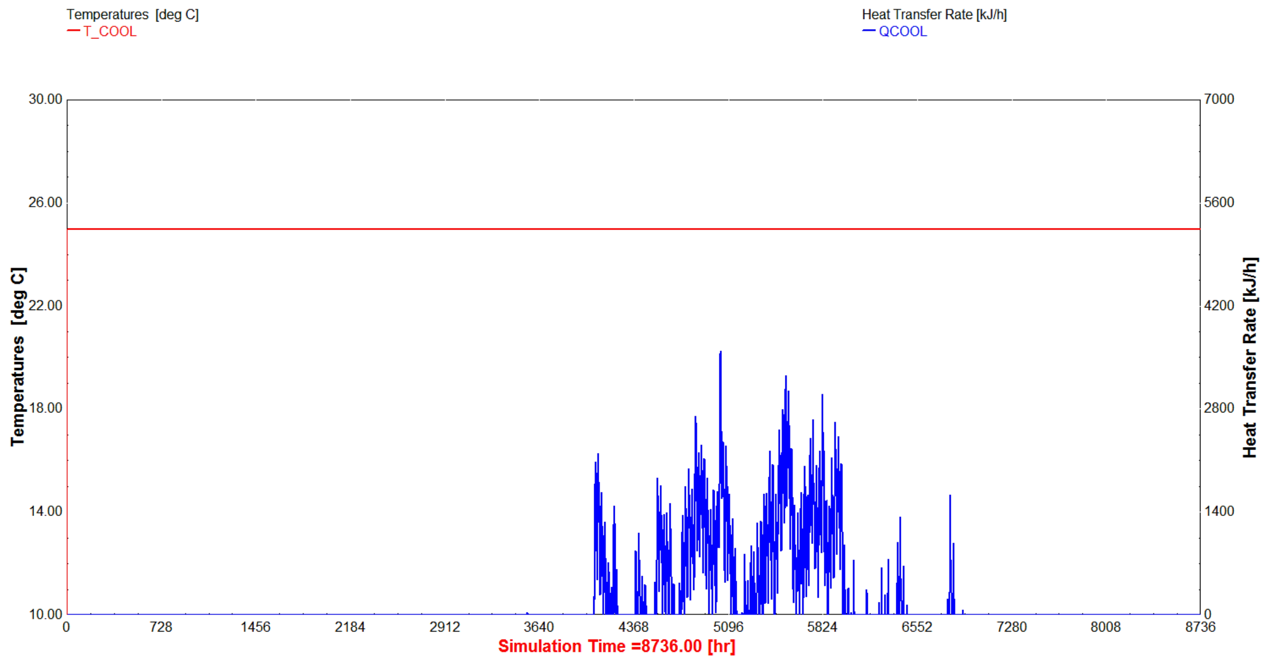

Figure 10. Evolution of Cooling Power for Bio-limestone Brick with 5% Eggshells

4.4.3. Evolution of Cooling Power for Bio-limestone Brick with 10% Eggshells

Figure 11 shows the cooling power required to maintain thermal comfort in a building constructed with Bio-limestone Brick containing 10% Eggshells. With a higher proportion of eggshells (10%), the Figure 11 indicates a more marked decrease in cooling power. This confirms that eggshells, in greater quantities, significantly improve the thermal performance of brick, reducing energy demands.

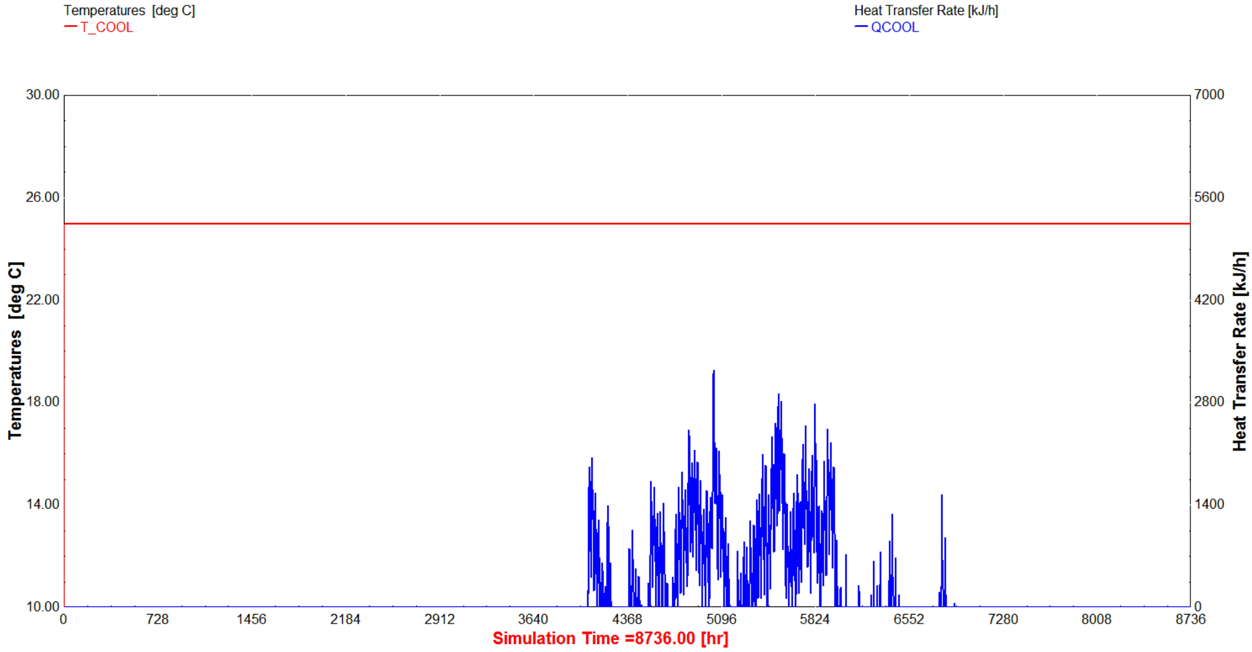

Figure 11. Evolution of Cooling Power for Bio-limestone Brick with 10% Eggshells

4.4.4. Evolution of Cooling Power for Bio-limestone Brick with 15% Eggshells

Figure 12 indicates the cooling power required to maintain thermal comfort in a building constructed with Bio-limestone Brick containing 15% Eggshells. At 15% eggshells, Figure 12 shows notable optimization of thermal insulation. The cooling power is significantly lower, suggesting that this composition could represent an ideal balance between eggshell addition and material performance.

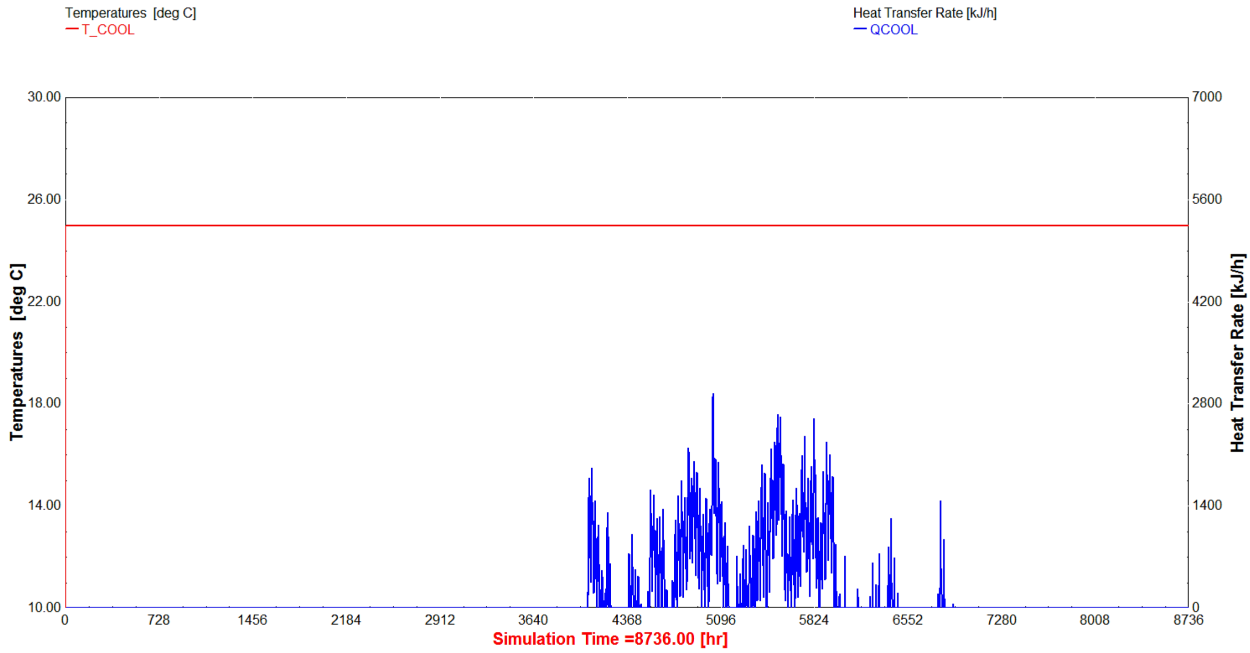

Figure 12. Evolution of Cooling Power for Bio-Limestone Brick with 15% Eggshells

4.4.5. Evolution of Cooling Power for Bio-Limestone Brick with 20% Eggshells

Figure 13 shows the cooling power required to maintain thermal comfort in a building constructed with Bio-limestone Brick containing 20% Eggshells. This figure clearly shows that adding eggshells to bio-limestone brick improves their thermal performance, thus reducing the required cooling power.

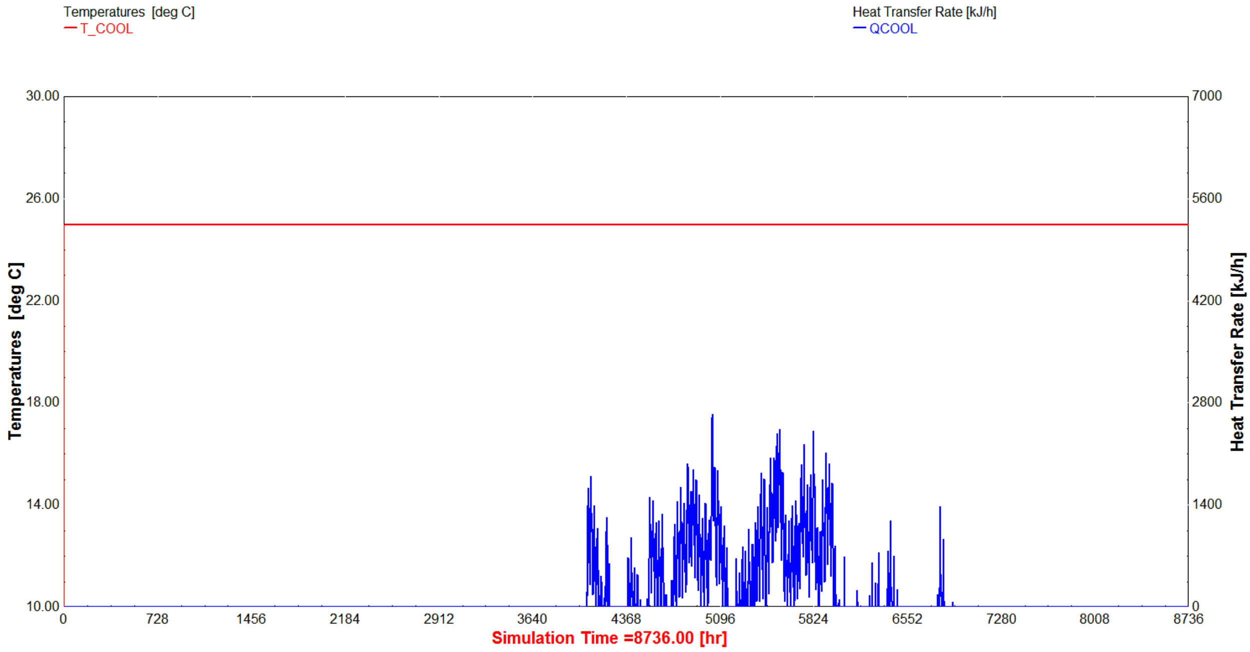

Figure 13. Evolution of Cooling Power for Bio-Limestone Brick with 20% Eggshells

4.4.6. Thermal Performance

According to the previous figures, Table 6 shows a substantial reduction in cooling load demand when replacing standard clay brick with bio-limestone alternatives. Based on Table 7, the standard brick requires a cooling power of 5400 W, while bio-limestone brick without additives reduces this power to 3700 W, a 31.5% reduction. Further improvements are achieved by incorporating eggshell waste, with the best performance observed for brick containing 20% eggshells, which reduce the cooling load to 2648 W**,** corresponding to a 50.9% decrease. These results confirm the superior thermal insulation properties provided by the bio-limestone matrix and the porous structure introduced by eggshell additives. The reduction in cooling demand directly translates into lower energy consumption and operating costs, making these bricks an effective passive solution for improving indoor thermal comfort and energy efficiency in hot climates.

Table 6. Comparative Cooling Power for Different Bricks

Brick Type	Cooling Power P (KJ/h)	Reduction vs. SB (%)	Observation
Standard Brick	5400	0%	Reference (poor performance)
Bio-Limestone Brick	3700	31,5%	Better base insulation
Bio-Limestone Brick + 5% Eggshells	3594	42,9%	Significant gain
Bio-Limestone Brick + 10% Eggshells	3241	40,0%	Slightly lower performance than 5%
Bio-Limestone Brick + 15% Eggshells	2944	45,5%	Interesting optimization
Bio-Limestone Brick + 20% Eggshells	2648	50,9%	Best performance

The progressive reduction in cooling load with increasing eggshell content, as summarized in Table 6, can be attributed to the combined effects of reduced thermal conductivity and enhanced thermal inertia conferred by the porous microstructure of eggshells. Eggshells, composed predominantly of calcium carbonate (CaCO2), introduce micro-pores during mixing and curing, which trap air a natural insulator. This results in a systematically lower thermal conductivity (λ), as evidenced in Table 2, where λ decreases from 1.98 KJ/h·m·K (0% eggshells) to 1.11 KJ/h·m·K (20% eggshells). This decline in thermal conductivity directly correlates with the reduction in cooling power demand, confirming the insulating role of the eggshell additive.

Moreover, the phase shift observed in Figure 7 where Bio-limestone Brick with 20% eggshells exhibits delayed and dampened temperature peaks indicates improved thermal lag. This property is particularly advantageous in Mediterranean climates, where external temperature fluctuations are pronounced. The brick's enhanced ability to absorb and slowly release heat reduces peak cooling demands, thereby flattening the daily cooling load profile. The 50.9% reduction in cooling power for the 20% eggshell formulation is not merely a linear improvement; it suggests a synergistic effect where eggshells optimize both insulation and thermal mass, making the brick especially effective under dynamic thermal conditions. This dual performance reducing both peak load and total energy demand positions eggshell-enriched bricks as a promising passive cooling solution for buildings in hot climates.

4.4.7. Economic Calculation in Tunisian Dinars (TND*)

Table 7 presents the impact of different types of bricks on refrigeration energy consumption, correlated annually with the Tunisian dinar (TND), enabling cost savings compared to standard bricks. The comparative analysis of different brick types highlights notable thermal performance improvements and a significant reduction in cooling energy consumption when replacing standard bricks with eggshell-enriched Bio-limestone Brick. The standard brick, used as a reference, has an annual consumption of 750 kWh, with an associated cost of 159.8 TND. Using Bio-limestone Brick reduces this consumption to 514 kWh, resulting in annual savings of 50.3 TND. The progressive incorporation of eggshells further enhances these performances: at 10%, consumption drops to 450 kWh (95.9 TND), with savings of 63.9 TND; at 15%, it reaches 409 kWh (87.2 TND), representing savings of 72.6 TND. The best performance is achieved with 20% eggshells, where consumption is 368 kWh and the annual cost is 78.3 TND, resulting in savings of 81.5 TND compared to the standard brick. These results confirm the technical and economic interest of integrating local organic waste, such as eggshells, into construction materials to reduce cooling energy demand and promote sustainable solutions.

Table 7. Energy Consumption and Annual Cost for Different Bricks

Brick Type	Annual Energy Consumption E (kWh)	Annual Cost C (TND)	Annual Savings Δc (TND/year)
Standard Brick	750	159,8	0
Bio-Limestone Brick	514	109,5	50,3
Bio-Limestone Brick + 5% Eggshells	500	106.3	53.5
Bio-Limestone Brick + 10% Eggshells	450	95,9	63,9
Bio-Limestone Brick + 15% Eggshells	409	87,2	72,6
Bio-Limestone Brick + 20% Eggshells	368	78,3	81,5

4.4.8. Payback Period (Return on Investment)

Table 8 compares different types of Bio-limestone Brick with varying percentages of eggshell additives (ranging from 0% to 20%). It presents three key indicators: the initial cost (Cs) in Tunisian dinars (TND), the annual savings (Δc) in TND/year, and the return on investment (ROI) in years.

The data shows that adding eggshells gradually increases the initial cost, from 80 TND (0% eggshells) to 100 TND (20% eggshells). However, it also enhances annual savings, which rise from 50.3 TND/year to 81.5 TND/year. The ROI, which indicates the time needed to recoup the investment, decreases with higher eggshell content, dropping from 1.59 years (0% and 5%) to 1.23 years (20%). This suggests that, despite the higher upfront cost, bricks with more eggshell additives offer better long-term profitability due to increased savings. The 20% eggshell formulation appears to be the most economically advantageous, with the shortest ROI (1.23 years). In summary, while eggshell additives raise production costs, they significantly improve cost-efficiency over time, making them a financially viable and sustainable option.

Table 8. Payback Period for Different Bricks

Brick Type	Cost Cs (TND) [27]	Δc (TND/year)	ROI (years)
Bio-Limestone Brick	80	50,3	1.59
Bio-Limestone Brick + 5% Eggshells	85	53.5	1.59
Bio-Limestone Brick + 10% Eggshells	90	63,9	1.41
Bio-Limestone Brick + 15% Eggshells	95	72,6	1.31
Bio-Limestone Brick + 20% Eggshells	100	81,5	1.23

The economic viability of eggshell-enriched bricks is demonstrated not only through annual energy savings but also through their accessibility within the local Tunisian market. The incremental cost increase from 80 TND (0% eggshells) to 100 TND (20% eggshells) is modest, especially when considering the rising costs of conventional insulation materials and electricity tariffs in Tunisia. The payback period of 1.23 years for the 20% eggshell brick is remarkably short, particularly within the construction sector where return-on-investment periods often exceed 5–10 years. This rapid return is driven by the substantial cooling energy savings (81.5 TND/year), which account for a significant portion of household energy expenses during summer months.

* 1 TND = 0.34 USD (December 2025)

4.4.9. Environmental Impact

Table 9 presents the environmental impact of different types of bricks used in construction. The environmental impact of using eggshell-enriched bio-limestone bricks is positive, particularly in terms of reducing greenhouse gas emissions. Replacing the standard brick with a Bio-limestone Brick results in a significant decrease in CO_2 emissions, from 531.75 kg/year to 364.73 kg/year, a reduction of 31.4%. This reduction is amplified with increasing eggshell content in the brick composition. At 20% incorporation, emissions drop to 260.51 kg/year, representing a 51% reduction compared to the reference. This not only reduces the building's carbon footprint over its lifecycle but also limits the environmental impacts associated with conventional construction materials. Thus, integrating eggshells into bricks represents a dual-benefit solution: improving building energy efficiency while promoting sustainability.

Table 9. Environmental Impact on Different Bricks

Brick Type	E (kWh)	ECO_2(kg/year)	ECO_2(%)
Standard Brick	750	531 ,75	-
Bio-Limestone Brick	514	364,73	31,4
Bio-Limestone Brick + 5% Eggshells	500	354,50	33,3
Bio-Limestone Brick + 10% Eggshells	450	319,05	40
Bio-Limestone Brick + 15% Eggshells	409	290,08	45,4
Bio-Limestone Brick + 20% Eggshells	368	260,51	51

The 51% reduction in operational CO_2 emissions for the 20% eggshell brick (Table 9) aligns closely with Tunisia's National Energy Strategy and its commitments under the Paris Agreement. This reduction is driven by two primary factors:

- Lower embodied carbon: Eggshells partially replace limestone, which is typically quarried and processed an energy-intensive activity with notable carbon emissions.
- Reduced operational energy: The improved thermal performance decreases electricity consumption for air conditioning, which in Tunisia is largely generated from natural gas, thus lowering associated greenhouse gas emissions.

When viewed through a life cycle lens, these bricks also contribute significantly to waste diversion. With approximately 50,000 tons of eggshells produced annually in Tunisia, their integration into construction materials could meaningfully reduce landfill use and associated methane emissions. This dual benefit mitigating both upstream (material) and downstream (operational) impacts positions eggshell-enriched bricks as a low-carbon material choice suitable for inclusion in sustainable building

5. Conclusions

This research demonstrates the viability and significant advantages of bio-limestone bricks enriched with eggshells for sustainable construction. The integrated assessment, combining validated dynamic thermal simulation, rigorous economic analysis, and a simplified life cycle analysis, reveals that incorporating 20% eggshells results in a material with high thermal performance. These innovative bricks reduce air conditioning needs by 50.9% compared to conventional clay bricks, directly translating into substantial annual energy savings of 81.5 Tunisian dinars (TND) for a typical residential building in a Mediterranean climate. The economic analysis confirms the financial attractiveness of this solution, with a return on investment of 1.23 years despite a slight increase in the initial material cost. This favorable return on investment stems from the significant reduction in energy expenditure related to air conditioning, a major factor in building energy consumption in hot regions.

From an environmental perspective, the use of eggshells in the construction sector addresses crucial waste management challenges while reducing the carbon footprint of buildings. The study quantifies a 51% reduction in CO_2 emissions related to energy consumption for air conditioning. The advantages of this study are:

- Diverting organic waste from landfills and reducing greenhouse gas emissions
- Positioning eggshell-enriched bricks as a compelling circular economy solution.

The results provide a robust multi-criteria framework for evaluating sustainable building materials, going beyond simply characterizing properties to achieve a holistic assessment of performance at the building system level. This research thus offers policymakers, industrial actors and researchers concrete evidence and a methodological model to promote the adoption of high-performance, economically viable and environmentally friendly building materials, contributing significantly to the objectives of energy transition and waste recovery in Tunisia and in similar climatic contexts.

This study, based on a validated dynamic simulation, nevertheless presents certain limitations that open avenues for future research. It assumes constant thermophysical properties for the bricks and a homogeneous quality of the eggshells, whereas these can vary depending on their origin and pretreatment. Furthermore, the environmental analysis focuses on operational emissions; a complete life cycle assessment (LCA) integrating the intrinsic carbon of manufacturing and long-term durability under real hygrothermal stresses would be necessary to establish a comprehensive environmental impact assessment. Finally, the economic model does not take into account the potential costs of industrial scale-up. It is precisely to address these limitations that the next phase of this work includes systematic experimental validation, including the fabrication of prototypes, accelerated durability tests, and in-situ monitoring in an instrumented test cell in Tunisia, in order to solidify the transition of this promising innovation to a practical and certified application.

6. Declarations

6.1. Author Contributions

Conceptualization, N.L. and D.H.; methodology, N.L.; software, N.L.; validation, N.L. and D.H.; formal analysis, N.L.; investigation, N.L.; resources, N.L.; data curation, N.L.; writing—original draft preparation, N.L.; writing—review and editing, N.L.; visualization, N.L.; supervision, D.H.; project administration, N.B.; funding acquisition, N.B. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

6.4. Conflicts of Interest

The authors declare no conflict of interest.

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