A Design and Feasibility Framework for Agro-Waste Bio-Composite Battery Casings in Electric Two/Three-Wheelers

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Abstract: The rapid growth of electric two- and three-wheelers has intensified demand for lightweight, thermally safe and sustainable battery enclosures. Conventional metallic casings are heavy and carbon-intensive, while plastic and glass-fibre composite casings lack adequate thermal stability and fire resistance. This paper reviews the current state of battery thermal management system (BTMS) casings and natural-fibre bio-composites, and proposes a design and fabrication framework for an agro-waste bio-composite casing for 18650 lithium-ion battery modules arranged in a 13s4p configuration. The proposed casing combines banana-pseudostem-fibre-reinforced bio-epoxy with boron nitride, alumina and ammonium-polyphosphate flame-retardant additives, compression-moulded with integrated passive cooling vents and cell-holding inserts. The literature synthesis shows that, although composite battery enclosures and flame-retardant natural-fibre composites have each been studied extensively, very little reported work combines agro-waste fibres, passive thermal venting and flame retardancy within a single casing purpose-built for cost-sensitive 2W/3W platforms. On the basis of the reviewed benchmarks, the proposed casing framework is targeted to achieve a 20-30% weight reduction over metal casings while meeting UL-94/limiting-oxygen-index (LOI) flame-safety benchmarks. The framework presented here defines the material formulation, mould design and characterization matrix that will guide the fabrication and testing phases of the ongoing project, and is directly applicable to EV battery-pack manufacturers and thermal-component suppliers seeking sustainable, cost-effective casing solutions.

Keywords: Bio-composite; Battery thermal management system; Banana pseudostem fibre; Flame retardancy; Electric vehicle; Compression moulding.

Introduction

Electric two-wheelers (2W) and three-wheelers (3W) are the fastest-growing segment of India's electric-vehicle (EV) market, and their 18650 cylindrical lithium-ion battery modules are increasingly packaged in compact, high-density configurations such as 13s4p. As pack density rises, the enclosure that houses the cells is no longer a passive shell: it must dissipate heat, resist fire, and remain light enough not to erode the vehicle's range. Battery thermal management system (BTMS) research over the last decade has produced a wide portfolio of active and passive cooling strategies, yet the enclosure material itself is frequently treated as a secondary design variable rather than an active contributor to thermal safety [1], [2].

Conventional aluminium casings resist heat well but add mass and embodied carbon; injection-moulded plastics (ABS, PETG, PLA) are light but soften and lose structural integrity well below thermal-runaway onset temperatures, and even flame-retardant grades such as FR-ABS only partially close this gap [3]. Glass-fibre composites improve stiffness but bring their own end-of-life and recyclability concerns. This creates a clear opening for bio-based composite casings that are simultaneously light, thermally tolerant, fire-resistant and derived from a renewable, low-cost feedstock. Agro-waste fibres such as banana pseudostem, generated in large volumes wherever bananas are cultivated, are mechanically competitive with several commercial natural fibres and are conventionally discarded as field residue [4]-[7].

This paper reports the first output of a one-year post-doctoral project that is developing a bio-composite thermal-management casing for 18650 battery modules. Consistent with the project's Phase-1 timeline (literature review, feasibility study and initial design, Months 1-3), the objective of this paper is to (i) consolidate the state of the art in BTMS casings and flame-retardant natural-fibre composites, (ii) identify the specific research gap that the project addresses, and (iii) present the design and characterization framework that will be executed in the subsequent fabrication and testing phases.

Related Work

Reviews of BTMS technology consistently show that passive strategies (heat-conductive housings, phase-change materials, vented enclosures) are attractive for 2W/3W platforms because they add negligible parasitic load compared with active air- or liquid-cooling loops, but most of this literature optimizes internal cooling elements rather than the casing material itself [1], [2]. Material-selection studies for EV battery-pack casings have compared metals with engineering thermoplastics (PLA, ABS, PETG, FR-ABS) and multi-criteria decision-making methods have been used to rank thermoplastics on thermal stability, mechanical strength and sustainability, confirming that polymer-based casings can approach metal-like performance once reinforced or additised, but these studies do not consider agro-waste natural-fibre reinforcement [3].

A separate stream of research has characterized banana-pseudostem fibre in detail: its extraction methods, chemical composition and surface treatments are now well documented [4], layer-wise mechanical and chemical variation within the pseudostem has been quantified [5], and the fibre has been evaluated as reinforcement in packaging boards and hybrid polymer composites, including hybrids with pineapple-leaf fibre that report tensile strengths up to about 28 MPa and flexural strengths above 55 MPa for optimized fibre loadings [6], [7]. None of these studies, however, targets battery-enclosure applications or evaluates the fibre alongside flame-retardant additives.

On the fire-safety side, reviews of eco-friendly flame retardants for natural-fibre composites describe how phosphorus-, boron- and mineral-based additives such as ammonium polyphosphate (APP), boron nitride and aluminium hydroxide promote char formation and intumescence in bio-based matrices [8], and experimental work on flax-fabric epoxy composites shows that 20-30 wt% APP loading can achieve self-extinguishing UL-94 vertical ratings within 10-30 s while producing measurable but manageable reductions in tensile strength [9]. Table 1 compares the present work against these four literature streams.

Reference	Passive Thermal Venting	Agro-Waste Fibre Feedstock	Flame-Retardant Additives	Purpose-Built for 2W/3W 18650 Casing
[1], [2]	Yes (active/passive review)	No	No	No
[3]	No	No	Partial (FR-ABS)	Yes (polymer casing)
[4]-[7]	No	Yes	No	No
[8], [9]	No	Partial (flax/general)	Yes	No
This work	Yes	Yes (banana pseudostem)	Yes	Yes (13s4p, 2W/3W)

Table 1. Comparison of the proposed casing with the four related-work streams identified in the literature.

Key Contribution

The key contribution of this paper is not a novel material chemistry in isolation, but the integration, within a single design framework, of four elements that the literature currently treats separately: (i) an agro-waste banana-pseudostem fibre feedstock, (ii) a bio-based epoxy matrix carrying APP/boron-nitride/alumina flame-retardant additives, (iii) a compression-moulded casing geometry with integrated passive thermal vents and precision cell-holding inserts, and (iv) a form factor engineered specifically for the 13s4p 18650 configuration used in 2W/3W EV packs. This integration converts the casing from a passive structural shell into an active, low-cost contributor to passive thermal management and fire safety, while remaining compatible with the compression-moulding infrastructure already used for low-volume component manufacturing in India, supporting the Make-in-India and Atmanirbhar Bharat objectives noted in the parent research proposal.

Method, Experiments and Results

As this paper corresponds to Phase 1 (Months 1-3) of the project timeline, the 'results' reported here are the design and characterization framework derived from the literature synthesis, rather than measured experimental data; fabrication and physical testing are scheduled for Phases 2-4 and will be reported in subsequent conference papers.

Fibre preparation: Raw banana pseudostem is mechanically pulped to extract fibre, which is washed, dried (ambient or sun-dried) and moisture-checked before being cut to a uniform length. The fibre pulp is refined through fine meshing (approx. 200 nm) prior to blending.

Matrix and additive formulation: Bio-based epoxy resin is proposed as the matrix, with boron nitride (BN) and aluminium oxide (Al_2O_3) included for thermal-conduction pathways and ammonium polyphosphate (APP) included as the primary intumescent flame retardant, following the additive classes shown to be effective for natural-fibre composites in [8] and [9]. Additive loading will be varied around the 20-30 wt% APP range reported to achieve self-extinguishing behaviour [9], balanced against the reported reduction in tensile strength at higher loadings.

Fabrication: Fibre pulp, resin and additives are blended and compression-moulded using a hand press with a 3D-printed negative mould, followed by demoulding, CNC/manual surface finishing, and assembly with the 13s4p 18650 cell array using alignment jigs. The mould incorporates passive vent channels and cell-holding inserts sized to the cylindrical cell geometry.

Planned characterization matrix: Table 2 summarizes the material, mechanical and thermal-safety tests that will be applied to the fabricated coupons and prototype casing in the subsequent project phases, benchmarked against the metal, plastic and glass-fibre composite casings reviewed in the Related Work section.

Category	Technique	Property Evaluated	Project Phase
Material	FTIR, XRD	Functional groups, crystallinity	Phase 2 (M4-6)
Material	SEM	Fibre-matrix adhesion	Phase 2 (M4-6)
Thermal	TGA, DSC	Degradation onset, Tg	Phase 2 (M4-6)
Mechanical	Tensile, flexural, impact, Shore-D	Strength, stiffness, hardness	Phase 4 (M10-12)
Thermal safety	K-type TC, UL-94/LOI	Passive-cooling profile, flame class	Phase 4 (M10-12)

Table 2. Planned characterization matrix for the bio-composite casing (Phases 2 and 4 of the project timeline).

Discussion

The literature reviewed above indicates that the principal engineering risk in this framework is moisture sensitivity and fibre-matrix interfacial bonding, which is a well-documented limitation of lignocellulosic fibres relative to metals and synthetic fibres [4]. This risk is mitigated in the proposed process through controlled drying, fine-mesh pulping, and the coupling behaviour reported for treated banana-pseudostem fibre in hybrid composites [6], [7]. A second consideration is the trade-off between flame-retardant loading and mechanical strength: the flax-fibre benchmark [9] suggests that APP loadings sufficient for a self-extinguishing UL-94 rating are achievable without a disproportionate loss of tensile performance, but this must be re-verified for the banana-fibre/bio-epoxy system specifically, since fibre type and resin chemistry both influence char formation [8].

From a systems perspective, a casing that combines structural support, passive heat dissipation and fire retardancy in one component simplifies the battery-pack bill of materials relative to designs that rely on separate metal housings, phase-change layers and intumescent coatings [1], [2]. Economically, sourcing fibre from agricultural waste streams offers a route to rural value creation alongside the technical benefits, which is consistent with the sustainability objectives of the parent post-doctoral proposal.

Conclusions

1. Problem addressed/motivation: Existing metallic, plastic and glass-fibre casings for 2W/3W EV battery modules cannot simultaneously deliver low weight, passive thermal management and adequate fire resistance at low cost.
2. Method used: A structured literature synthesis across BTMS casings, banana-pseudostem-fibre composites and flame-retardant natural-fibre composites was used to derive a compression-moulding-based design and characterization framework for a 13s4p 18650 casing.
3. Key findings: The four elements required for a viable solution-agro-waste fibre, bio-epoxy matrix with APP/BN/Al2O3 additives, passive vent/insert geometry, and a 2W/3W-specific form factor-are each individually supported by the literature but have not previously been reported together; benchmark data from related flax-fibre composites suggest a self-extinguishing flame class is achievable in the 20-30 wt% APP range.
4. Limitations and future work: This paper reports a design framework derived from secondary literature; no physical prototype has yet been fabricated or tested. The next phases of the project (Months 4-12) will execute the fibre and resin characterization (FTIR, SEM, TGA/DSC, XRD), fabricate coupons and a prototype casing, and report measured mechanical, thermal-conductivity and UL-94/LOI results in subsequent conference papers, followed by comparison against the metal, plastic and glass-fibre benchmarks identified in this review.

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