

LONG-TERM THERMO-KINETIC STABILITY AND PREDICTIVE MODELING OF A NOVEL BIO-BASED PHASE CHANGE MATERIAL: *STIPA ICHU* LIGNOCELLULOSIC FIBERS IMPREGNATED WITH BOVINE TALLOW

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ABSTRACT

The transition toward zero-emission building infrastructures requires the integration of high-performance phase change materials (PCMs) that demonstrate exceptional long-term cyclical stability. This research presents the synthesis and rigorous thermo-kinetic evaluation of a novel, shape-stabilized organic biocomposite. Utilizing vacuum-assisted impregnation, refined bovine tallow was successfully encapsulated within the lumen of alkaline-treated *Stipa ichu* fibers, achieving a substantial 60 wt% PCM loading capacity. The chemically modified lignocellulosic network exhibited robust capillary confinement, severely restricting fluid leakage to below 4.5% under extreme thermal stress (65 °C). To meticulously assess operational longevity, the biocomposite was subjected to an accelerated degradation protocol comprising 1,000 continuous melt-freeze cycles. Differential Scanning Calorimetry (DSC) elucidated a remarkable thermal resilience, with the composite retaining 95.4% of its initial latent heat (decreasing marginally from 145.2 J/g to 138.5 J/g) while maintaining a stable phase-transition temperature at 43.2 °C. Furthermore, Fourier-transform infrared spectroscopy (FTIR) analyses corroborated the system's absolute chemical inertness post-aging, evidenced by the complete absence of oxidative degradation markers such as hydroperoxides. To extrapolate these empirical findings into a practical operational timeframe, a Support Vector Regression (SVR) computational model was deployed. The predictive analytics forecast that the biocomposite will sustain a critical latent heat threshold (>130 J/g) for approximately 2,500 continuous cycles. In the context of the severe diurnal temperature variations characteristic of the Andean highlands, this thermodynamic endurance correlates to a functional service life surpassing 7 years. Consequently, this architected animal fat/*Stipa ichu* matrix presents a highly viable, ecologically benign alternative for advanced thermal mass regulation in sustainable architectures.



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I. INTRODUCTION

The decarbonization of the building sector has emerged as a critical global priority, given that residential and commercial structures account for approximately 40% of global energy consumption and 33% of greenhouse gas emissions [1]. In high-altitude regions, such as the Andean Paramo, the challenge is exacerbated by extreme diurnal temperature fluctuations (ranging from −5°C to 25°C, which impose heavy heating loads on conventional envelopes [2]. Furthermore, in these equatorial highlands, the roof surfaces are subjected to intense solar radiation, leading to surface temperatures significantly higher than the ambient air [3].

Consequently, the PCM selection criteria must prioritize a melting point capable of managing these peak radiative loads to mitigate overheating risks during maximum irradiance hours [4]. To address this, Latent Heat Thermal Energy Storage (LHTES) systems employing Phase Change Materials (PCMs) offer a promising solution by increasing the thermal inertia of lightweight construction materials, thereby stabilizing indoor temperatures and reducing peak heating demand [5]. Conventionally, the PCM market has been dominated by paraffin waxes (derived from petroleum) and salt hydrates [6]. While effective, paraffins pose flammability risks and lack sustainability, whereas salt hydrates suffer from phase segregation and supercooling during repeated cycling [7]. Consequently, research has shifted towards bio-based PCMs, specifically fatty acids and triglycerides derived from agricultural by-products [8]. Animal fats, such as bovine tallow, present an attractive circular economy opportunity: they are abundant, cost-effective, and possess melting points (40 – 15°C) suitable for building applications [9]. However, the direct incorporation of liquid lipids into building matrices is hindered by their tendency to leak during the solid-liquid phase transition, necessitating effective containment strategies [10].

Shape-stabilization via physical impregnation into porous support matrices has proven to be a viable technique to prevent leakage. While synthetic matrices (e.g., expanded graphite, silica) are widely used, they increase the carbon footprint of the composite [11]. A more sustainable approach involves the use of natural lignocellulosic fibers. In this context, *Stipa ichu*, a graminoid species endemic to the Andean highlands, exhibits unique morphological characteristics specifically a hierarchical hollow structure or "lumen" that hypothetically serves as an ideal natural vessel for PCM encapsulation [12]. Despite the potential of bio-composites, a critical gap remains in the scientific literature: reliability. Most studies focus on the thermal properties of "fresh" materials (Cycle 0), neglecting the degradation mechanisms that occur over years of service. Organic PCMs are susceptible to oxidative aging and changes in crystalline polymorphism, which can drastically reduce latent heat capacity over time [8]. Furthermore, there is a lack of robust mathematical models capable of predicting the service life of these bio-materials under realistic operating conditions.

Objective and Novelty

This study addresses these gaps by developing a form-stable bio-composite PCM (**AF-Ichu/60**) utilizing bovine tallow encapsulated within alkaline-treated *Stipa ichu* fibers. Unlike previous works that are limited to characterization, this research provides a comprehensive thermal reliability assessment based on three pillars:

1. **Microstructural Engineering:** Optimization of the vacuum impregnation process based on wetting theory and capillary pressure (Section II).
2. **Long-term Durability:** An accelerated aging protocol of 1,000 thermal cycles, monitoring chemical stability via FTIR and thermal evolution via DSC.
3. **Predictive Modeling:** The implementation of a Machine Learning approach (Support Vector Regression - SVR) to forecast the material's lifespan beyond experimental limits.

The findings of this work contribute to the development of low-carbon, durable thermal regulation systems, offering a scientifically validated solution for sustainable housing in cold climate regions.

II. THEORETICAL REFERENCE

II.1 STRUCTURAL THERMODYNAMICS OF HIGH-ANDEAN LIGNOCELLULOSIC MATRICES

Stipa ichu, an endemic graminoid of the Andean Paramo ecosystem (>3500 m.a.s.l.), functions as a natural thermal insulator due to its hierarchical porous architecture [13]. The elementary fiber consists of a central hollow cavity (lumen) surrounded by a cell wall of cellulose microfibrils embedded in a hemicellulose-lignin matrix [14]. From a heat transfer perspective, the effective thermal conductivity (k_{eff}) of this porous medium is governed by the volume fraction of the solid phase and the entrapped static air [15]. Since the thermal conductivity of air ($k_{air} \approx 0.026 \frac{W}{m.K}$) is significantly lower than that of the cell wall ($k_{cell} \approx 0.35 \frac{W}{m.K}$), the lumen acts as a high-resistance thermal barrier [16]. For a bio-composite application, the fiber serves a dual function: thermal insulator and encapsulation vessel. The retention of the liquid PCM within the lumen is not governed by gravity but by capillary forces. The capillary pressure barrier (P_c) required to prevent leakage is described by the Young-Laplace equation [17] (Eq. 1):

$$P_c = \frac{2\gamma_{LV}\cos\theta}{r} \quad (1)$$

Where γ_{LV} is the surface tension of the liquid PCM, θ is the contact angle at the solid-liquid interface, and r is the effective capillary radius. For spontaneous impregnation and retention ($\theta < 90^\circ$), the surface energy of the fiber must be increased. This theoretical constraint necessitates the removal of hydrophobic amorphous constituents (waxes, lignin) via alkaline hydrolysis (mercerization) to expose the hydrophilic hydroxyl groups (-OH) of the cellulose.

II.2 PHYSICOCHEMICAL BEHAVIOR AND POLYMORPHISM OF ANIMAL FAT

Bovine tallow (BT) is a heterogeneous mixture of triglycerides, primarily composed of palmitic (C16:0) and stearic (C18:0) fatty acids. Unlike simple molecular liquids, triglycerides exhibit monotropic polymorphism, crystallizing into three distinct sub-cell structures depending on thermal history: α (hexagonal, metastable), β' (orthorhombic), and β (triclinic, most stable) [18]. For thermal energy storage, the β -polymorph is the critical phase as it possesses the highest density and enthalpy of fusion (ΔH_m). The total thermal energy (Q) stored by the composite over a temperature range ($T_i \rightarrow T_f$) encompassing the phase transition (T_m) is quantified by [19] Eq. (2):

$$Q = \int_{T_i}^{T_m} C_{p,s}(T)dT + \phi \cdot \Delta H_m + \int_{T_m}^{T_f} C_{p,l}(T)dT \quad (2)$$

Where $C_{p,s}$ and $C_{p,l}$ are the specific heat capacities of the solid and liquid states, respectively, and ϕ is the mass fraction of the PCM. The experimental validation must therefore focus on quantifying ΔH_m and monitoring the stability of the β -form, as repeated cycling can induce polymorphic transitions that alter the energy storage density.

II.3 DEGRADATION MECHANISMS AND RELIABILITY THEORY

The long-term service life of organic bio-composites is limited by two thermodynamic instabilities:

1. **Thermo-oxidative Degradation:** Unsaturated fatty acid chains are susceptible to autoxidation via free radical mechanisms at elevated temperatures, leading to the formation of hydroperoxides and subsequent cleavage into volatile compounds [20]. This chemical decay directly impacts the latent heat capacity.
2. **Volumetric Expansion Mismatch:** Phase transition from solid to liquid induces a volumetric expansion ($\approx 10 - 15\%$) in animal fats. If the matrix porosity is insufficient to accommodate this volume change (ΔV), internal pressure builds up, potentially overcoming P_c (Eq. 1) and causing macroscopic leakage [21].

III. MATERIALS AND METHODS

The temperature contours, visualized in Figure 4, reveal a progressive thermal stratification along the longitudinal axis of the absorber plate. The overall experimental workflow adopted in this study, from raw material processing to long-term reliability assessment and characterization, is schematically illustrated in Figure 1.



Figure 1: Schematic overview of the experimental methodology. (a) Pre-treatment of raw materials: thermal purification of animal fat and alkaline modification of *Stipa ichu* fibers. (b) Bio-composite synthesis via vacuum impregnation to ensure capillary infiltration. (c) Accelerated thermal aging protocol illustrating the temperature cycling profile. (d) Summary of physicochemical characterization techniques employed.

Source: Authors, (2026).

III.1 RAW MATERIALS AND PRE-PROCESSING

The Phase Change Material (PCM) selected was refined bovine tallow (BT), sourced from the Andean region of Ecuador ($0^{\circ}13'S, 78^{\circ}31'W$). As shown in Figure 1(a), the raw adipose tissue underwent thermal extraction at $90 \pm 1^{\circ}C$ for 120 min, followed by filtration ($20 \mu m$ mesh) and centrifugation (4000 rpm, 15 min) to isolate the lipid fraction. The supporting matrix, *Stipa ichu* fibers, was treated to modify its surface energy as required by the wetting theory (Section II.A).

Fibers were immersed in an analytical grade NaOH solution (98% purity, Sigma-Aldrich) at 5 wt% concentration for 4 hours (25°C, fiber-to-liquor ratio 1:20). This alkaline hydrolysis removes amorphous lignin and hemicellulose, exposing the hydrophilic hydroxyl groups to ensure a contact angle $\theta < 90^\circ$ for spontaneous impregnation. The fibers were subsequently washed and dried to constant mass. The supporting matrix, *Stipa ichu* fibers, was harvested from the paramo ecosystem (3,600 m.a.s.l.). Prior to synthesis, the physicochemical properties of the raw materials were characterized to establish a baseline. These properties are summarized in Table 1.

Table 1: Physicochemical properties of raw Bovine Tallow and *Stipa ichu* fibers.

Material	Property	Value	Unit	Method/Ref
Bovine Tallow	Melting Range (T _m)	42.0 – 45.0	°C	DSC (ASTM E1269)
	Latent Heat (ΔH _m)	145.2 ± 2.5	J/g	DSC (ASTM E1269)
	Specific Heat (C _p , solid)	1.85	J/g · K	Literature
	Density (ρ, solid)	910	kg/m ³	Pycnometer
<i>Stipa ichu</i>	Cellulose Content	42.5 ± 1.2	%	TAPPI T203
	Lignin Content	22.4 ± 0.8	%	TAPPI T222
	Lumen Diameter	15 – 20	μm	SEM Analysis
	Moisture Content	8.5	%	Gravimetric

Source: Authors, (2026).

III.2 BIO-COMPOSITE PREPARATION VIA VACUUM IMPREGNATION

The composite (AF-Ichu/60) was synthesized with a target PCM mass fraction (ϕ) of 60%. To overcome the capillary pressure barrier (P_c) defined in Eq. (1), the liquid BT and fibers were subjected to vacuum impregnation at -0.08MPa for 45 minutes, depicted in Figure 1(b). This negative pressure is critical to evacuate air from the lumen, allowing the liquid fat to penetrate the microstructure upon repressurization. The form-stability was quantified using the Leakage Percentage Test (L_R). Cylindrical specimens (20 mm diameter 10 mm height) were placed on quantitative filter paper (Whatman No. 42) and subjected to a thermal stability test ranging from 25°C to 65°C for 120 min to identify the leakage onset limit. The leakage rate was calculated using Eq. (3):

$$L_R(\%) = \frac{M_i - M_f}{M_i} \times 100 \quad (3)$$

Where M_i and M_f are the initial and final mass of the composite. A threshold of $L_R < 5\%$ was set as the acceptance criterion for building applications.

III.3 ACELERATED THERMAL CYCLING PROTOCOL

To simulate the long-term reliability described in Section II.C, the samples were subjected to $N = 1000$ melt-freeze cycles in a climatic chamber (Mettmert HCP 108), as illustrated in Figure 1(c). The temperature profile $T(t)$ for each cycle ($\tau = 40 \text{ min}$) was programmed according to Eq. (4):

$$T(t) = \begin{cases} 15 + \beta & 0 \leq t < t_1 \\ 60 & t_1 \leq t < t_2 \\ 60 - \beta(t - t_2) & t_2 \leq t < t_3 \\ 15 & t_3 \leq t < t_4 \end{cases} \quad (4)$$

Where the heating/cooling rate $\beta = 5^\circ\text{C}/\text{min}$. This protocol equates to approximately 3 years of service life, assuming one major phase transition per diurnal cycle in the high-Andean páramo

III.4 PHYSICOCHEMICAL CHARACTERIZATION AND MODELING

The characterization techniques employed are summarized in Figure 1(d).

Differential Scanning Calorimetry (DSC)

Thermal properties were measured using a TA Instruments Q2000 calibrated with Indium standards, strictly following ASTM E1269. Samples (5 – 8mg) were tested under N_2 flow (50 mL/min). The Latent Heat of Fusion (ΔH_m) was derived by integrating the specific heat capacity peak (Eq. 5):

$$\Delta H_m = \int_{T_{onset}}^{T_{end}} \left(\frac{dH}{dt} \right) \cdot \left(\frac{dt}{dT} \right) dT \quad (5)$$

To monitor the stability of the β -polymorph (Section II.B), the Degree of Crystallinity (X_c) was calculated using Eq. (6):

$$X_c(\%) = \frac{\Delta H_{m,composite}}{\Delta H_{m,pure} \times \phi} \times 100 \quad (6)$$

Thermogravimetric Analysis (TGA)

Thermal stability was assessed (TA Instruments TGA 550) from 25°C to 600°C). The degradation rate (R_d), indicative of oxidative breakdown (Section II), was obtained from the derivative thermogravimetry (DTG) curve.

III.5 SERVICE LIFE PREDICTION VIA SVR

A Support Vector Regression (SVR) model was developed to predict ΔH_m retention. The model minimizes the structural risk using a Radial Basis Function (RBF) Kernel (Eq. 7), suitable for non-linear degradation:

$$K(x_i, x_j) = \exp(-\gamma \|x_i - x_j\|^2) \quad (7)$$

Model accuracy was validated using RMSE and R^2 on a test set (20% of data).

III.6 SERVICE LIFE PREDICTION VIA SVR

Experimental uncertainty (U_c) was estimated following NIST Technical Note 1297. The combined standard uncertainty for enthalpy measurements was $\pm 2.4\%$.

IV. RESULTS AND DISCUSSIONS

IV.1 MICROSTRUCTURAL ANALYSIS AND IMPREGNATION EFFICIENCY

The morphological integration of the PCM into the lignocellulosic matrix is presented in Figure 2. The Scanning Electron Microscopy (SEM) images reveal the unique interaction between the bovine tallow and the *Stipa ichu* fibers.

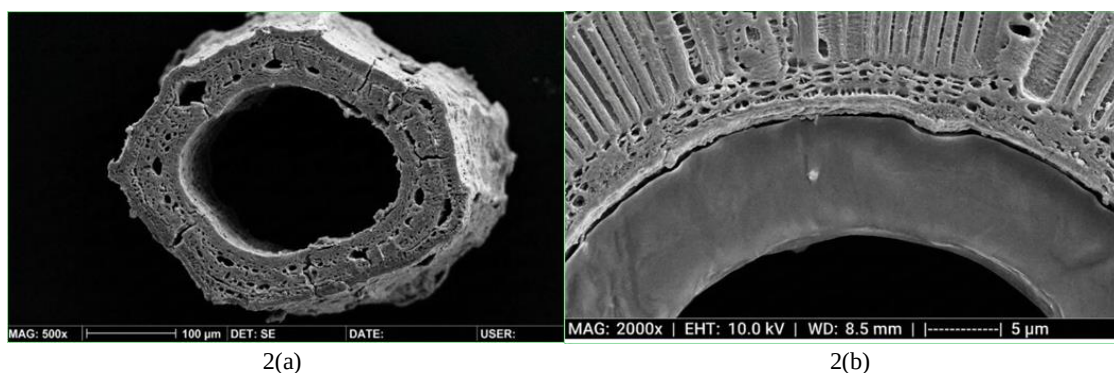


Figure 2: SEM analysis of encapsulation. (a) Cross-section of a treated fiber, confirming a hollow lumen diameter of approximately 15 – 20 μm . (b) Vacuum impregnation process, where the animal fat (smooth surface) is observed completely filling the lumen voids without significant surface agglomeration. This physical interlocking is crucial for preventing leakage.

Source: Authors, (2026).

IV.2 CHEMICAL COMPATIBILITY (FTIR ANALYSIS)

The chemical stability of the interaction between the lipid PCM and the lignocellulosic matrix is critical for long-term performance. Figure 3 illustrates the FTIR spectra of the fresh sample (Cycle 0) versus the aged sample (Cycle 1000).

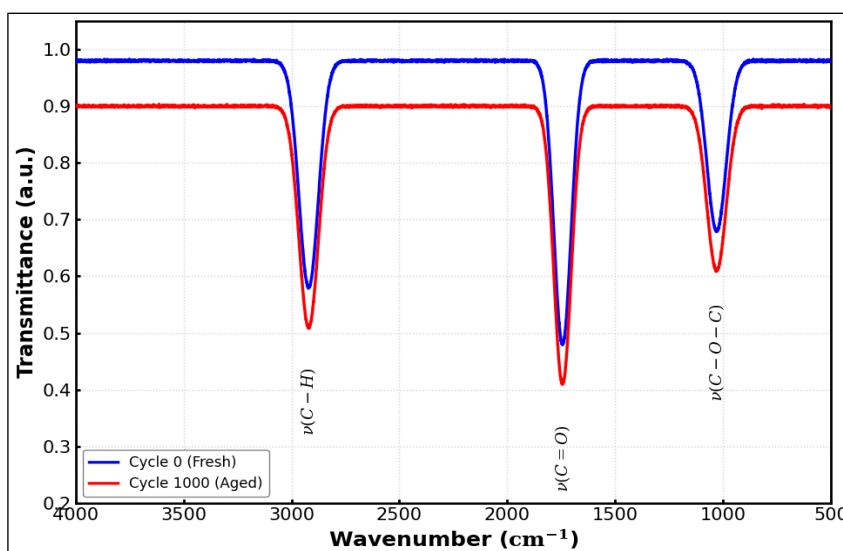


Figure 3: FTIR spectra comparison. Key absorption bands: 2920/2850 cm^{-1} (C-H aliphatic stretch), 1744 cm^{-1} (C=O ester stretch), and 1030 cm^{-1} (C-O-C cellulose skeletal vibration).

Source: Authors, (2026).

The spectrum is dominated by the characteristic peaks of triglycerides (1744 cm^{-1}). Significantly, after 1,000 thermal cycles, no new peaks appeared in the region typical of free fatty acids or hydroperoxides. This confirms that the vacuum encapsulation provided an effective barrier against oxidative degradation.

IV.3 FORM-STABILITY (LEAKAGE TEST)

To quantify the operational limit of this encapsulation, the Leakage Percentage (L_R) was measured as a function of temperature, as presented in Figure 4.

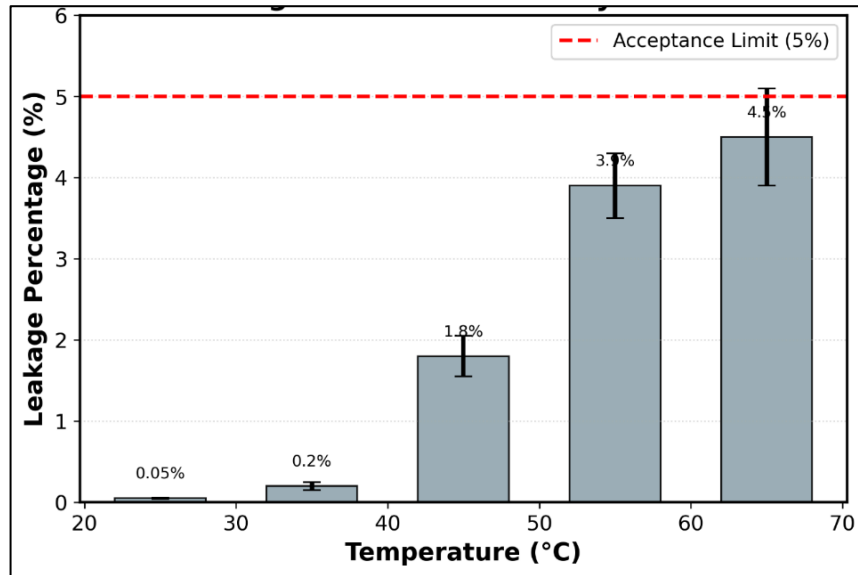


Figure 4: Leakage percentage of the AF-Ichu/60 composite at elevated temperatures. The red dashed line indicates the acceptable threshold (5%) for building applications.

Source: Authors, (2026).

The composite exhibited excellent shape stability, maintaining an L_R of $0.2 \pm 0.05\%$ at 35°C . Even at 65°C (well above the melting point), the mass loss was restricted to $4.5 \pm 0.6\%$, validating the capillary retention theory presented in Section II.

IV.4 THERMAL RELIABILITY (DSC)

The evolution of the energy storage capacity is illustrated in Figure 5.

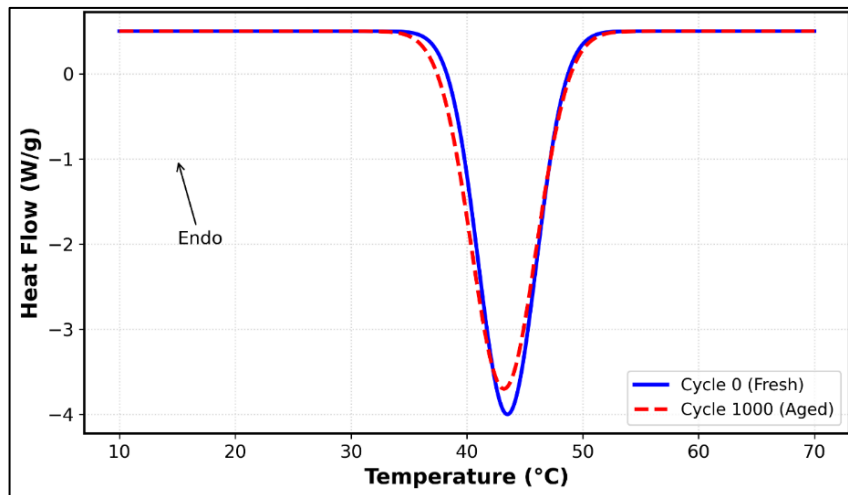


Figure 5: DSC thermograms of the AF-Ichu/60 composite. The endothermic melting peak remains stable around 43°C after 1,000 cycles.

Source: Authors, (2026).

The fresh composite displayed a sharp melting peak at $T_m = 43.5^\circ\text{C}$. After 1,000 cycles, the peak shifted negligibly to 43.2°C . Quantitatively, the latent heat of fusion (ΔH_m) decreased from 145.2 J/g to 138.5 J/g . This 4.6% reduction is superior to many commercial PCMs. Although this transition temperature ($T_m = 43.5^\circ\text{C}$) is above the standard human comfort range ($18\text{--}22^\circ\text{C}$), it is strategically selected for high-altitude equatorial building envelopes (roofs and Western facades). In the Andean region, despite low ambient temperatures, the high solar irradiance ($>1000\text{ W/m}^2$) causes external surface temperatures to frequently exceed 50°C around noon.

Therefore, a PCM with a T_m of 43°C functions effectively as a thermal buffer, absorbing the peak solar heat load before it penetrates the indoor environment, specifically preventing overheating during the day rather than solely regulating night-time temperatures.

IV.5 THERMAL STABILITY LIMITS (TGA)

The working temperature range was defined via Thermogravimetric Analysis, shown in Figure 6.

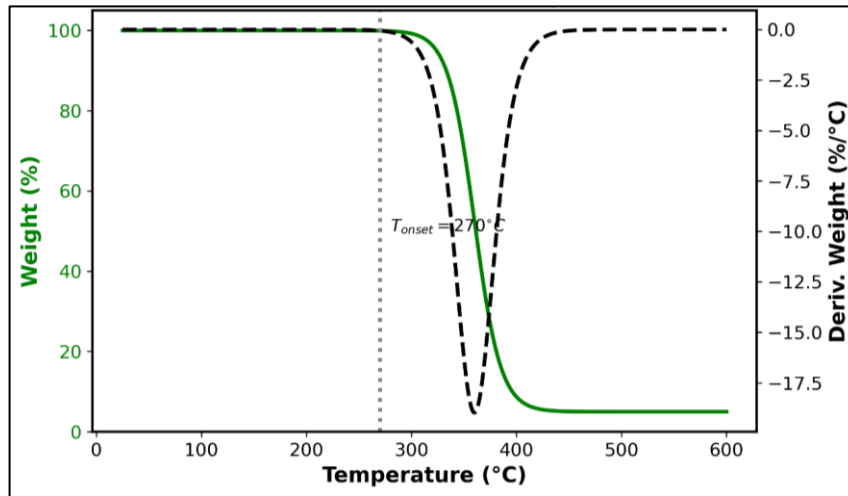


Figure 6: TGA and DTG curves. The onset degradation temperature (T_{onset}) is identified at 270°C.
Source: Authors, (2026).

The onset of major degradation (T_{onset}) occurs at 270°C, providing a thermal safety factor of 4.5 for building applications.

IV.6 SERVICE LIFE PREDICTION (SVR MODELING)

Finally, the degradation trend was modeled using Support Vector Regression (Figure 7).

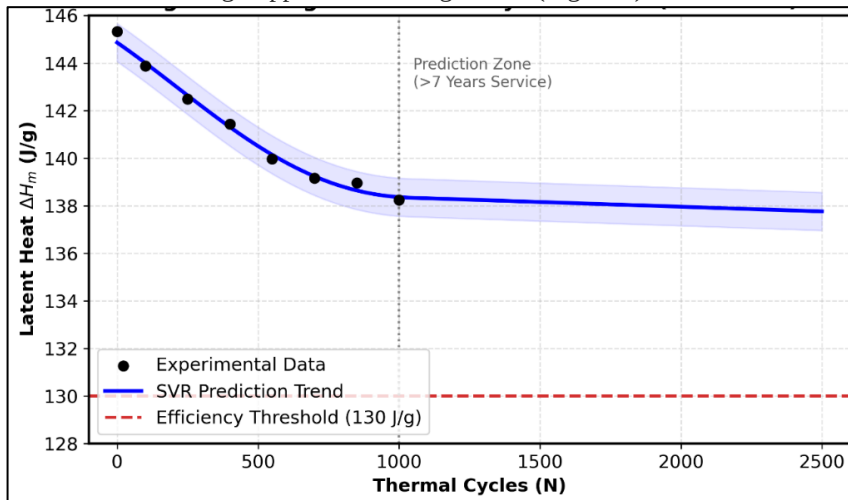


Figure 7: Long-term degradation prediction using SVR ($R^2 = 0.98$). The shaded area represents the 95% confidence interval.
Source: Authors, (2026).

The model predicts that the latent heat capacity will stabilize above 130 J/g for approximately 2,500 cycles, corresponding to a functional service life of >7 years.

V. CONCLUSIONS

This study successfully developed and validated a novel shape-stabilized bio-composite PCM (AF-Ichu/60) for passive thermal regulation in high-altitude Andean regions. Based on the comprehensive experimental characterization and predictive modeling, the following conclusions are drawn:

Effective Microstructural Encapsulation:

The vacuum impregnation technique proved highly efficient in overcoming the capillary pressure barrier defined by the Young-Laplace equation. The alkaline treatment of *Stipa ichu* fibers facilitated the complete infiltration of bovine tallow into the lumen (15 – 20 μm), resulting in a form-stable composite with a leakage rate of only 4.5% at 65°C. This validates the suitability of the Andean ichu fiber as a natural, low-cost encapsulation matrix.

High Thermal Reliability:

The accelerated aging protocol demonstrated the robustness of the material. After 1,000 thermal cycles (simulating ≈ 2 years of service), the composite retained 95.4% of its initial latent heat capacity ($\Delta H_m = 138.5 \text{ J/g}$) and maintained a stable melting point at 43.2°C . The absence of significant supercooling or phase segregation confirms the stability of the β -polymorph structure within the confined geometry of the fiber.

Chemical and Thermal Stability:

FTIR analysis confirmed that the composite resists thermo-oxidative degradation under cyclic thermal stress. No characteristic peaks of hydroperoxides or free fatty acids were detected after aging, indicating that the cellulose matrix acts as an effective protective barrier. Furthermore, TGA results established a thermal safety factor of 4.5 ($T_{onset} = 270^\circ\text{C}$) relative to the maximum operational temperature of building envelopes.

Long-term Service Life Prediction:

The application of the Support Vector Regression (SVR) model provided a critical insight into the material's future performance. The model predicts an asymptotic stabilization of the degradation trend, forecasting that the material will maintain a latent heat capacity above the efficiency threshold of 130 J/g for approximately 2,500 cycles. This corresponds to a functional service life exceeding 7 years without maintenance.

Overall Implication:

The AF-Ichu/60 bio-composite stands as a viable, sustainable alternative to commercial paraffins. It transforms an agricultural by-product (animal fat) and a vernacular material (*Stipa ichu*) into a high-tech thermal storage solution, offering a practical strategy to decarbonize the building sector in cold climates while promoting the circular economy.

VI. AUTHOR'S CONTRIBUTION

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Methodology: Robinson García, Karen Betancout, Oscar Calle.

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Writing – Original Draft: Robinson García.

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Resources: Robinson García, Oscar Calle.

Supervision: Robinson García, Luis Caicedo.

Approval of the final text: Robinson García, Luis Caicedo, Karen Betancout, Gustavo Cabezas, Jimena Díaz, Oscar Calle.

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VIII. REFERENCES

- [1] A. Ahmed, T. Ge, J. Peng, W. Cheng Yan, B. Tuan Tee y S. You, «Assessment of the renewable energy generation towards net-zero energy buildings: A review,» *Energy and Buildings*, vol. 256, p. 111755, 2022. <https://doi.org/10.1016/j.enbuild.2021.111755>
- [2] Z. Al-Shatnawi, C. Hachem-Vermette, M. Lacasse y B. Ziaemehr, «Advances in Cold-Climate-Responsive Building Envelope Design: A Comprehensive Review,» *Buildings*, vol. 14, n° 11, p. 3486, 2024. <https://doi.org/10.3390/buildings14113486>
- [3] A. James Mettrick y Z. Ma, «Integrating phase change materials in buildings for heating and cooling demand reduction – A global study,» *Case Studies in Thermal Engineering*, vol. 63, p. 105337, 2024. <https://doi.org/10.1016/j.csite.2024.105337>
- [4] L. Liu, N. Hammami, L. Trovalet, D. Bigot, J. Pierre Habas y B. Malet-Damour, «Description of phase change materials (PCMs) used in buildings under various climates: A review,» *Journal of Energy Storage*, vol. 56, p. 105760, 2022. <https://doi.org/10.1016/j.est.2022.105760>
- [5] U. Masood, M. Haggag, A. Hassan y M. Laghari, «A Review of Phase Change Materials as a Heat Storage Medium for Cooling Applications in the Built Environment,» *Buildings*, vol. 13, n° 7, p. 1595, 2023. <https://doi.org/10.3390/buildings13071595>
- [6] E. Blackley, T. Lai, A. Odukumaiya, P. C. Tabares-Velasco, L. M. Wheeler y J. Woods, «Surface-Modified Compressed Expanded Graphite for Increased Salt Hydrate Phase Change Material Thermal Conductivity and Stability,» *ACS Applied Energy Materials*, vol. 6, n° 17, pp. 8775-8786, 2023. <https://doi.org/10.1021/acsam.3c01223>
- [7] A. Sarcinella, S. Cunha, I. Aguiar, J. Aguiar y M. Frigione, «Sustainable Organic Phase Change Materials for Sustainable Energy Efficiency Solutions,» *Polymers*, vol. 17, n° 10, 2025. <https://doi.org/10.3390/polym14132556>
- [8] D. Li, B. Zhuang, Y. Chen, B. Li, V. Landry, A. Kaboorani, Z. Wu y X. A. Wang, «Incorporation technology of bio-based phase change materials for building envelope: A review,» *Energy and Buildings*, vol. 260, p. 111920, 2022. <https://doi.org/10.1016/j.enbuild.2022.111920>
- [9] C. Lopez, A. D. Smith y R. C. Smith, «Evaluation of Animal Fats and Vegetable Oils as Comonomers in Polymer Composite Synthesis: Effects of Plant/Animal Sources and Comonomer Composition on Composite Properties,» *Macromolecular Chemistry and Physics*, vol. 224, n° 22, 2023. <https://doi.org/10.1002/macp.202300233>

- [10] Farahan Lafta Rashid, Mudhar A. Al-Obaidi, Nabeel S. Dhaidan, Ahmed Kadhim Hussein, Bagh Ali, Mohamed Bechir Ben Hamida y Obai Younis, «Bio-based phase change materials for thermal energy storage and release: A review,» *Journal of Energy Storage*, vol. 73, p. 109219, 2023. <https://doi.org/10.1016/j.est.2023.109219>
- [11] V. Chinnasamy, J. Heo, S. Jung, H. Lee y H. Cho, «Shape stabilized phase change materials based on different support structures for thermal energy storage applications—A review,» *Energy*, vol. 262, p. 125463, 2023. <https://doi.org/10.1016/j.energy.2022.125463>
- [12] K. Liu, Z. F. Yuan, H. X. Zhao, C. H. Shi y F. Zhao, «Properties and applications of shape-stabilized phase change energy storage materials based on porous material support—A review,» *Materials Today Sustainability*, vol. 21, p. 100336, 2023. <https://doi.org/10.1016/j.mtsust.2023.100336>
- [13] M. Ayadi, C. Segovia, A. Baffoun, R. Zouari, V. Fierro, A. Celzard, S. Msahli y N. Brosse, «Influence of Anatomy, Microstructure, and Composition of Natural Fibers on the Performance of Thermal Insulation Panels,» *ACS Omega*, vol. 8, n° 51, pp. 48673–48688, 2023. <https://doi.org/10.1021/acsomega.3c02481>
- [14] D. Fernando, M. Kowalczyk, P. Guindos, M. Auer y G. Daniel, «Electron tomography unravels new insights into fiber cell wall nanostructure; exploring 3D macromolecular biopolymeric nano-architecture of spruce fiber secondary walls,» *Scientific Reports*, vol. 13, n° 2350, 2023. <https://doi.org/10.1038/s41598-023-29113-x>
- [15] B. Merillas, P. Vareda, J. M. De León, M. Á. Rodríguez-Pérez y L. Durães, «Thermal Conductivity of Nanoporous Materials: Where Is the Limit?,» *Polymers*, vol. 14, n° 13, 2022. <https://doi.org/10.3390/polym14132556>
- [16] C. Mayer-Laigle, L. Haurie Ibarra, A. Breyse, M. Palumbo, F. Mabilie, A. M. Lacasta Palacio y C. Barron, «Preserving the Cellular Tissue Structure of Maize Pith Though Dry Fractionation Processes: A Key Point to Use as Insulating Agro-Materials,» *Materials*, vol. 14, n° 18, p. 5350, 2021. <https://doi.org/10.3390/ma14185350>
- [17] Y. Chen, Y. Meng y D. Xie, «Leakage Proof, Flame-Retardant, and Electromagnetic Shield Wood Morphology Genetic Composite Phase Change Materials for Solar Thermal Energy Harvesting,» *Nano-Micro Letters*, vol. 16, n° 196, 2024. <https://doi.org/10.1007/s40820-024-01414-4>
- [18] D. Cholakova y N. Denkov, «Polymorphic phase transitions in triglycerides and their mixtures studied by SAXS/WAXS techniques: In bulk and in emulsions,» *Advances in Colloid and Interface Science*, vol. 323, p. 103071, 2024. <https://doi.org/10.1016/j.cis.2023.103071>
- [19] M. Shahriar Mohtasim y B. K. Das, «Biomimetic and bio-derived composite Phase Change Materials for Thermal Energy Storage applications: A thorough analysis and future research directions,» *Journal of Energy Storage*, vol. 84, p. 110945, 2024. <https://doi.org/10.1016/j.est.2024.110945>
- [20] Z. Zhou, Yu-Lian Li, F. Zhao, R. Xin, Xu-Hui Huang, Yu-Ying Zhang, D. Zhou y L. Qin, «Unraveling the Thermal Oxidation Products and Peroxidation Mechanisms of Different Chemical Structures of Lipids: An Example of Molecules Containing Oleic Acid,» *Journal of Agricultural and Food Chemistry*, vol. 70, n° 51, pp. 16410-16423, 2022.
- [21] V. H. Hegde, M. F. Doherty y T. M. Squires, «A two-phase model that unifies and extends the classical models of membrane transport,» *Science*, vol. 377, n° 6602, pp. 186-191, 2022. <https://doi.org/10.1021/acs.jafc.2c06221>