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Passive Thermal Management of Battery Packs Using Agricultural-Waste-Derived Carbon-Supported Bio-Based Phase Change Materials: A Reduced-Order Design-Space Study

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ABSTRACT

The effectiveness of passive phase change material (PCM) buffering depends on whether heat can enter the latent reservoir throughout the duty time. PCM buffering can lower short-duration battery temperature rise without continuous auxiliary power. This study reframes an agricultural-waste-supported bio-based PCM concept as a reduced-order design-space analysis rather than an experimentally validated material ranking. A twelve-cell equivalent battery node is coupled to a PCM buffer through an effective conductance. The matrix is anchored to an experimentally characterized lauric-acid/stearic-acid eutectic 189.5 kJ kg⁻¹ melting enthalpy; 39.29 °C melting peak), while an 80 wt% active-PCM composite represents agricultural-residue carbon support. Conductance is treated as a design variable rather than a feedstock-specific measured property. Under a prescribed high thermal duty of 32 W for 1200 s at 25 °C, the bare module reaches 61.07 °C, whereas lower- and higher-coupling composite cases reach 55.99 °C and 52.24 °C, corresponding to temperature-rise reductions of 14.1% and 24.5%. The higher-coupling case nevertheless accesses only 11.7% of its nominal latent reservoir. Sensitivity analysis and a conductance-latent-heat design map show that final temperature is substantially more sensitive to thermal coupling than to $\pm 20\%$ changes in nominal latent heat in this regime. The methodological novelty is the combined use of a latent-utilization ratio, a dimensionless thermal-access number, and a two-parameter design map to distinguish nominal latent storage from thermally accessible storage. The framework identifies when carbon-supported PCM can improve finite-duty buffering and defines the measurements required before practical battery validation.

INTRODUCTION

Electrochemical energy stored in battery packs is converted into electrical energy during operation, while a fraction of the stored energy is released as heat due to irreversible and reversible electrochemical processes. The lack of heat rejection leads to an increase in cell temperature and creates an unfavorable condition for cell operation (Afzal *et al.*, 2023). Contemporary thermal models emphasize that heat generation and heat rejection must be represented consistently, and that cell heat capacity, thermal resistance, state of charge, chemistry, and boundary conditions can all affect predicted temperature (Maleki *et al.*, 1999; Steinhart *et al.*, 2021). According to the previous studies, the ideal operating temperature range for many lithium-ion applications is typically 15-40 °C; precise limits vary by duty and chemistry (Mattia *et al.*, 2025; Sohail, 2026). Therefore, it is important to consider the absolute temperature that results, temperature uniformity, mass penalty, recoverability between cycles, and safety limitations in addition to whether a thermal-management concept lowers temperature in comparison to an uncooled reference.

Passive phase change materials capture heat by sensibly warming and a solid to liquid transformation. Their main advantage is the ability to absorb a large amount of heat within a narrow phase-transition temperature interval.

This buffering might postpone temperature rise during a limited operating time (Yu *et al.*, 2023). It does not negate the need to release stored heat to the environment. After the transition is finished, sensible heat capacity becomes the major contributor of the material, and its capacity to limit further temperature increase reduces. Their main limitation is the low thermal conductivity of many organic PCMs. Recent reviews show that conductivity enhancement using graphite, metal foams, fins, carbonaceous fillers, and hybrid cooling can substantially improve heat transfer, but can introduce mass, volume, electrical-conductivity, manufacturing, or cost penalties (Fathimathul Faseena & Sreekumar, 2025; Liu *et al.*, 2022; Wazeer *et al.*, 2022). The central engineering problem is therefore not to maximize latent heat or thermal conductivity independently, but to obtain sufficient heat-transfer rate while retaining enough storage capacity.

Bio-based fatty acids and agricultural-residue-derived porous carbons have become increasingly relevant to that trade-off. Fan *et al.* (2022) measured lauric-acid-based binary eutectics with transition temperatures suitable for low-temperature thermal storage; their lauric-acid/stearic-acid eutectic showed a melting enthalpy of 189.5 kJ kg⁻¹ and a melting temperature of 39.29 °C after experimental characterization and cycling. At the same time, agricultural-waste-derived matrices such as rice-

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husk carbon, rice-husk ash, and coconut-shell biochar have been investigated as porous supports or conductive additives for PCMs (Mehrali *et al.*, 2016; Rajamony *et al.*, 2024; Vidyanto *et al.*, 2026). A 2026 review specifically identified biomass-derived carbon scaffolds as promising shape-stabilizing matrices while also emphasizing the lack of standardized biomass classification, system-level validation, and complete environmental assessment (Costa Pereira *et al.*, 2026).

The use of agricultural-residue-derived carbon supports in PCM systems is therefore no longer a standalone novelty. Recent battery-oriented studies include biomass-derived carbon-enhanced paraffin for lithium-ion thermal management (Li *et al.*, 2026), rice-husk-derived Fe₃O₄ additives in a twelve-cell PCM battery pack with experimental and CFD evaluation (Yi *et al.*, 2025), coconut-shell-biochar-enhanced organic PCMs (Rajamony *et al.*, 2024; Vidyanto *et al.*, 2026), and numerical bio-based PCM studies under high discharge rates and elevated ambient temperatures (Shravan Kumar & Amba Prasad Rao, 2026; Srivastav *et al.*, 2025). Therefore, a credible contribution cannot be based solely on the statement that agricultural waste is used with a PCM.

The present study investigates a passive agricultural-residue-supported PCM buffer and repositions the contribution at the system-design level. The central research question is whether enhanced battery-to-buffer thermal coupling (Kilic, 2023) can compensate for the reduction in latent-storage capacity associated with the incorporation of a non-melting carbon support under finite thermal-duty conditions. The contributions of this work have four contributions. First, all numerical inputs are classified into measured literature values, values derived from literature data, and explicitly defined design variables to improve transparency and reproducibility. Second, battery heat generation is represented as a prescribed thermal duty rather than assigned to specific C-rate conditions when the required electrochemical parameters are unavailable. Third, latent-heat utilization and a dimensionless thermal-accessibility parameter are introduced to distinguish nominal storage capacity from the fraction of latent storage accessed during operation. Fourth, a conductance-latent-heat design map is developed to identify conditions under which composite PCM buffers provide improved thermal performance compared with the unbuffered module.

Physical basis and material design

A general battery energy balance includes irreversible and reversible heat sources. In a commonly used Bernardi-type form, the net heat generation can be expressed in terms of current, terminal voltage, open-circuit voltage, and the entropic coefficient (Bernardi *et al.*, 1985):

$$\dot{Q} = I(U_{oc} - V) - IT(dU_{oc}/dT) \quad (1)$$

Equation (1) expresses the physical origin of battery heat. The sign convention is $I > 0$ during discharge; therefore, $I(U_{oc} - V)$ is positive irreversible heat when the terminal voltage is below the open-circuit voltage, while

the reversible term may be positive or negative depending on dU_{oc}/dT . In the calculations below, $\dot{Q}$ is prescribed directly. This choice is appropriate for a screening model as long as the thermal load is not presented as a validated electrochemical discharge condition. A future cell-specific version should obtain $\dot{Q}$ from calorimetry, a validated equivalent-circuit/electrothermal model, or an electrochemical model (Mattia *et al.*, 2025; Steinhart *et al.*, 2021).

The active matrix is represented by the 82/18 wt% lauric-acid/stearic-acid (LA-SA) eutectic reported by Fan *et al.* (2022), which has a measured melting peak of 39.29 °C and melting enthalpy of 189.50 kJ kg⁻¹. Fatty acids can be supplied through renewable routes; however, Fan *et al.* (2022) did not establish the agricultural-waste origin of the investigated material. Therefore, LA-SA is considered a representative potentially bio-based PCM matrix in the present study. For sensible heat outside the transition interval, a screening specific heat capacity c_p of 1.735 kJ kg⁻¹ K⁻¹ is derived by mass-weighting published supplier values for pure lauric and stearic acids (1.60 and 2.35 kJ kg⁻¹ K⁻¹) at the 82/18 composition (Wang *et al.*, 2022). In the composite cases, the active PCM fraction is set to 0.80 by mass and the remaining 0.20 is treated as a non-melting carbon support. The composite latent heat is therefore $L_{comp} = 0.80 \times 189.5 = 151.6$ kJ kg⁻¹, and the screening sensible heat capacity is $c_{p,comp} = 0.80 \times 1.735 + 0.20 \times 1.062 = 1.600$ kJ kg⁻¹ K⁻¹. The carbon-support specific heat capacity of 1.062 kJ kg⁻¹ K⁻¹ is adopted as an activated-carbon literature proxy (Anupam *et al.*, 2013). These are mixture-rule estimates; surface chemistry, improper impregnation, pore confinement, and crystallization suppression can change measured parameters and must be determined experimentally for a real feedstock.

Rice husk and coconut shell are considered as realistic agricultural-residue pathways rather than as quantitative rankings. Carbonized rice husk has been shown to enhance PCM thermal conductivity (Mehrali *et al.*, 2016), rice-husk-derived additives have been tested in a battery pack (Yi *et al.*, 2025), and coconut-shell biochar has improved thermal conductivity in organic PCM composites (Rajamony *et al.*, 2024; Vidyanto *et al.*, 2026). However, those studies use different PCM matrices, biochar preparation routes, loading fractions, geometries, and test methods. Transferring their measured conductivity values directly into a common battery conductance would therefore be scientifically inappropriate. The model instead treats effective conductance as a design variable and uses the literature to support the plausibility—not the exact numerical value—of conductivity enhancement. The novelty of this study is not a claim that biomass carbon or fatty-acid PCM is newly discovered. In fact, an LA-SA eutectic supported by carbonized corn-cob waste was experimentally reported in 2019, with 77.9 wt% PCM retention, 148.3 kJ kg⁻¹ melting enthalpy, and an 87.5% conductivity increase relative to neat LA-SA (Zhang *et al.*, 2019). It is the clear division of storage accessibility

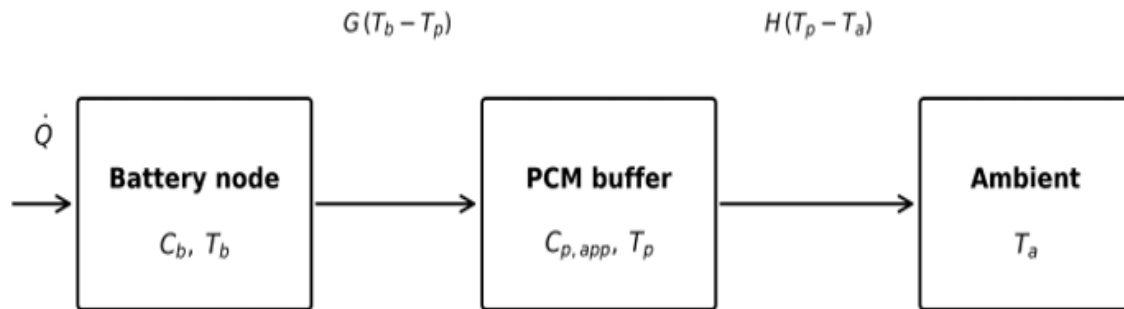
from storage capacity. If the battery-to-buffer thermal time constant is excessively lengthy, a buffer may still function badly even though it contains more latent energy than the battery releases during a single duty period. On the other hand, during a brief high-load event, adding carbon may increase the useable proportion of that latent reservoir while decreasing latent heat per kilogram. Latent utilization and thermal-access indicators are used below to quantify this competing mechanism.

MATERIALS AND METHODS

Reduced-order thermal network

Two uniform-temperature nodes—a battery node and a

PCM-buffer node—represent the buffered module. The topology is equivalent to a fully PCM-jacketed module, where battery → PCM → ambient is the primary heat-rejection path. The bare casing rejects heat directly to ambient because it is the same module without the PCM jacket. This topology is not applicable to all battery packs and must be understood as a particular enclosure concept. Validation should take into account any large parallel battery-to-ambient bypass path present in a real pack. The reduced-order thermal network and the battery–PCM–ambient heat-transfer pathways are illustrated in **Figure 1**.



Buffered topology: battery → PCM buffer → ambient. The bare case uses direct battery → ambient heat rejection.

Figure 1: The buffered arrangement makes use of a reduced-order thermal network. Bulk conduction, contact resistance, shape, and transfer area are all included in effective conductance G , which differs from intrinsic material thermal conductivity k .

Based on the thermal network illustrated in Figure 1, conservation of energy is applied separately to the battery and PCM-buffer nodes, yielding **Equations (2) and (3)**, respectively. For the bare module, the PCM buffer is absent, and heat is rejected directly from the battery to the ambient, as described by **Equation (4)**.

$$C_b dT_b/dt = \dot{Q} - G(T_b - T_p) \quad (2)$$

$$C_{p,app}(T_p) dT_p/dt = G(T_b - T_p) - H(T_p - T_a) \quad (3)$$

$$C_b dT_b/dt = \dot{Q} - H(T_b - T_a) \quad (\text{bare module}) \quad (4)$$

Here C_b is battery thermal capacitance (JK^{-1}), $C_{p,app}$ is buffer apparent thermal capacitance (JK^{-1}), G is effective battery-to-buffer conductance (W K^{-1}), H is effective external conductance (W K^{-1}), $\dot{Q}$ is the prescribed module heat generation (W), and T_b , T_p , and T_a are battery, buffer, and ambient temperatures, respectively. Effective conductance G should not be interpreted as an intrinsic material conductivity in $\text{Wm}^{-1}\text{K}^{-1}$. It combines conductivity with geometry, contact resistance, packing, interface quality, and heat-transfer area.

Apparent heat capacity and melt fraction

The phase transition is represented using an apparent heat-capacity method, a standard approach for distributed phase change when explicit motion of the melt front is not resolved (Khattari *et al.*, 2020). A 37–41 °C numerical smoothing interval is centered at the empirically determined 39.29 °C melting peak for the fatty acid cases (Fan *et al.*, 2022). This 4 °C interval is not an actually determined solidus–liquidus interval; rather, it is a numerical representation. RT42 uses the manufacturer-reported 38–43 °C melting area (Rubitherm Technologies GmbH, 2020). The RT42 data sheet explicitly combines sensible and latent heat, reporting a total heat-storage capacity of 165 kJ kg^{-1} across 35–50 °C. To avoid double-counting sensible heat in Eq. (5), the model derives an effective latent term $\text{Leff} = 165 - (2 \text{ kJ kg}^{-1} \text{ K}^{-1}) (50 - 35 \text{ K}) = 135 \text{ kJ kg}^{-1}$ while retaining $c_p = 2 \text{ kJ kg}^{-1} \text{ K}^{-1}$. This makes the modeled 35–50 °C enthalpy rise consistent with the manufacturer value rather than incorrectly treating 165 kJ kg^{-1} as pure latent heat. The temperature-dependent apparent thermal capacitance of the PCM buffer and its corresponding melt fraction are

expressed as follows:

$$C_{p,app} = m_p c_p ; \quad \text{for } T_p < T_s \text{ or } T_p > T_l \quad (5a)$$

$$C_{p,app} = m_p [c_p + L / (T_l - T_s)] ; \quad \text{for } T_s \leq T_p \leq T_l \quad (5b)$$

$$f_m = \text{clip}[(T_p - T_s) / (T_l - T_s), 0, 1] \quad (6)$$

Here, m_p is the PCM-buffer mass, L is the specific latent heat, T_s and T_l are the lower and upper boundaries of the assumed phase-transition interval, respectively, and f_m is the modeled melt fraction. The function $\text{clip}(x, 0, 1)$ restricts the melt fraction to values between 0 and 1.

Since $m_p L$ is obtained by integrating the additional heat-capacity term throughout the transition period, the apparent heat-capacity formulation preserves the required latent enthalpy. The model ignores hysteresis, anisotropy, local contact fluctuation, and natural convection within melted PCM in favor of a spatially constant buffer temperature.

Latent accessibility and thermal-access metrics

To evaluate latent-storage utilization and battery-to-buffer thermal accessibility during a prescribed duty period, two dimensionless metrics are defined as follows:

$$\eta_L = \frac{E_{\text{latent,used}}}{m_p L} = f_m \quad (7)$$

$$\Pi_G = G \frac{t_d}{c_b} \quad (8)$$

The fraction of nominal latent storage accessed by the end of the duty period under the uniform linear-melt approximation is measured by the latent-utilization ratio η_L . The battery-to-buffer coupling time scale C_b/G and the duty duration t_d are compared using the dimensionless thermal-access number Π_G . A larger Π_G indicates that the duty duration is longer relative to the battery-to-buffer thermal coupling time scale.

The percentage reduction in battery temperature rise relative to the bare module is calculated as:

$$R_T = 100 \frac{T_{b,bare} - T_{b,buffered}}{T_{b,bare} - T_a} \quad (9)$$

Here, $T_{(b,bare)}$ and $T_{(b,buffered)}$ are the final battery temperatures of the bare and PCM-buffered modules, respectively, and T_a is the ambient temperature. Positive values of R_T indicate a reduction in battery temperature rise relative to the bare module.

Model inputs

Table 1 clearly distinguishes source-backed measurements from derived values and study design factors. This distinction is crucial because a numerical paper can be replicated without suggesting that all of the inputs for the suggested hardware have been measured experimentally. To compare the effects of latent-storage capacity

Table 1: Provenance classification and model inputs.

Parameter	Value	Status	Provenance/interpretation
Battery module mass	0.60 kg	Study design value	Assumed battery-module mass for the numerical analysis.
Battery specific heat	0.90 kJ kg ⁻¹ K ⁻¹	Study design value	Within the broad range reported for Li-ion cells/jelly rolls; cell-specific values should be measured (Al-Zareer <i>et al.</i> , 2021; Maleki <i>et al.</i> , 1999; Steinhardt <i>et al.</i> , 2021)
Battery thermal capacitance, C_b	540 J K ⁻¹	Derived	Calculated as 0.60 kg × 900 J kg ⁻¹ K ⁻¹
Buffer mass, m_p	0.45 kg	Design variable	Base-case buffer mass; mass sensitivity evaluated.
External conductance, H	0.70 W K ⁻¹	Design variable	Effective enclosure/ambient conductance; not a material property
Initial/ambient temperature	25 °C	Design variable	Base boundary condition
Low thermal duty	8 W for 3600 s	Design variable	28.8 kJ supplied
Intermediate thermal duty	18 W for 1800 s	Design variable	32.4 kJ supplied
High thermal duty	32 W for 1200 s	Design variable	38.4 kJ supplied
LA-SA eutectic latent heat	189.5 kJ kg ⁻¹	Measured literature	Fan <i>et al.</i> (2022)
LA-SA melting peak	39.29 °C	Measured literature	Fan <i>et al.</i> (2022)
LA-SA sensible c_p	1.735 kJ kg ⁻¹ K ⁻¹	Derived proxy	82/18 mass-weighted from pure-acid c_p values reported by Wang <i>et al.</i> (2022)
Carbon-support specific heat	1.062 kJ kg ⁻¹ K ⁻¹	Measured literature proxy	Activated carbon measurement; used only as screening proxy (Anupam <i>et al.</i> , 2013)

RT42 melting area	38–43 °C	Manufacturer data	Rubitherm RT42 technical data sheet (Rubitherm Technologies GmbH, 2020)
RT42 total storage, 35–50 °C	165 kJ kg ⁻¹	Manufacturer data	Combination of latent + sensible heat, not pure latent heat (Rubitherm Technologies GmbH, 2020)
RT42 effective latent term	135 kJ kg ⁻¹	Derived	165 – 2×15; used so apparent-cp model reproduces the stated 35–50 °C storage

and effective thermal conductance, four PCM-buffer configurations are defined, as summarized in **Table 2**.

As shown in **Table 2**, Composite-L and Composite-H represent the lower-conductance $G=1.50 \text{ W K}^{-1}$

Table 2: Thermal-buffer configurations.

Configuration	Active PCM fraction	L (kJ kg ⁻¹)	cp (kJ kg ⁻¹ K ⁻¹)	Transition interval (°C)	G (W K ⁻¹)	Interpretation
Fatty-acid PCM	1.00	189.5	1.735	37–41*	0.80	Measured/derived matrix data + design G
Composite-L	0.80	151.6	1.600	37–41*	1.50	Mixture-rule storage + design G
Composite-H	0.80	151.6	1.600	37–41*	2.00	Mixture-rule storage + design G
RT42 paraffin	1.00	135.0†	2.000	38–43	1.00	Derived effective latent term + design G

* The 37–41 °C transition interval is an assumed numerical smoothing range, not an experimentally measured solidus–liquidus interval.

† The RT42 effective latent-heat value (135 kJ kg⁻¹) is derived by subtracting the modeled sensible heat (30 kJ kg⁻¹) from the manufacturer-reported total heat-storage capacity (165 kJ kg⁻¹) over 35–50 °C.

and higher-conductance $G=2.00 \text{ W K}^{-1}$ composite configurations, respectively. Both configurations have identical PCM fractions and thermal-storage properties, and their conductance values are assumed design inputs rather than measured properties of specific agricultural-residue-derived carbons.

Numerical solution and sensitivity analysis

The thermal responses of the configurations presented in **Table 2** are calculated using an adaptive Runge–Kutta solver to integrate **Equations (2)–(5)**. For reported results, the maximum time step is 0.5 s, and the relative and absolute tolerances are 10⁻⁹ and 10⁻¹¹, respectively. An energy-closure residual is calculated from supplied heat, battery sensible storage, buffer enthalpy change, and time-integrated external heat rejection. A 1.0 s maximum-step solution is contrasted with the 0.5 s solution. The implementation accuracy is confirmed by small numerical

residuals, but neither the physical assumptions nor the selected effective conductances are validated.

Heat input, ambient temperature, buffer mass, effective conductance, and latent heat are varied individually in a one-factor-at-a-time sensitivity analysis of the high-duty Composite-H case. Furthermore, while keeping the other Composite-H assumptions constant, a two-parameter design map covers $G = 0.4\text{--}3.5 \text{ W K}^{-1}$ and $L = 80\text{--}210 \text{ kJ kg}^{-1}$. Rather than optimizing a particular produced composite, the goal of this map is to find conductance-limited and storage-limited regimes.

RESULTS AND DISCUSSION

End-of-duty temperatures

The predicted battery temperatures at the end of the low, intermediate, and high thermal-duty cases are summarized in **Table 3**.

Table 3: Calculated battery-node temperatures at the end of each specified thermal duty.

Configuration	Low duty (°C)	Intermediate duty (°C)	High duty (°C)
Bare module	36.32	48.22	61.07
Fatty-acid PCM	42.59	53.80	65.03
Composite-L	39.27	47.93	55.99
Composite-H	38.21	45.65	52.24
RT42 paraffin	40.84	51.02	61.57

Under the low-duty case, all four PCM-buffer configurations produce higher final battery temperatures than the bare module, which reaches 36.32 °C. The neat fatty-acid and RT42 cases, for example, reach 42.59 and 40.84 °C, respectively. Their comparatively low G values add an intermediate thermal barrier and slow access to the initially cool buffer in the chosen completely jacketed design. This outcome demonstrates that a weakly coupled PCM jacket can perform worse than direct ambient heat rejection during a finite duty period, but it does not indicate that fatty-acid or paraffin PCMs are inherently unsuitable.

Higher-coupling composites provide improved thermal performance under intermediate and high thermal duties. Compared with 48.22 and 61.07 °C for the bare module, Composite-H reaches 45.65 °C under the intermediate duty and 52.24 °C under the high duty. These results represent thermal mitigation rather than complete temperature control, since the final temperature of 52.24 °C remains above the commonly preferred operating range for lithium-ion batteries (Mattia *et al.*, 2025). The corresponding battery-temperature histories for the high-duty case are presented in **Figure 2**.

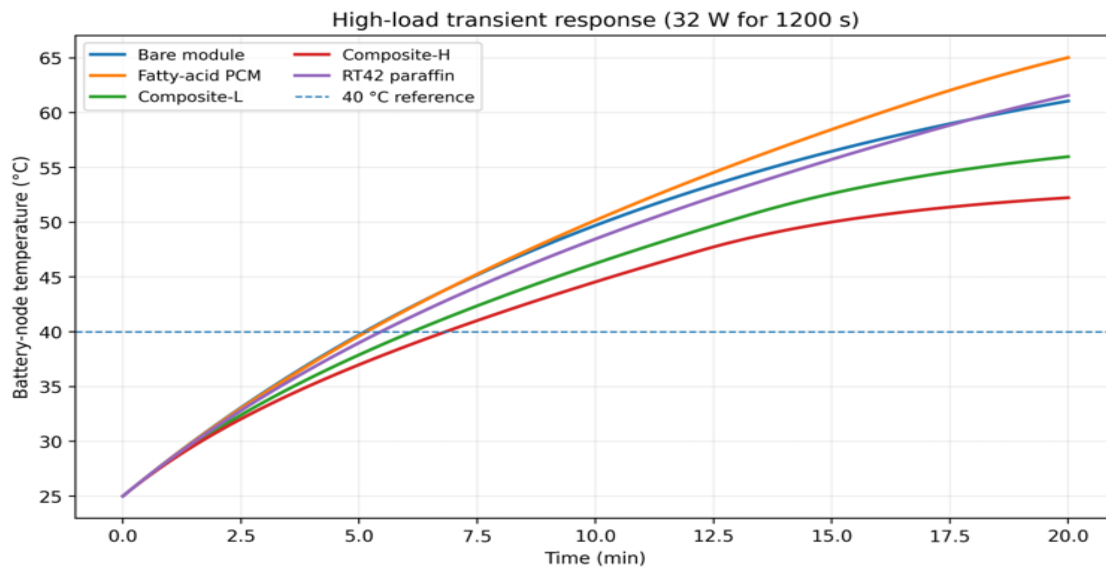


Figure 2: Temperature histories of battery nodes for high thermal duty. The dashed 40 °C line represents a reference temperature rather than a universal safety limit.

High-load latent utilization and thermal benefit

Table 4 summarizes the thermal-access number, latent-

heat utilization, and battery-temperature response of the PCM-buffer configurations under the high-duty case.

Table 4: Latent-heat utilization and thermal performance of PCM-buffer configurations under the high-duty case.

Configuration	Battery (°C)	Buffer (°C)	Melt used (%)	ΔT vs bare (°C)	Rise reduction (%)	Π_G
Fatty-acid PCM	65.03	37.10	2.6	-3.97	-11.0	1.78
Composite-L	55.99	37.37	9.4	5.08	14.1	3.33
Composite-H	52.24	37.47	11.7	8.83	24.5	4.44
RT42 paraffin	61.57	38.12	2.5	-0.50	-1.4	2.22

Note. Melt used (%) represents $100\eta_L$. The temperature difference relative to the bare module is calculated as $(T_{b,bare} - T_{b,buffer})$. Temperature-rise reduction (%) is calculated relative to the bare-module temperature rise above ambient.

The discrepancy between nominal and utilized latent storage is the main outcome. The nominal latent capacity of the Composite-H buffer is $0.45 \times 151.6 = 68.22$ kJ, which is 1.78 times the total high-duty heat input of 38.4 kJ. However, by the end of the 1200-s duty period, only 11.7% of that latent capacity has been utilized. As a result, the lumped buffer stays at 37.47 °C while the battery reaches 52.24 °C. Rather than indicating a shortage of nominal latent capacity, the substantial temperature

difference between the battery and buffer points to a heat-transfer limitation.

Even greater nominal latent storage (85.28 kJ) is available in the pristine fatty-acid scenario, but because effective conductance G is low, only roughly 2.6% is accessed during the high duty. As a result, its battery temperature is higher than the bare outcome. Because the heat reservoir becomes more accessible within the finite duty time, the higher-coupling composite performs significantly better

despite sacrificing 20% of the active PCM mass. This is the principal design mechanism demonstrated by the model.

Conductance-latent-heat design space

The combined effects of effective battery-to-buffer conductance and composite latent heat on the final

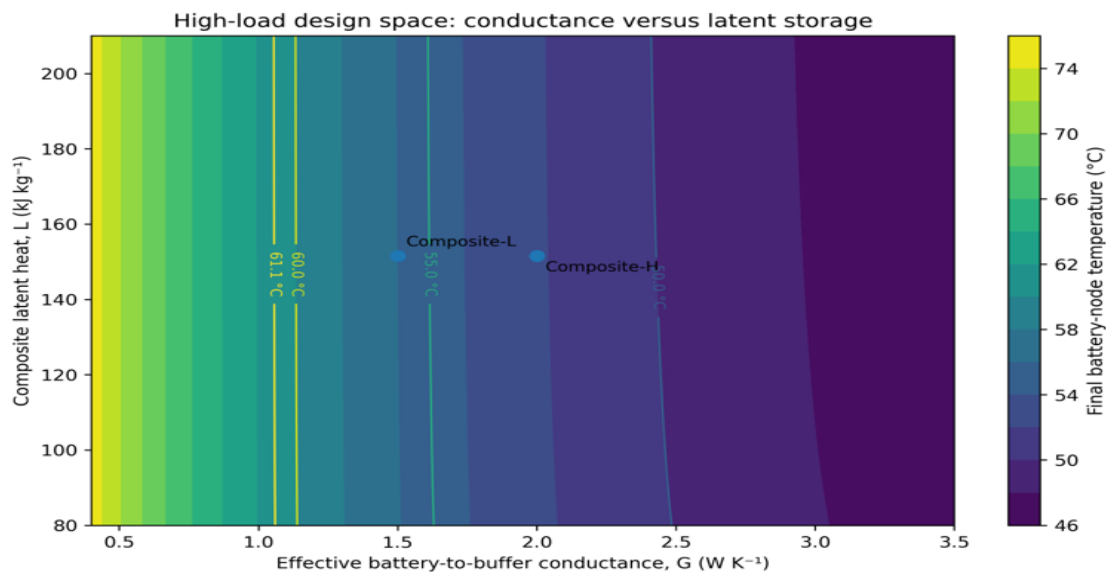


Figure 3: Final battery-node temperature for the high-duty case as a function of effective conductance and composite latent heat. The map is a design-space result; it is not a feedstock property map.

battery temperature are illustrated in **Figure 3**.

Figure 3 shows that conductance dominates the transition from detrimental to beneficial buffering in the investigated region. Around the bare-module final temperature of 61.07 °C, the break-even conductance is approximately 1.06 W K⁻¹ across a wide latent-heat range. This threshold depends weakly on L because the buffer is only beginning to enter the transition region near the break-even point. Increasing latent heat cannot help if heat does not arrive at the buffer quickly enough. At larger G, latent heat becomes progressively more useful because a larger fraction of the transition reservoir is reached.

This behavior is consistent with the broader PCM literature, which identifies low thermal conductivity as a major limitation and investigates conductive frameworks, particles, and hybrid structures to improve heat transfer (Barnes & Li, 2020; Deng *et al.*, 2021; Fathimathul Faseena

& Sreekumar, 2025; Guo *et al.*, 2022; Sohail, 2026; Sun *et al.*, 2023; Wazeer *et al.*, 2022; Zhou *et al.*, 2026).

The predicted break-even threshold applies to the assumed battery-PCM-ambient thermal network. A substantial parallel battery-to-ambient heat-transfer pathway could alter the temperature response and the corresponding threshold. Moreover, the conductance values are numerical design assumptions rather than experimentally measured properties of rice-husk or coconut-shell composites. The present results therefore do not establish a performance ranking between these agricultural-residue feedstocks.

Sensitivity of the higher-coupling composite

The effects of individual variations in heat input, ambient temperature, buffer mass, effective conductance, and latent heat on the Composite-H high-duty response are summarized in **Table 5**.

Table 5: One-factor sensitivity of the Composite-H high-duty case.

Condition	Battery (°C)	Buffer (°C)	Melt used (%)	Latent energy used (kJ)
Base case	52.24	37.47	11.7	7.98
Heat input -20%	48.47	37.19	4.8	3.29
Heat input +20%	55.79	37.76	19.1	13.00
Ambient 30 °C	53.14	37.91	22.6	15.45
Ambient 35 °C	53.77	38.40	35.0	23.86
Buffer mass 0.30 kg	52.72	37.87	21.6	9.84
Buffer mass 0.60 kg	51.82	37.26	6.6	6.00
Conductance -25%	55.99	37.37	9.4	6.38
Conductance +25%	49.68	37.53	13.3	9.08

Latent heat -20%	52.29	37.58	14.4	7.86
Latent heat +20%	52.20	37.39	9.8	8.06

The corresponding changes in final battery temperature relative to the Composite-H base case are presented in

Figure 4.

The sensitivity results reinforce the accessibility

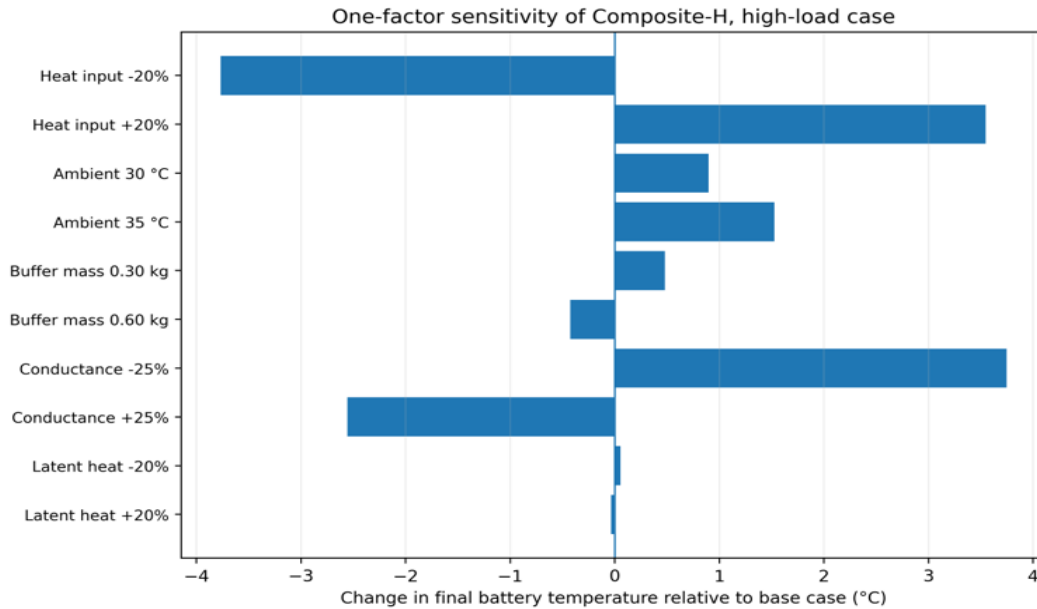


Figure 4: Change in final battery temperature relative to the Composite-H base case.

interpretation. Reducing G by 25% increases final battery temperature from 52.24 to 55.99 °C, whereas increasing G by 25% lowers it to 49.68 °C. By contrast, reducing latent heat by 20% changes final temperature by only +0.05 °C, and increasing latent heat by 20% changes it by only -0.04 °C. The small temperature response to L does not mean latent heat is unimportant in general. It means that, for this finite high-duty case, the latent reservoir remains underutilized because battery-to-buffer heat transfer is limiting under the investigated high-duty conditions.

Raising ambient temperature increases the final battery temperature despite increasing the melt fraction. This apparently counterintuitive combination occurs because a warmer initial/ambient state brings the buffer closer

to its transition range while simultaneously reducing the temperature difference available for external heat rejection. Similarly, a larger buffer mass lowers battery temperature but can reduce the fraction of material melted because the same transferred energy is distributed over a larger sensible and latent reservoir. Therefore, melt fraction alone is not a sufficient performance metric.

Numerical consistency

Numerical consistency was assessed through maximum-time-step refinement and energy-balance closure. The results for the high-duty buffered configurations are summarized in **Table 6**.

At the reported precision, the step-refinement differences

Table 6: Numerical step-refinement and energy-closure checks for the high-duty buffered cases.

Configuration	Final battery-temperature difference (°C)	Absolute energy-closure residual (%)
Fatty-acid PCM	0.000000	0.000118
Composite-L	0.000002	0.000158
Composite-H	0.000001	0.000028
RT42 paraffin	0.000000	0.000075

Note. Temperature differences are calculated between solutions obtained using maximum solver time steps of 1.0 s and 0.5 s

do not exceed 2×10^{-6} °C, and the absolute energy-closure residuals remain below 0.001%. These checks demonstrate numerical consistency for the stated **equations** and model inputs. They do not establish experimental validity of the effective conductances, buffer geometry, heat-generation rates, or agricultural-

residue-derived material properties.

Engineering Implications, Limitations, and Future Validation

The first engineering implication is that intrinsic PCM properties should be given the same consideration

as interface and packaging design. If there are voids, inadequate wetting, substantial electrically insulating barriers, lengthy conduction paths, or a small contact area, a highly conductive composite may still have a low effective conductance, (G). Conversely, improved enclosure contact can increase (G) without changing the PCM chemistry. Experimental work should therefore report both intrinsic thermal conductivity and module-level thermal resistance or conductance.

Mass efficiency is the second consideration. The base buffer mass of 0.45 kg corresponds to 75% of the assumed battery-module mass of 0.60 kg. In a practical battery pack, such a penalty might not be acceptable, even though the sensitivity analysis indicates a thermal benefit from additional buffer mass. Therefore, rather than focusing only on temperature reduction, future design optimization should take into account temperature reduction per kilogram and per unit volume. The current buffer mass is treated as a study design value rather than an optimized commercial configuration.

The third implication is recovery between cycles. All buffered cases start at ambient temperature with a completely solid PCM. Repeated duty cycles can leave residual melt and elevated buffer temperature, reducing available storage in subsequent cycles. Passive PCM systems therefore require either sufficient rest time or an auxiliary heat-rejection path to restore the initial thermal state. Recent reviews similarly identify heat rejection after melting as a central limitation of purely passive PCM systems (Fathimathul Faseena & Sreekumar, 2025; Sohail, 2026; Zhou *et al.*, 2026).

The fourth implication is electrical and fire safety. Agricultural-residue-derived carbons can be electrically conductive. Any battery integration must prevent contact with live terminals and busbars, and the thermal resistance of an electrical-insulation layer must be included in measured module conductance. Organic PCMs also require assessment of flammability, containment, leakage, compatibility, and abuse behavior. Lower temperature under a normal prescribed heat load must not be presented as proof of thermal-runaway suppression.

This work is deliberately a reduced-order feasibility study. The battery and PCM are represented by uniform-temperature nodes, so the model cannot predict the hottest individual cell, radial or axial cell gradients, temperature non-uniformity across a pack, local contact defects, or melt-front geometry. It also neglects state-of-charge dependence of battery heat capacity and heat generation, temperature-dependent properties, natural convection in liquid PCM, radiation, PCM supercooling and hysteresis, and changes in crystallization behavior caused by pore confinement. These limitations prevent direct translation of the reported temperatures into a certification or safety claim.

A credible experimental program should proceed in the following sequence. First, rice husk and coconut shell batches should be processed using a documented

pyrolysis or activation route and characterized for proximate and ultimate composition, ash content, BET surface area, pore-size distribution, density, and electrical resistivity. Second, the fatty-acid PCM and each final composite should be characterized by DSC for melting and freezing onset, peak and completion temperatures, and enthalpy; thermal conductivity; specific heat; density; leakage and shape stability; and repeated thermal cycling sufficient to quantify drift and stability for the intended application. Third, the electrical-isolation layer and the complete battery-PCM interface should be measured as an effective thermal resistance, because that quantity corresponds most directly to (G) in the present model.

Fourth, module testing should use a defined commercial cell with documented capacity, chemistry, state of charge, current profile, and cell-to-cell matching. Heat generation should be measured calorimetrically or calculated with a validated electrothermal model rather than inferred solely from nominal C-rate. Central and peripheral cell temperatures and PCM temperatures should be measured during single and repeated duty cycles. The reduced-order model should then be calibrated on one condition and validated against separate conditions without re-fitting. Finally, leakage, electrical isolation, flame response, vent clearance, and post-cycle material integrity should be assessed before any claim of practical battery suitability.

CONCLUSION

A literature-anchored reduced-order model was developed for passive battery thermal buffering using a bio-based fatty-acid PCM concept with an agricultural-residue-derived carbon support. The model treats effective conductance values as design assumptions rather than measured properties of specific rice-husk or coconut-shell composites and uses prescribed thermal loads instead of electrochemical C-rate labels. Under the high thermal duty of 32 W for 1200 s at 25 °C, the bare module reaches 61.07 °C, while the lower- and higher-coupling composite cases reach 55.99 and 52.24 °C, respectively. The higher-coupling case reduces temperature rise above ambient by 24.5% relative to the bare module, but its final temperature remains above a commonly preferred battery operating region and should therefore be interpreted as mitigation, not complete thermal control.

The principal finding is that nominal latent storage and accessible latent storage are not equivalent. The nominal latent capacity of the higher-coupling composite is 68.22 kJ, which is greater than the 38.4 kJ supplied during the high-duty period. However, only approximately 11.7% of that latent reservoir is accessed. Under the investigated conditions, the final battery temperature is more sensitive to variations in effective conductance than to $\pm 20\%$ variations in latent heat. Despite having substantial latent capacity, the PCM jacket may perform worse than the bare module below a case-specific break-even effective conductance of approximately 1.06 W K^{-1} , according to the conductance-latent-heat design map.

Data availability

No experimental dataset was generated in this study. All numerical input values used for the reported reduced-order computations are provided in the manuscript tables. Governing equations, response definitions, design variables, and literature-derived material properties are documented with appropriate references.

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