



Research article

Upcycling pomelo peel and eggplant biomass into form-stable PCMs

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ARTICLE INFO

Keywords:

PCM
Sustainability
Energy Materials
Porous Materials
Biomass

ABSTRACT

Eggplant tissue and pomelo peel waste were converted into lightweight biomass porous foams via freeze-drying and subsequently used as sustainable scaffolds for shape-stable PCMs. Paraffin (PA) and PEG 20 K were incorporated into the biomass-derived foams, where the naturally interconnected cellular structures provided abundant capillary channels for PCM uptake and confinement. The resulting composites achieved high PCM loadings of 81.44–93.50 wt%. The melting enthalpies of Eggplant-PA, Pomelo-PA, Eggplant-20K, and Pomelo-20K reached 169.31, 166.11, 155.76, and 143.56 J g⁻¹, respectively, confirming their considerable latent heat storage capability. In particular, Eggplant-20K and Pomelo-20K exhibited high enthalpy efficiencies of 106.77% and 112.98%, respectively, indicating that the latent heat storage capacity of PEG 20 K was well preserved after incorporation into the biomass-derived porous scaffolds. In the leakage resistance test, Eggplant-20K retained 98.08% of its initial mass after 3.5 h of heating, demonstrating good shape stability and leakage resistance. These results highlight a simple and green strategy for upcycling porous plant biomass into high-loading, shape-stabilized PCMs with promising potential for passive thermal regulation and energy-saving applications.

1. Introduction

Phase change materials (PCMs) have attracted growing interest for thermal energy storage and passive thermal regulation because they can store and release large amounts of latent heat during reversible phase transitions. [1] Organic PCMs, such as paraffin (PA) [2] and polyethylene glycol (PEG), [3] are widely used owing to their suitable phase-change temperatures, high latent heat, chemical stability, and low supercooling. However, their practical use is limited by leakage during melting, poor shape stability, and low thermal conductivity.

To overcome these limitations, considerable efforts have been devoted to the development of composite PCMs with improved shape stability, heat-transfer capability, and application adaptability. Various strategies have been explored, including the incorporation of thermally conductive fillers, the construction of polymer-based phase-change networks, the use of aerogel or porous scaffolds, and the fabrication of flexible phase-change films. For example, highly thermally conductive composite PCMs enabled by CNT-modified PVA aerogels have been reported for solar energy storage and thermal management of electronic components, demonstrating the importance of interconnected porous networks for improving heat transfer. [4] Recent polymer-based

composite PCMs have also been designed for battery thermal management, where flexibility, adaptability, and stable thermal buffering are required. [5] In addition, intrinsically flexible solid–solid phase-change films with photothermal conversion capability have been developed for human thermal management, highlighting the increasing demand for multifunctional PCMs that combine latent heat storage with flexibility, photothermal response, and practical applicability. [6] More recently, intrinsically photothermal polyurethane PCMs based on π – π conjugation were reported for personal thermal management, showing integrated photothermal conversion, flexibility, high-temperature morphological stability, and mechanical robustness. [7] For building thermal management, PEG encapsulated within P/N co-doped rGO aerogels was shown to achieve a balance between high latent heat storage and low thermal conductivity, together with flame retardancy, electromagnetic shielding, and temperature-adaptive thermal regulation. [8] In another study, sodium silicate-reinforced anisotropic aerogel-stabilized eutectic composite PCMs exhibited high latent heat, low thermal conductivity, leakage resistance, mechanical stability, and dual-function thermal management in buildings. [9] These studies indicate that the current development of composite PCMs is moving from simple leakage prevention toward multifunctional thermal management systems for

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<https://doi.org/10.1016/j.nxmte.2026.103101>

Received 9 June 2026; Received in revised form 3 August 2026; Accepted 6 August 2026

Available online 7 August 2026

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Table 1
Specific indicators of the selected samples.

Samples	$T_{m, \text{ peak}}$ (°C)	$T_{s, \text{ peak}}$ (°C)	Melting enthalpy (J/g)	Solidification enthalpy (J/g)	PCM loading (%)	Enthalpy efficiency (%)
PA	56.73	50.42	218.95	209.20	-	-
Eggplant-PA	55.51	48.10	169.31	171.47	91.16 ± 0.95	84.83
Pomelo-PA	56.32	48.96	166.11	161.81	90.24 ± 0.57	84.07
PEG 20 K	65.70	43.59	156.02	152.65	-	-
Eggplant-20K	66.41	42.63	155.76	152.11	93.50 ± 1.35	106.77
Pomelo-20K	67.22	42.24	143.56	138.75	81.44 ± 0.36	112.98

diverse applications.

Among these strategies, embedding PCMs into porous supports is an effective strategy to suppress leakage and develop shape-stabilized PCMs. [10] Porous scaffolds can confine molten PCMs through capillary forces, [11] surface tension, and physical adsorption, while

preserving their latent heat storage capacity. Among various supporting materials, biomass-derived porous scaffolds [12] have attracted increasing attention because they are renewable, lightweight, low-cost, and intrinsically possess hierarchical porous structures. In particular, plant-derived biomass [13] provides a sustainable platform for PCM

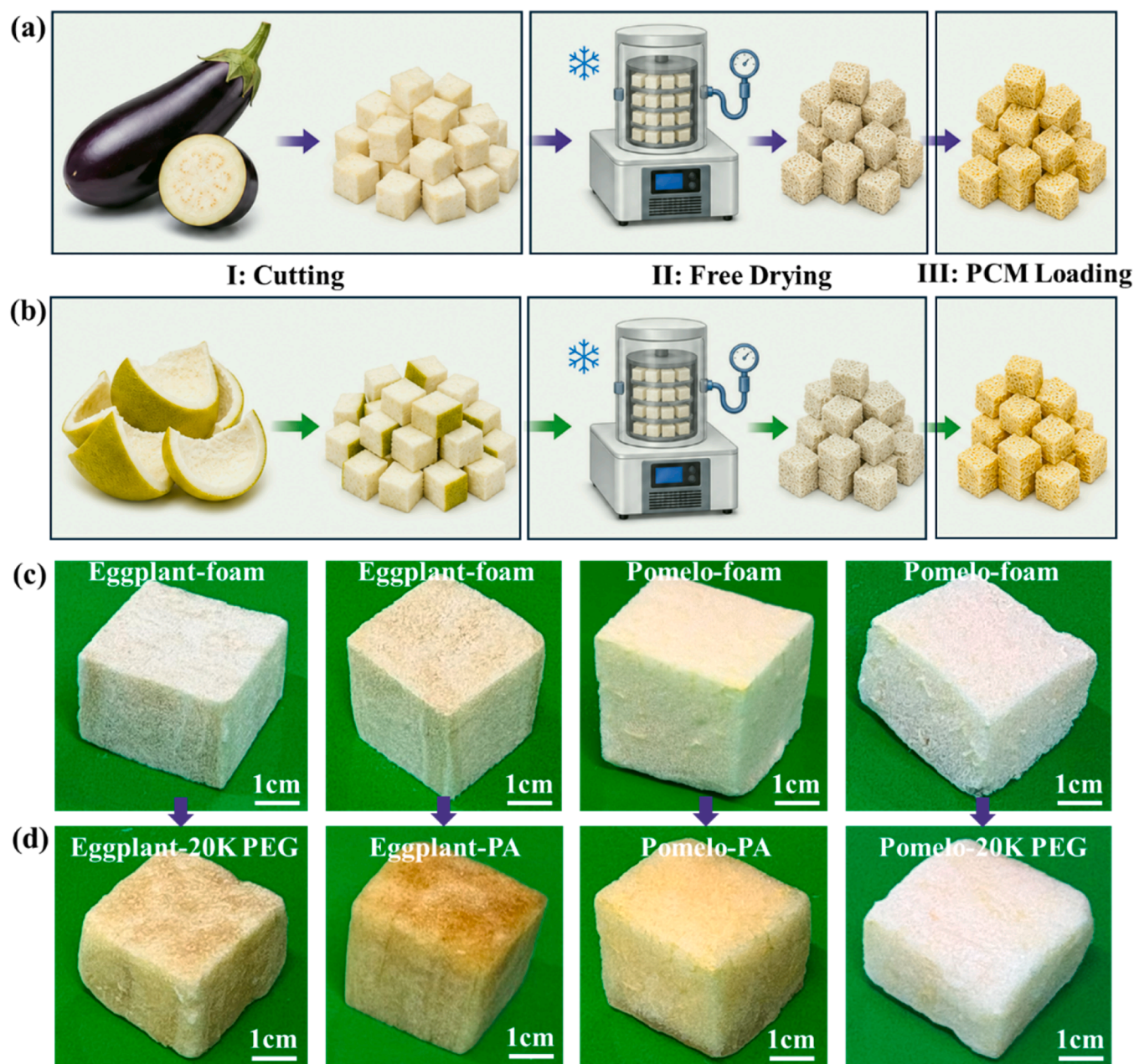


Fig. 1. (a-b) Digital photographs of pristine freeze-dried bio-based foams and the corresponding PCM-loaded composites prepared by impregnation at 80 °C. (c-d) The upper row shows the pristine foams, while the lower row shows Eggplant-20K, Eggplant-PA, Pomelo-PA, and Pomelo-20K.

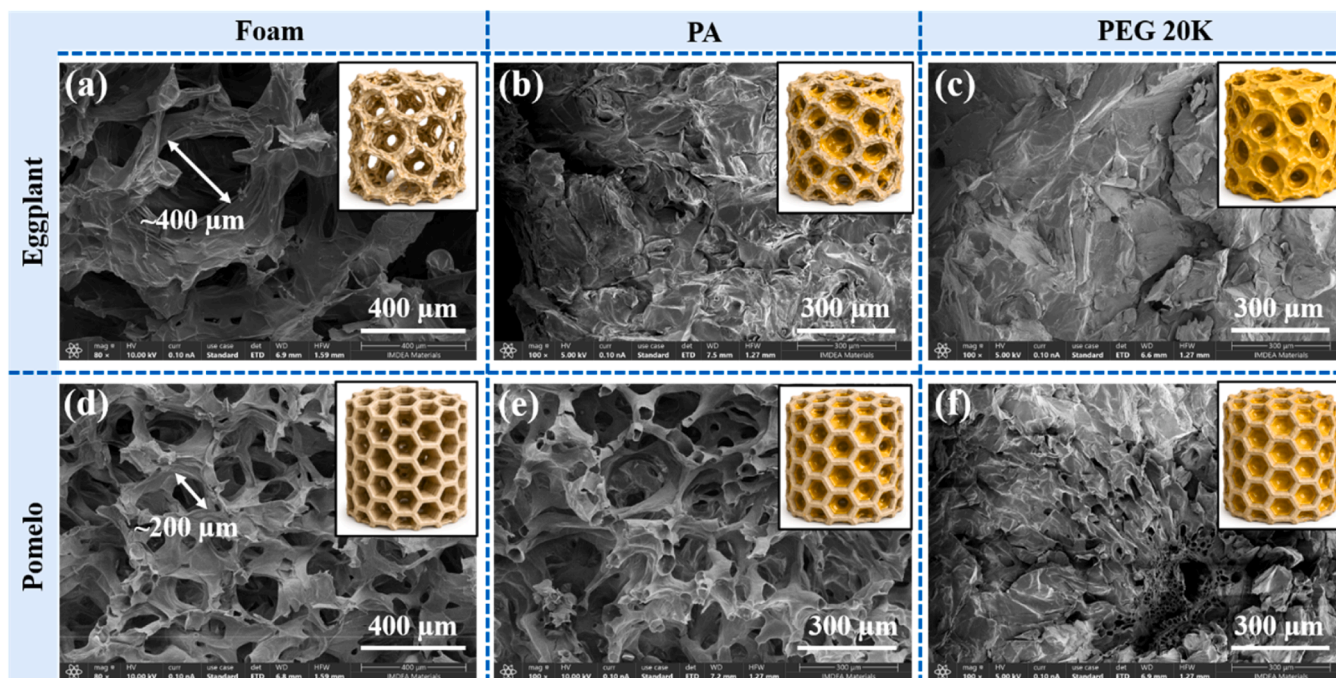


Fig. 2. SEM images and corresponding schematic models of pristine and PCM-loaded biomass-derived foams: (a) eggplant-derived foam, (b) Eggplant-PA, (c) Eggplant-PEG 20 K, (d) pomelo peel-derived foam, (e) Pomelo-PA, and (f) Pomelo-20K.

encapsulation, as many fruits and vegetables contain naturally formed interconnected cellular architectures. [14] Freeze-drying can remove water while largely preserving these cellular frameworks, thereby producing lightweight porous foams without the need for complex chemical synthesis, templates, or harsh processing conditions.

In this work, eggplant tissue and pomelo peel were selected as representative plant-derived porous biomasses for PCM encapsulation. Pomelo peel, a typical fruit peel waste, contains a thick sponge-like pith layer with an inherent porous framework, while eggplant tissue was used as a low-cost vegetable biomass and model porous plant tissue owing to its soft and interconnected cellular structure. Eggplant- and pomelo-peel-derived porous foams will be fabricated by freeze-drying and subsequently used as scaffolds for PA and PEG 20 K through vacuum impregnation. The resulting biomass foam/PCM composites will be systematically investigated in terms of PCM loading, normalized uptake, morphology, chemical structure, phase-change behavior, thermal stability, leakage resistance, and thermal regulation performance. Unlike many reported composite PCMs that rely on synthetic polymers, carbon nanomaterials, or complex scaffold fabrication processes, this work directly utilizes natural porous plant tissues as low-cost biomass scaffolds. The comparison between eggplant tissue and pomelo peel further provides insight into how different plant-derived cellular structures influence PCM uptake, leakage resistance, and thermal regulation performance. This work provides a facile and sustainable strategy for converting plant-derived porous biomass into high-loading shape-stabilized PCMs for thermal energy storage and passive thermal management applications.

2. Experimental

Materials. Eggplant and pomelo peel were purchased from a local market and used as biomass precursors. PA (Sigma-Aldrich, mp. 53–58 °C (ASTM D 87)) and polyethylene glycol with an average molecular weight of 20000 g mol⁻¹ (PEG 20 K, Sigma-Aldrich, (stabilised) for synthesis) were used as PCMs. All chemicals were used as received without further purification.

Preparation of PCM composites. The prepared eggplant tissue and

pomelo peel samples were first frozen at −20 °C for 12 h and then freeze-dried at approximately −50 °C for 48 h to obtain lightweight porous biomass foams. The dried biomass foams were subsequently used as scaffolds for PCM impregnation. PA or PEG 20 K was heated above its melting temperature until completely melted. The freeze-dried foams were immersed in the molten PCM and vacuum-impregnated overnight under a vacuum level of −0.08 to −0.09 MPa to ensure sufficient PCM infiltration into the hierarchical porous structure. After impregnation, the samples were removed from the molten PCM, and the excess PCM on the surface was gently wiped off with filter paper. Finally, the samples were cooled to room temperature to obtain the biomass foam/PCM composites.

Characterization. The morphology and porous structure of the biomass-derived foams and the four PCM composites were observed by scanning electron microscopy (SEM). Phase change properties were analyzed by differential scanning calorimetry (DSC, TA-Q25) under nitrogen at a heating/cooling rate of 10 °C min⁻¹, and the phase change temperatures and enthalpies were obtained. The enthalpy efficiency of PCMs can be determined by the following Equation, [15] *Enthalpy efficiency* % = $\frac{\Delta H_m}{w \Delta H_{PCM}} \times 100\%$, where ΔH_m (J/g) is the melting enthalpy of the PCM composites, ΔH_{PCM} (J/g) represents the melting enthalpy of corresponding PCM work substances, and w (%) represents the loading of PCMs in the PCM composites. The calculated results are presented in Table 1. Leakage resistance and shape stability were evaluated by heating the composites on filter paper at 80 °C, with leakage behavior recorded every 30 min by observing PCM residues (weight percentage). The PCM loading content, representing the mass fraction of PEG20K or paraffin in the resulting composite phase-change materials, was calculated using the following equation: PCM loading (wt. %) = $\frac{m_2 - m_1}{m_2} \times 100\%$, where m_1 and m_2 denote the masses of the foam before and after PCM impregnation, respectively.

3. Results and discussion

As illustrated in Fig. 1a, b, eggplant tissue and pomelo peel were used as plant-derived biomass precursors to fabricate porous bio-based foams for PCM encapsulation. Eggplant and pomelo peel were cut into

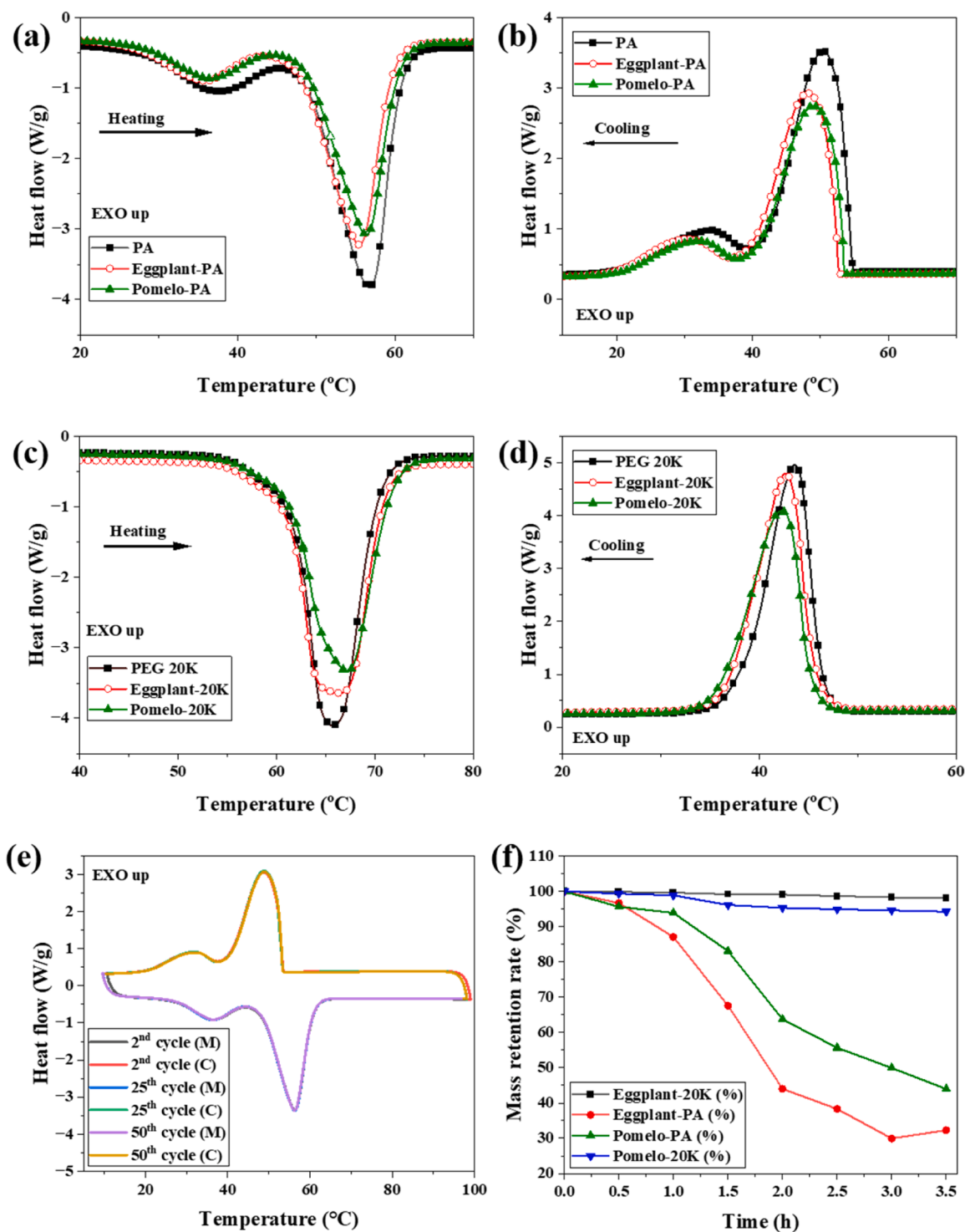


Fig. 3. (a, b) DSC heating and cooling curves of pure PA, Eggplant-PA, and Pomelo-PA. (c, d) DSC curves of pure PEG20K, Eggplant-20K, and Pomelo-20K. (e) DSC curves of Eggplant-PA during the 2nd, 25th, and 50th melting–crystallization cycles. M and C denote the melting and crystallization processes, respectively. (f) Mass retention rate of Eggplant-20K, Eggplant-PA, Pomelo-PA, and Pomelo-20K during continuous heating.

cubes (Step I). After freeze-drying (Step II), lightweight porous scaffolds were obtained and subsequently vacuum-impregnated with molten PA or PEG 20 K at 80 °C (Step III). Upon cooling, the PCMs solidified within the porous networks, forming shape-stable Eggplant-PA, Eggplant-20K, Pomelo-PA, and Pomelo-20K composites. As shown in Fig. 1c, the freeze-dried eggplant and pomelo peel foams maintained a regular cubic shape, indicating that the freeze-drying process effectively preserved the macroscopic structure of the plant tissues. After PCM impregnation, all

composites generally retained their cubic morphology without obvious collapse or deformation (Fig. 1d), confirming that both biomass-derived foams could act as self-supporting matrices for PA and PEG 20 K encapsulation.

The SEM images and schematic models reveal the structural evolution of the biomass-derived foams before and after PCM loading. As shown in Fig. 2, pristine eggplant foam exhibited a three-dimensional porous structure with large open pores (~400 μm), thin pore walls,

and pronounced surface wrinkles. Although the relatively large open pores may provide abundant space for PCM uptake, they are not expected to generate strong capillary confinement alone. Instead, the wrinkled and tortuous cell-wall structure can increase the contact area with the PCM and provide steric hindrance against melt flow. In contrast, pristine pomelo peel foam showed a more continuous honeycomb-like porous framework with better structural integrity and smaller pores ($\sim 200\ \mu\text{m}$). These structural differences are consistent with the PCM loading results, as the more open eggplant-derived porous network favored higher PCM uptake, while the denser pomelo peel framework led to a relatively lower PCM mass fraction.

After PA impregnation, Eggplant-PA exhibited a more compact morphology with markedly fewer visible voids, indicating relatively effective pore filling by PA. In contrast, Pomelo-PA still retained a partially interconnected porous structure. The PA phase was difficult to clearly distinguish in the fractured cross-section, which may be attributed to its weak interfacial interaction with the biomass scaffold and possible partial detachment during brittle fracture preparation for SEM observation. For the PEG 20K-loaded samples, Eggplant-20K displayed a denser and smoother morphology with a relatively continuous PCM-filled phase, whereas Pomelo-20K still preserved part of its porous structure. Compared with PA, PEG 20 K may be more effectively retained within the biomass scaffold because of its higher melt viscosity, lower melt mobility, and stronger physical adhesion with the hydroxyl-rich biomass cell walls. These observations further confirm that the biomass-derived porous architectures can accommodate PCMs within their internal networks, while pore size, framework density, cell-wall morphology, and PCM characteristics jointly influence the final PCM distribution, loading efficiency, and leakage resistance.

As shown in Table 1, all composites achieved high PCM loading contents ranging from 81.44 ± 0.36 – $93.50 \pm 1.35\ \text{wt}\%$, indicating the excellent PCM uptake capability of the freeze-dried biomass scaffolds. Eggplant-derived foams showed slightly higher PCM loading than pomelo peel-derived foams for PA and much higher loading for PEG 20 K. This difference may be related to the more open and less dense cellular structure of the eggplant-derived scaffold, whereas the pomelo peel scaffold possesses a heavier and more robust framework, as further supported by the SEM observations discussed below. In particular, the lower PCM loading of Pomelo-20K may also be associated with the relatively high viscosity of molten PEG 20 K, which could hinder its infiltration into smaller or more tortuous pores. Nevertheless, the high PCM loading contents of all samples demonstrate that both eggplant- and pomelo peel-derived foams are effective sustainable porous supports for shape-stabilized PCMs.

DSC results (Fig. 3a–d) confirmed that all composites retained distinct melting and crystallization peaks, indicating reversible phase-change behavior after incorporation into the biomass scaffolds. Eggplant-PA and Pomelo-PA exhibited melting enthalpies of 169.31 and $166.11\ \text{J g}^{-1}$, respectively. The PEG 20K-loaded samples also showed high latent heat storage capacities, with melting enthalpies of $155.76\ \text{J g}^{-1}$ for Eggplant-20K and $143.56\ \text{J g}^{-1}$ for Pomelo-20K. According to the calculated values listed in Table 1, Eggplant-20K and Pomelo-20K exhibited enthalpy efficiencies of 106.77% and 112.98% , respectively, indicating that the latent heat storage capacity of PEG 20 K was well preserved within the biomass-derived porous scaffolds. The enthalpy efficiencies exceeding 100% may be attributed to scaffold microstructure-induced crystallization of PEG 20 K within the biomass porous frameworks, together with minor deviations in PCM loading determination.

As a typical example, the thermal cycling DSC curves of Eggplant-PA are shown in Fig. 3e, confirming that the composite maintained reversible melting–crystallization behavior after repeated thermal cycles. Leakage tests (Fig. 3f) showed that Eggplant-20K and Pomelo-20K retained 98.08% and 94.25% of their initial mass after $3.5\ \text{h}$ of heating, respectively, demonstrating excellent leakage resistance. Based on the SEM observations discussed above, the superior leakage resistance of

Eggplant-20K should not be attributed solely to capillary confinement, because the eggplant-derived scaffold contains relatively large and open pores. Instead, it may be mainly associated with the combined effects of physical adhesion between PEG 20 K and the biomass cell walls, the high melt viscosity and low mobility of PEG 20 K, and the steric hindrance provided by the wrinkled and tortuous cell-wall structure. The rough and folded cell walls can increase the contact area with PEG 20 K and provide physical barriers against melt flow, while the high viscosity of molten PEG 20 K further reduces its mobility within the open porous network. In contrast, PA-loaded composites showed rapid mass loss, with Eggplant-PA retaining only approximately 32% and Pomelo-PA approximately 44% of their initial mass after $3.5\ \text{h}$. Overall, the leakage resistance followed the order Eggplant-20K > Pomelo-20K > Pomelo-PA > Eggplant-PA, indicating that PCM viscosity, scaffold surface characteristics, and cell-wall morphology jointly determine the leakage resistance and thermal storage performance of biomass foam/PCM composites.

4. Conclusion

Eggplant tissue and pomelo peel waste were successfully upcycled into lightweight plant-derived porous foams via a simple freeze-drying process and used as sustainable scaffolds for shape-stabilized PCMs. The naturally interconnected cellular structures of the biomass foams enabled efficient uptake and retention of PA and PEG 20 K introduced by vacuum impregnation. The resulting composites achieved high PCM loadings of 81.44 – $93.50\ \text{wt}\%$ and retained considerable latent heat storage capacity, with melting enthalpies ranging from 143.56 to $169.31\ \text{J g}^{-1}$. In particular, Eggplant-20K exhibited the highest PCM loading and excellent leakage resistance, retaining 98.08% of its initial mass after heating at $80\ ^\circ\text{C}$ for $3.5\ \text{h}$. This behavior was mainly associated with the combined effects of PEG 20 K characteristics and the wrinkled cell-wall structure of the eggplant-derived scaffold, which contributed to physical adhesion, reduced melt mobility, and restricted PCM leakage. These findings demonstrate a facile and sustainable biomass-upcycling strategy for developing high-loading shape-stabilized PCMs for thermal energy storage and passive thermal regulation.

CRediT authorship contribution statement

Guang-Zhong Yin: Writing – review & editing, Funding acquisition.
Xiao-Mei Yang: Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests.

Acknowledgment

This work was supported by NEWSAFE (No.: PID2022-143324NA-I00) Projects funded by: Ministerio de Ciencia, Innovación y Universidades/AEI (Agencia Estatal de Investigación)/10.13039/501100011033 and, as appropriate, by “ERDF/EU”; and Ramón y Cajal Fellowship (No.: RYC2023-045023-I) funded by: MICIU, and, as appropriate, “ESF Investing in your future”. This work was partially supported by INC-UDIT–2025-PRO21 and INC-UDIT–2026JCR47.

References

- [1] E. Revello, et al., *Energy Convers. Manag.* 349 (2026) 120816.
- [2] Y. Xiong, et al., *Mater. Lett.* 406 (2025) 139851.
- [3] A.K. Sharma, et al., *Mater. Lett.* 386 (2025) 138218.
- [4] W.-X. Luo, et al., *J. Energy Storage* 88 (2024) 111583.
- [5] J. Wang, et al., *Composites Part B Engineering* 313 (2026) 113416.
- [6] G.-Y. Zhu, et al., *Sol. Energy Mater. Sol. Cells* 298 (2026) 114158.

- [7] W. Luo, et al., *Mater. Today Phys.* (2026) 102039.
- [8] J. Hu, et al., *Chem. Eng. J.* (2026) 175841.
- [9] S. Zou, et al., *Chem. Eng. J.* 530 (2026) 173768.
- [10] J. Zhang, et al., *Mater. Lett.* 400 (2025) 139159.
- [11] Z. Cai, et al., *Chem. Eng. J.* 503 (2025) 158484.
- [12] W. Chen, et al., *Chem. Eng. J.* 531 (2026) 173979.
- [13] Y. Liu, et al., *Earth-Sci. Rev.* 277 (2026) 105457.
- [14] G. Manar, et al., *Polymers* 17 (2025) 2925.
- [15] G.-Y. Yin, et al., *Mater. Today Commun.* 48 (2025) 113373.