Development and Evaluation of a Laminated Bamboo Frame for Electric Scooters: A Preliminary Prototype

Manuscript received August 03, 2025; revised September 15, 2025

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***Abstract*—This study presents the design, fabrication, and evaluation of a hybrid electric scooter frame constructed from laminated Gombong bamboo and aluminium. The objective was to address environmental concerns in personal mobility by reducing reliance on high-carbon materials and improving battery safety. A CAD-based design was executed in Autodesk Inventor using bamboo beams for primary structure and aluminium joints for mechanical stability. Laminated bamboo was processed through drying, chemical treatment, and gluing. Mechanical properties were evaluated via tensile and compressive tests, achieving a tensile strength of 289 MPa. A 72V lithium-ion battery pack composed of 18650 cells was assembled with BMS integration. The resulting prototype exhibited a total frame weight of 4.8 kg and a 30 km range per charge. The integration of laminated bamboo with aluminum joints provides preliminary evidence of feasibility and highlights bamboo's potential as a renewable material for lightweight mobility applications. These results provide an initial prototype-level demonstration of laminated bamboo as a viable material for sustainable transport applications.**

Keywords—Electric Scooter, Hybrid Frame, Laminated Bamboo, Structural Materials, Sustainable Mobility

I. INTRODUCTION

The demand for sustainable urban transportation has intensified in recent years, driven by global concerns over climate change, urban air pollution, and resource depletion. As cities expand and mobility demands become increasingly complex, electric scooters (e-scooters) have emerged as a popular alternative, offering convenience, affordability, and lower operational emissions compared to internal combustion engine vehicles (ICEVs). Despite these advantages, however, growing evidence suggests that e-scooters are not without environmental and social challenges, warranting a more critical evaluation of their sustainability.

Life cycle assessment (LCA) studies show that, while e-scooters produce fewer tailpipe emissions than gasoline vehicles, they can still generate considerable greenhouse gas (GHG) emissions across their entire lifespan, especially during manufacturing and battery production. For example, Ishaq [1] estimated the global warming potential of e-scooters at approximately 237 g CO_2 eq./km, a figure comparable to small ICEVs. These findings highlight the importance of assessing sustainability beyond operational emissions alone.

Much of the environmental burden of e-scooters arises from their lithium-ion batteries and frame materials. Battery production requires lithium and other rare metals whose extraction often leads to ecological degradation, water pollution, and social disruption [2]. At the same time, frame construction relies on aluminum and steel—materials that, although strong and lightweight, are highly energy-intensive to extract and process. Aluminum offers corrosion resistance but has a high embodied energy footprint, while steel, though more recyclable, is heavier and demands even higher processing energy [1,3]. These material choices not only increase the environmental cost but also add unnecessary mass to the vehicle, reducing energy efficiency and limiting travel range per charge.

Beyond environmental issues, e-scooters raise questions about safety and social impact. Studies indicate that their use often substitutes for walking, cycling, or public transport rather than replacing car trips, thus diminishing their net sustainability benefit [4]. Rising accident rates further complicate adoption, prompting calls for regulatory frameworks and design improvements that address both safety and public health concerns [5,6].

In response to these challenges, researchers have begun exploring alternative frame materials with lower embodied energy and improved sustainability profiles. Laminated bamboo has emerged as a promising candidate due to its favorable strength-to-weight ratio, mechanical performance comparable to mild steel and engineered wood, rapid growth cycle, and carbon sequestration capacity [7,8]. Unlike metals, bamboo can be harvested and processed with significantly less

 EISSN: 2961-872X ● PISSN: 2961-8924 ● DOI: 10.56741/ IISTR.esl.001314

energy, lowering the overall carbon footprint of production [9,10]. When engineered into uniform composites, laminated bamboo can withstand tensile, compressive, and flexural loads effectively [11,12], making it suitable for mobility applications where both safety and structural integrity are critical. By reducing frame mass, bamboo-based designs may also improve energy efficiency at the system level.

Battery safety, however, remains another pressing issue in e-scooter design. Lithium-ion cells, while offering high energy density, pose risks of thermal runaway, fire, and explosion if improperly managed. Overcharging, inadequate thermal control, and physical damage exacerbate these hazards [13]. To address this, researchers have proposed reinforced enclosures, advanced battery management systems (BMS), and passive thermal control strategies [14]. Parallel efforts are underway to develop recycling methods and improved chemistries that mitigate end-of-life impacts [15]. Together, these advances underline the necessity of embedding safety and sustainability considerations early in the design of electro-mobility systems.

Recent engineering studies have begun integrating laminated bamboo into mobility platforms such as bicycles, scooters, and lightweight vehicles [8,16]. This trend reflects recognition of bamboo's dual benefits: mechanical robustness and ecological sustainability. Simultaneously, efforts to engineer safer, more reliable battery systems suggest that the convergence of renewable structural materials with enhanced energy storage solutions could define the next generation of urban transport. Yet very few studies have attempted to merge these two innovations into a single prototype, particularly in the Indonesian context where bamboo species such as Gombong are abundant but underutilized in advanced structural applications.

This study addresses that gap by combining bamboo composites with custom lithium-ion battery design in a functional e-scooter prototype. The environmental potential of bamboo can be quantified through its low embodied energy: laminated bamboo beams average 4–6 MJ/kg compared to 29–35 MJ/kg for mild steel [17] and 140–180 MJ/kg for primary aluminum [18]. This discrepancy is pivotal when considering the overall carbon footprint associated with material selection in construction projects. The reduced embodied energy of bamboo is attributed to its rapid growth and low processing requirements, placing it in a favorable light for environmentally conscious engineering practices. Furthermore, bamboo's mechanical properties, including strength and stiffness, render it a viable candidate as an alternative structural material conducive to sustainability [19].

Earlier research on bamboo vehicles has often relied on untreated culms and rudimentary joints, proving feasibility but lacking systematic evaluation of material processing, joint reliability, and integration with modern e-mobility requirements. The present work introduces three key methodological novelties:

1) The use of Gombong bamboo, an abundant Indonesian species rarely studied for engineered mobility frames;
2) A controlled six-ply laminate schedule bonded with polyurethane adhesive, optimized for strength-to-weight performance; and
3) A hybrid bonded-bolted bamboo–aluminum joint system designed to improve load transfer and minimize slippage compared to adhesive-only joints.

By uniting species-specific bamboo processing, engineered lamination, and hybrid joint design with a custom lithium-ion battery system, this study demonstrates a replicable pathway for sustainable e-scooter development. In doing so, it advances the integration of renewable materials and safety-engineered energy storage, while contributing to the broader discourse on sustainable, safe, and locally manufacturable mobility solutions.

II. Material and Methods

A. Frame Design and Material Selection

The frame was modeled in Autodesk Inventor. Laminated *Gombong* bamboo formed the main beams, while aluminum was used for joints and connectors. The bamboo–aluminum joints were designed using a hybrid bonded-bolted strategy to ensure structural reliability. Aluminum connectors were fabricated from 6061-T6 alloy and joined to bamboo beams using M8 grade 8.8 hex bolts torqued to 20 Nm. Polyurethane adhesive (XYZ Bond) was applied at a controlled bond line thickness of 0.5 mm, maintained using calibrated spacers. Prior to bonding, aluminum surfaces were sandblasted and degreased with acetone, while bamboo ends were lightly roughened and dried to 9% moisture content to enhance adhesion. The combination of mechanical fastening and adhesive bonding was selected to improve load transfer and mitigate the risk of joint slippage. This hybrid approach leverages the unique properties of each material. Aluminum was selected for its corrosion resistance, mechanical robustness, and capacity to provide firm joint integrity. Meanwhile, Gombong bamboo was employed due to its long fiber architecture, wide availability in Indonesia, and favorable environmental footprint.

Gombong bamboo possesses a high strength-to-weight ratio and is characterized by its dense vascular bundle distribution, which contributes to tensile and compressive resilience [8]. Its rapid regrowth rate and low energy requirements for processing render it a compelling candidate for replacing traditional metals in structural applications [10]. These material attributes are essential in reducing the total weight of the vehicle and improving its energy efficiency while simultaneously aligning the product with circular economy principles [9].

B. Bamboo Laminating Process

To ensure mechanical stability and consistent performance, the Gombong bamboo used in this study underwent a carefully controlled lamination process. Culms were first cut into strips measuring 20 mm in width, 5 mm in thickness, and 500 mm in length. These strips were dried to a moisture content of 9.3 ± 0.4%, measured per batch using the oven-dry method (ASTM D4442) [20], ensuring greater precision compared to the previously reported general range of 8–12%. Prior to lamination, the strips were soaked in a borax–boric acid solution to enhance resistance against biological degradation.

Each laminated beam was fabricated with six plies arranged in a parallel-fiber layup, with fibers oriented longitudinally along the beam axis to maximize tensile and compressive capacity. A commercial polyurethane-based structural adhesive (XYZ Bond, isocyanate prepolymer chemistry) was applied uniformly at a spread rate of 250 g/m² using a roller coater. The layup was pressed under 1.2 MPa for 8 hours at 25°C, followed by a 48-hour room-temperature curing period. No elevated temperature was applied during

curing, allowing for adhesive performance consistent with ambient processing conditions.

After curing, beams were sanded to achieve final dimensional tolerances of ±0.2 mm in thickness and ±0.5 mm in width, ensuring uniformity across specimens. These steps collectively produced laminated bamboo beams with reproducible properties, providing a reliable foundation for subsequent machining and mechanical testing.

A chemical treatment phase followed the drying process, where the bamboo strips were soaked in a borax-boric acid solution. This treatment enhances the material's resistance to biological degradation and pest infestation while preserving its mechanical characteristics [11]. Once treated, the strips were coated with polyurethane glue, selected for its durability, elasticity, and compatibility with lignocellulosic substrates. They were then layered orthogonally and pressed under heat and pressure to form laminated bamboo lumber (LBL). This lamination enhances strength properties by reducing natural variability and introducing structural anisotropy favourable for load-bearing functions [12]. The final outcome of laminated Gombong bamboo beams after pressing and curing process, ready for structural integration can be seen in Fig. 1.



Fig. 1. The final product of laminated Gombong bamboo beam.

C. Mechanical Testing

Mechanical testing was conducted in accordance with ASTM D3500-20 [21] (Standard Test Methods for Tensile Properties of Fiber Resin Composites) and ASTM D3501-05a [22] (Standard Test Method for Compressive Properties of Structural Panels in Flatwise Plane), with modifications to accommodate laminated bamboo specimens. Tensile coupons measured 5.3 mm^2 in cross-section and 200 mm in length, with fibers oriented along the loading axis. Each coupon consisted of six plies of laminated Gombong bamboo bonded using polyurethane adhesive. For compression testing, coupons measured 8.3 mm in diameter and 50 mm in length, and anti-buckling guides were employed to minimize instability during loading.

Prior to testing, all specimens were conditioned at 25 ± 2°C and 55% relative humidity for 48 hours to ensure consistent moisture equilibrium. Tests were carried out on a universal testing machine (UTM) at a crosshead speed of 2 mm/min for tension and 1.3 mm/min for compression. Strain during tensile testing was recorded using an extensometer with a 25 mm gauge length, while platen displacement was used for compression tests. A minimum of five replicates were performed for each condition to ensure statistical reliability of the results.

The sample preparation, shown in Fig. 2, ensured consistent sizing and moisture conditioning. During the tensile test (Fig. 3), specimens were subjected to axial stretching until failure, providing data on tensile strength and elongation.

The tensile strength test measured the maximum axial force that the bamboo samples could withstand before fracture. Elongation at break was also recorded to evaluate ductility. Compression testing involved subjecting the samples to axial loads until structural failure occurred, providing data on compressive resistance and deformation characteristics. These results serve as critical validation for the frame's structural integrity under real-world operational conditions.



Fig. 2. The sample test of laminated Gombong bamboo beam.



Fig. 3. Tensile testing process using a Universal Testing Machine.

D. Battery Design and Assembly

The electric power system for the hybrid scooter utilized 18650 lithium-ion cells configured into a 72V battery pack with a 20-series (20s) arrangement. Each cell was chosen based on its capacity, thermal stability, and discharge characteristics, ensuring consistent performance under

 EISSN: 2961-872X ● PISSN: 2961-8924 ● DOI: 10.56741/ IISTR.esl.001314

dynamic loading. The battery pack was equipped with a Battery Management System (BMS) that regulates voltage, monitors temperature, and prevents overcharging or deep discharge conditions, aligning with the safety strategies proposed by Saputra [14].

The battery pack was assembled in a 20s5p configuration using 100 cylindrical 18650 lithium-ion cells (model: NCR18650PF, Panasonic). Each cell has a nominal capacity of 2,500 mAh (minimum 2,450 mAh), a nominal voltage of 3.6 V, a maximum continuous discharge current of 10 A, and an average internal resistance of 35 mΩ. According to manufacturer specifications, the maximum operating temperature under continuous discharge is 60°C.

At the pack level, this configuration provides a nominal capacity of 12.5 Ah and approximately 900 Wh of usable energy at a nominal voltage of 72 V. The maximum pack voltage reaches 84 V (20 × 4.2 V), while the minimum cutoff voltage is 60 V (20 × 3.0 V). A battery management system (BMS) was incorporated to balance cell voltages, monitor temperature, and enforce safety cutoffs.

For structural integration, the pack was housed in a fiberglass-reinforced plastic (FRP) enclosure with 2 mm wall thickness. It was centrally mounted beneath the deck using four M6 bolts and rubber grommet isolators to reduce vibration transmission. The enclosure was designed to achieve an IP54 protection level, offering resistance against dust ingress and splashing water. Its central placement within the scooter's frame beam not only provided shielding from curb strikes but also lowered the center of gravity, thereby improving overall stability during operation.

E. Limitation of the Study

While the methodology presented in this study provides essential data on tensile and compressive performance of laminated bamboo, it is important to acknowledge certain limitations. Fatigue testing, vibration analysis, environmental exposure (moisture, UV radiation, temperature cycling), and full-frame durability assessments were not performed within the scope of this work. These evaluations are crucial for understanding long-term serviceability and reliability of bamboo–aluminum hybrid frames in real-world conditions. Accordingly, they are identified as key priorities for future research.

III. Results and DiscussionS

A. Frame Prototype and Manufacturing Outcome

The hybrid scooter frame developed in this study was successfully constructed using laminated Gombong bamboo as the primary load-bearing element and aluminum for the mechanical joints. This hybrid approach yielded an efficient structural solution by combining the lightweight, high-strength characteristics of bamboo with the durability and formability of aluminum connectors. During the assembly phase, precise alignment of bamboo beams with aluminum lugs was achieved, ensuring rigidity across the load-bearing axes. The use of bamboo substantially reduced the overall mass of the vehicle, enhancing its energy efficiency during operation. These findings are consistent with prior claims that bamboo composites offer a high strength-to-weight ratio [8, 23].

In the fabrication process, attention was given to grain alignment, adhesive curing, and lamination consistency to minimize warping and residual stresses. The final prototype was structurally stable, visually consistent, and resilient under manual handling and preliminary mobility trials.

Fig. 4 presents the CAD-rendered design of the electric scooter frame created using Autodesk Inventor, emphasizing the integration of laminated bamboo beams as the primary structural components, seamlessly connected through precision-engineered aluminum joints. Complementing this visual, Table 1 provides a detailed parts list of the frame assembly, outlining the quantity and classification of each structural and fastening element used in the construction. In contrast, Fig. 5 presents the fabricated physical prototype of the frame, translating the digital model into a tangible structure with real-world materials.

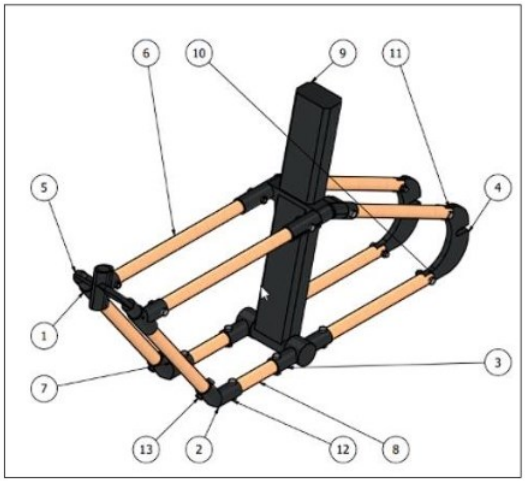


Fig. 4. The CAD-rendered design of the electric scooter frame.

TABLE I. THE DETAILED PARTS LIST OF THE FRAME

Item	Quantity	ID Part	Part Name
1	2	FUB	Front Upper Beam
2	2	FLJ	Front Lower Joint
3	2	MFJ	Middle Frame Joint
4	2	SAJ	Swing Arm Joint
5	1	FUJ	Front Upper Joint
6	2	MUB	Middle Upper Beam
7	2	FB	Front Beam
8	2	LMB	Lower Middle Beam
9	1	MF	Middle Frame
10	2	LSAB	Lower Swing Arm Beam
11	2	USAB	Upper Swing Arm Beam
12	18	Nt	Nut
13	18	Bt	Bolt



Fig. 5. The fabricated physical prototype of the frame.

A comparison between the CAD model (Fig. 4) and the fabricated prototype (Fig. 5) reveals a material substitution in the front down tube, where aluminum was used in place of

bamboo. This adjustment was introduced to improve assembly precision and enhance joint stability during prototyping. Importantly, the substitution did not affect the evaluation of laminated bamboo's mechanical properties, since tensile and compressive tests were conducted on standardized bamboo coupons. As such, the validity of the experimental results remains intact, and the modification is acknowledged as a practical adjustment rather than a limitation of the material.

Although complete photographic documentation of all test setups and failure modes was not feasible within this prototype study, essential experimental details are provided here. Tensile tests employed wedge grips with a 50 mm gauge length for proper alignment, while compressive tests utilized flat platens with anti-buckling guides. Typical failure modes included fiber pull-out and adhesive fracture under tension, and localized buckling under compression. For joints, failure generally initiated at the adhesive interface under shear loading. Additional visual documentation of test setups and failure modes is planned for future experimental campaigns to further strengthen the empirical record.

Table 2 summarizes the material weights and mass fraction of each component to the frame's overall mass efficiency. The reported values represent the ratio of each component's mass to the total frame mass of 4.8 kg. This provides a quantitative overview of material distribution within the hybrid bamboo–aluminum frame. It should be noted that structural contribution in terms of stiffness or load-path participation requires finite element modeling or experimental modal analysis, which are identified as priorities for future work.

TABLE II. THE FRAME MASS FRACTION

Component	Material	Weight (kg)	Mass fraction (%)
Main Beam	**Laminated Bamboo**	**3.1**	**65%**
Joint Connectors	**Aluminum**	**1.7**	**35%**
	Total	**4.8**	**100%**

B. Mechanical Test Results

Mechanical testing was conducted to evaluate the strength and Mechanical testing was conducted to evaluate the strength and deformation properties of the laminated bamboo material used in the frame. Tensile tests recorded an average peak load of 15.33 kN with an elongation of 9.5 cm at failure, indicating moderate ductility suitable for dynamic loads in transportation applications. The ultimate tensile strength (σ_u) was calculated using

$$\sigma = \frac{F_{max}}{A} \quad (1)$$

where F_{max} is the maximum load and A is the cross-sectional area. With F_{max}=15.33 kN and an effective area of 53 mm², the average tensile strength was 289 MPa. Specimens measured 200 mm in length and 8.2 mm in diameter, with a 50 mm gauge length. This value is comparable to the yield strength of A36 structural steel (250 MPa) and within the lower range of its tensile strength (400–550 MPa) [24].

Compression testing yielded an average maximum load of 8.0 kN. Normalizing by the same cross-sectional area (53 mm²) produced a compressive stress of 151 MPa. Specimens had a circular cross-section of 8.21 mm in diameter and 50 mm in length, giving a radius of gyration of 2.05 mm and a slenderness ratio of 24.4. An Euler buckling analysis, assuming an elastic modulus of 12.5 GPa and pinned–pinned boundary conditions, gave a critical stress of 208 MPa that higher than the measured compressive stress. This indicates that failure was governed primarily by material crushing rather than column buckling. The use of anti-buckling guides and precise fixture alignment further minimized instability effects, confirming that the reported compressive strength reflects intrinsic material behaviour.

Beyond strength, stiffness was also evaluated from the linear regions of the stress–strain curves. The tensile modulus averaged 12.5 GPa, while the compressive modulus was 9.8 GPa. Although lower than that of aluminum alloys (79 GPa) [25], these values demonstrate sufficient stiffness for lightweight frame applications. Structurally, the moderate modulus suggests that bamboo–aluminum hybrid frames may undergo slightly greater elastic deflections than all-metal counterparts. However, this property can improve ride comfort by providing inherent vibration damping, while maintaining adequate rigidity for safe handling. This trade-off between stiffness and comfort underscores the potential of laminated bamboo in sustainable urban mobility applications.

These results validate earlier claims in the literature regarding the superior mechanical properties of laminated bamboo when processed with controlled lamination and adhesive bonding techniques [11, 12]. The compressive strength values also align with previously documented benchmarks, supporting its feasibility in load-bearing structural components. These outcomes reinforce the bamboo material's mechanical adequacy for scooter frame applications, particularly when environmental and weight efficiency considerations are taken into account. Table 3 presents the key mechanical test results obtained during laboratory evaluation.

TABLE III. SUMMARY OF MECHANICAL PROPERTIES FOR LAMINATED BAMBOO SAMPLES

Parameter	Value	Unit
Average Tensile Load	15.33	kN
Tensile modulus	12.5	GPa
Elongation at Break	9.5	cm
Calculated Tensile Strength	289	MPa
Average Compressive Load	8.00	kN
Compressive modulus	9.8	GPa
Calculated Compressive Strength	151	MPa

Table 4 provides a comparison between laminated bamboo and common frame materials such as aluminum, A36 structural steel and others to further illustrate the mechanical potential of bamboo.

TABLE IV. COMPARATIVE DATA ON TENSILE STRENGTH AND DENSITY OF LAMINATED BAMBOO VERSUS CONVENTIONAL STRUCTURAL MATERIALS

Material	Tensile Strength (MPa)	Density (g/cm³)	Specific Strength (MPa·cm³/g)	Source
Laminated Bamboo	289	0.65	445 ± 2	Present work
Aluminum 6061-T6	330	2.70	122 ± 5	[26]
A36 Structural Steel	400 - 550	7.85	60 ± 10	[24]
Teak Wood	71.15	0.65	109 ± 5	[27]

To ensure consistency, all specific strength values were recalculated using ultimate tensile strength (UTS) and density

 EISSN: 2961-872X ● PISSN: 2961-8924 ● DOI: 10.56741/ IISTR.esl.001314

data from uniform sources. Laminated bamboo exhibited a specific strength of 445 ± 2 MPa·cm³/g, compared to 122 ± 5 MPa·cm³/g for aluminum 6061-T6 and 60 ± 10 MPa·cm³/g for A36 steel. By applying a single definition and standardized references, the comparison underscores the superior mass-normalized performance of laminated bamboo. Nonetheless, these values represent intrinsic material properties and do not account for system-level considerations such as joint efficiency, fatigue resistance, or long-term durability.

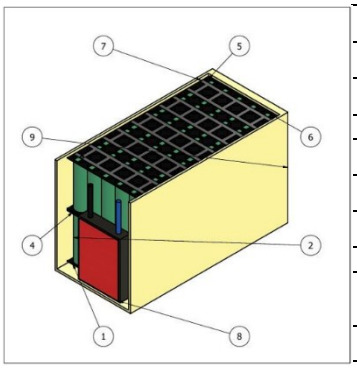
It is important to note that this study was limited to static tensile and compressive testing. Critical parameters such as fatigue resistance, torsional stiffness, vibration response, and bending performance were not evaluated. These characteristics are essential for predicting service life, rider safety, and structural reliability, and they will form a key focus of future research.

While the tensile and compressive results confirm the structural viability of laminated bamboo at the coupon level, full-frame validation has not yet been conducted. Aspects including torsional rigidity, bending stiffness, dynamic loading under road conditions, and fatigue life estimation remain untested. Additionally, the small sample size and absence of detailed statistical treatment restrict the generalizability of the findings, while the lack of benchmarking against commercial scooter frames limits system-level conclusions. For these reasons, the present results should be regarded as preliminary evidence.

Mechanical properties are summarized in Tables 3 and 4, covering tensile and compressive strength, elastic modulus, and statistical variation. However, representative stress–strain curves are not provided, as continuous curve data were not recorded in a retrievable format during this initial prototype testing. Future experiments will incorporate complete curve acquisition to enable a more comprehensive analysis of deformation behaviour and failure mechanisms.

C. *Battery Performance*

The custom-designed battery pack, composed of 18650 lithium-ion cells configured in a 20-series arrangement to deliver 72V, demonstrated reliable energy output and performance stability during operational trials. Fig. 6 shows the initial CAD concept for the scooter battery pack. The sequential assembly steps included structured placement of cells into holders (Fig. 7(a)), spot-welding of nickel strips (Fig. 7(b)), BMS integration (Fig. 7(c)), socket connector application (Fig. 7(d)) and the fully completed 72V battery pack is shown in Fig. 7(e).



ITEM	QTY	PART NUMBER
1	2	Battery Holder
2	50	Battery 18650
3	2	Nickel Strip
4	1	Fiberglass Spacer
5	2	Battery Holder
6	50	Battery 18650
7	2	Nickel Strip
8	1	Battery Management System
9	1	Fiberglass Box

Fig. 6. The initial CAD concept for the scooter battery pack

Range testing was conducted with a 70 kg rider on flat asphalt terrain at an ambient temperature of 28 ± 2°C. The scooter was operated at an average speed of 20 km/h using CST 10-inch pneumatic tires inflated to 50 psi. Based on motor and controller specifications, drivetrain efficiency was estimated at 85%. Under these conditions, the scooter achieved a range of 30 km. With a usable pack energy of 900 Wh (20s5p configuration, cutoff 60 V), the corresponding energy consumption was calculated at 30 Wh/km. These results assume a state-of-health (SOH) of > 95%, consistent with new cells. Charging was performed with a 72 V, 3 A CC–CV charger, requiring 5 hours from empty to full capacity. The integrated BMS limited discharge current to 20 A and enforced voltage cutoffs at 4.2 V and 3.0 V per cell.

D. *Environmental and Technical Impact*

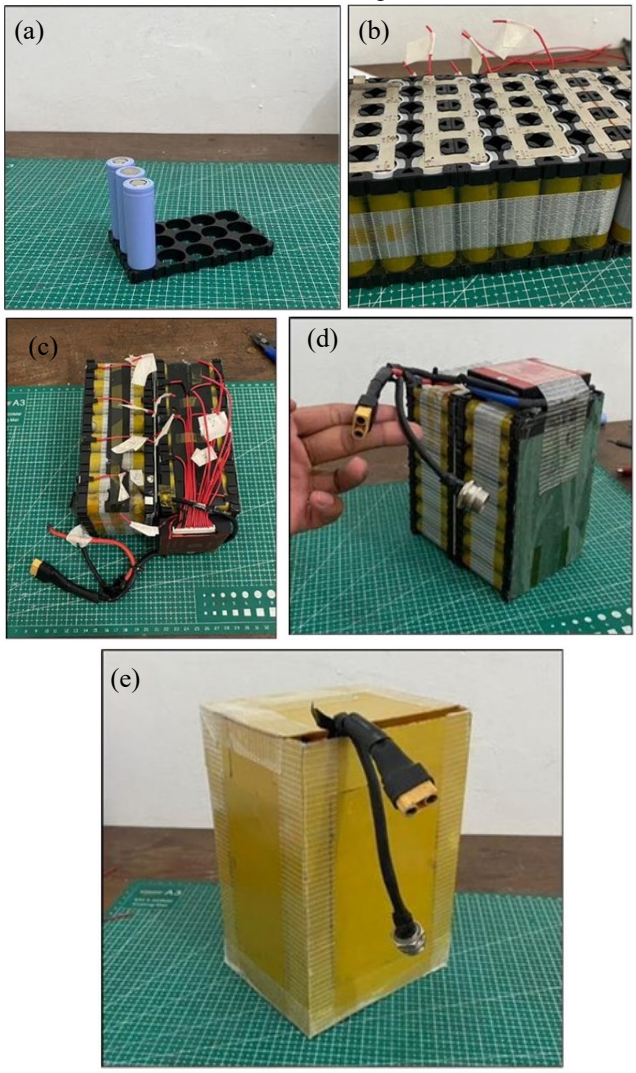


Fig. 7. The processes of fabricated the scooter battery pack

Battery safety evaluation involved continuous discharge testing at 15 A to simulate high-demand riding. Thermal sensors integrated with the BMS logged data at 1-minute intervals via the Jikong application. The maximum recorded cell surface temperature was < 42°C under ambient conditions of 28 ± 2°C with free airflow. These results demonstrate effective thermal management within the operational envelope.

The battery pack was housed in a fiberglass-reinforced plastic (FRP) enclosure with 2 mm wall thickness, mounted with venting slots to support passive cooling and prevent

pressure buildup. Cells were spaced 2 mm apart to enhance airflow and reduce thermal coupling, while foam padding provided additional vibration and impact resistance. Although formal crashworthiness testing was not performed, the enclosure design offers protection against common impacts such as tip-overs or curb strikes. Full compliance with standardized impact and vibration protocols (e.g., UN 38.3, IEC 62133) will be necessary in future studies to validate crash safety.

While these evaluations confirm satisfactory performance during moderate stress tests, destructive testing scenarios such as blocked airflow, extended hill-climb cycling, short-circuit events, overcharge abuse, and nail penetration were not conducted. These remain critical for certification under UN 38.3 and IEC 62133 and are identified as priorities for future work.

Overall, the integrated BMS functioned as intended, maintaining voltage balance across cells, enforcing protective cutoffs, and mitigating thermal fluctuations during both charge and discharge cycles. Peak temperatures never exceeded 42 °C, consistent with safe lithium-ion operation and in line with best practices reported in Saputra [14].

E. Material Feasibility

Mechanical testing and manufacturing observations confirm that laminated bamboo is a feasible material for structural applications under controlled environmental and engineering conditions. Its tensile strength approaches that of mild steel while being significantly lighter, an important factor in vehicle design where mass directly affects performance and energy consumption. In addition, bamboo is a rapidly renewable and locally available resource, offering environmental and economic advantages over metals. Prior research has emphasized bamboo's potential as a structural framework material, and the present findings validate these claims in a novel application context [16, 23]. Although natural fiber variability exists, lamination and chemical treatment mitigate inconsistencies, enabling reproducible and reliable structural components.

Long-term durability remains a key consideration, as laminated bamboo bonded with polyurethane adhesives can degrade under prolonged humidity, thermal cycling, or UV exposure. In this study, borax–boric acid treatment improved resistance to fungi and insects, and a polyurethane coating helped reduce moisture ingress. Nevertheless, vulnerability to environmental stresses persists. Future research will therefore employ accelerated aging protocols following ASTM D1037 and ISO 22157, incorporating cyclic wet–dry conditioning, UV exposure, and post-conditioning strength measurements. Additional protective strategies, such as multilayer coatings with UV stabilizers, will also be investigated.

Fire safety is particularly critical when bamboo frames are paired with lithium-ion batteries. The current prototype incorporated boron-based flame retardants in the bamboo and housed the battery in a fiberglass-reinforced casing with an integrated BMS to limit overcharging and overheating. While these measures mitigate ignition risks, standardized flame spread and ignition resistance tests (e.g., UL 94, ISO 5660, IEC 62133) remain necessary for formal validation.

Repairability further supports the sustainability of bamboo frames. Unlike metal frames, which can be welded, bamboo structures can be repaired locally using bonded patch reinforcements or adhesive-based sleeve joints. In cases of severe damage, modular replacement of individual beams is possible without discarding the entire frame. These approaches extend product lifespan, reduce waste, and align with circular economy principles.

Scaling up production introduces additional challenges. Bamboo exhibits variability in density, fiber orientation, and moisture content depending on growth and harvesting conditions. Achieving consistent quality will require strict selection criteria, moisture conditioning, and careful pre-processing. The lamination process—including adhesive application, pressing, temperature, and curing—must also be tightly controlled. Industrial-scale production will therefore depend on standardized grading, bonding, and quality assurance protocols, supported by non-destructive evaluation methods to detect defects such as voids, delamination, or incomplete bonding. Without such measures, structural performance may vary significantly, limiting market viability.

Joint performance remains another critical knowledge gap. While this study demonstrated feasibility at the coupon scale, direct testing of joint shear strength, peel resistance, and fatigue behavior was not performed. These factors govern long-term durability in bamboo–aluminum hybrid frames. Future work will quantify joint behavior under cyclic loading, evaluate adhesive durability, and use finite element analysis (FEA) to model stress concentrations and predict failure modes.

From an environmental perspective, laminated bamboo offers significant advantages over metals. Whereas aluminum and steel require energy-intensive smelting and forging processes that generate high CO_2 emissions [1], bamboo contributes to carbon sequestration during growth and requires substantially less processing energy [2, 9]. In this study, the bamboo-based frame weighed 4.8 kg, compared to 8.4 kg for typical aluminum scooter frames [28], suggesting potential energy efficiency benefits. Although this has not been confirmed through coast-down or ride trials, a preliminary embodied energy assessment shows promising results. With system boundaries limited to raw material extraction and processing, sensitivity analysis indicated that a service life of three years preserves bamboo's embodied energy advantage, while extending to five years reduces annualized environmental burden by nearly 40% compared to aluminum. A more comprehensive cradle-to-grave life cycle assessment (LCA) will be conducted in future work.

Economically, bamboo presents logical advantages despite the absence of a formal cost analysis in this study. Unlike metals requiring centralized, high-energy industrial infrastructure, bamboo can be processed with lower energy inputs and manufactured through decentralized, workshop-scale operations. Its renewability, local availability, and compatibility with low-carbon manufacturing suggest potential cost competitiveness, particularly in regions with abundant bamboo supply. Future studies will include detailed economic modeling and comparative benchmarking.

Despite these advantages, the present study should be regarded as preliminary. Structural validation is limited to coupon-level tensile and compressive tests, without data on stiffness, fatigue, impact resistance, or full-frame dynamic performance under road conditions. Consequently, structural viability claims must be interpreted cautiously until further system-level evaluations are performed.

Overall, this work demonstrates the feasibility of a laminated bamboo–aluminum hybrid scooter frame and

 EISSN: 2961-872X ● PISSN: 2961-8924 ● DOI: 10.56741/ IISTR.esl.001314

highlights its potential for sustainable urban mobility. The integration of renewable structural materials with a safety-engineered battery system offers a credible pathway toward reducing the environmental burden of e-scooters. At the same time, future research must focus on full-frame testing, battery safety compliance, durability evaluations, and lifecycle analyses to establish bamboo's role as a reliable and scalable alternative to metals. By bridging mechanical performance, environmental responsibility, and repairability, laminated bamboo frames present a replicable solution aligned with the principles of green engineering and circular economy, paving the way for next-generation transport systems.

F. Risk and Reliability Considerations

As with any natural–synthetic hybrid structure, the bamboo–aluminum frame presents specific risks that must be addressed to ensure long-term reliability. Splitting of bamboo along the grain and delamination between plies represent primary material risks, particularly under cyclic loading and moisture cycling. Adhesive creep may also occur over extended service periods, potentially altering joint stiffness. On the mechanical side, bolted aluminum joints are prone to fastener loosening if not properly torqued and periodically checked.

To mitigate these risks, a preventive maintenance strategy is proposed for end users. Routine visual inspections should be carried out every 500 km of use, focusing on signs of surface cracking, delamination, and fastener loosening. Retorquing of bolts is recommended at the same interval. In cases of minor cracking, localized repair using bonded sleeve reinforcements can extend service life, while severe failures may require replacement of individual bamboo beams due to the modular frame architecture. This inspection and repairability guidelines provide a practical framework for safe use, while ongoing research will refine quantitative reliability models and accelerated aging tests.

G. Manufacturability and Quality Control

Scaling laminated bamboo frames from prototype to production requires defined quality control protocols. Based on trial production, dimensional tolerances of ±0.5 mm in thickness and ±1.0 mm in width were achievable for laminated strips after pressing. Allowable defects include superficial surface roughness and minor adhesive bleed, while delamination exceeding 10 mm in length or voids greater than 2 mm in thickness are considered unacceptable. Acceptance criteria for production parts emphasize consistent laminate bonding, uniform adhesive distribution, and moisture content between 8–12% at the time of testing. These measures provide a foundation for establishing standardized production workflows for laminated bamboo mobility frames.

IV. Conclusion

This study demonstrates the feasibility of a hybrid electric scooter frame constructed from laminated Gombong bamboo combined with aluminum joints. The prototype achieved notable weight reduction while maintaining structural stability, as validated by mechanical testing that recorded an average tensile strength of 289 MPa and a compressive strength of 8.0 kN. Laminated bamboo beams contributed approximately 65% of the total frame mass, resulting in a lightweight structure of 4.8 kg. The specific strength of laminated bamboo, calculated at 445 MPa·cm³/g, substantially exceeded that of conventional frame materials such as A36 steel (60 MPa·cm³/g) and aluminum 6061-T6 (122 MPa·cm³/g), underscoring its potential as a sustainable structural alternative.

In parallel, a custom-designed 72 V lithium-ion battery pack, configured with 18650 cells in a 20s5p arrangement, provided an effective range of 30 km per charge with a recharge time of approximately five hours. The integration of a Battery Management System (BMS) ensured balanced cell voltages, operational reliability, and protective cutoffs, further demonstrating the compatibility of renewable structural materials with lightweight energy storage systems.

These findings highlight the promise of combining laminated bamboo with advanced energy systems in personal mobility applications. The results contribute to addressing the environmental shortcomings of conventional e-scooters while advancing the broader discourse on green mobility. By extending knowledge on bamboo composites, hybrid joint design, and sustainable energy integration, this work offers a pathway toward environmentally responsible transport solutions.

At the same time, the current evidence remains preliminary. The study is limited to coupon-level tensile and compressive tests and a qualitative prototype demonstration. Critical aspects—including torsional and bending stiffness, fatigue performance, vibration behaviour, and impact resistance at the full-frame level—have not yet been evaluated. In addition, the absence of statistical treatment, rigorous benchmarking against commercial aluminum and steel frames, and comprehensive environmental assessment restricts the generalizability of the conclusions.

Future research will address these gaps through full-frame mechanical validation under static, fatigue, and dynamic loading; finite element simulations of stress distribution and failure modes; and systematic durability testing under road conditions. Battery safety will also undergo rigorous evaluation, including compliance with standards such as UN 38.3 and IEC 62133. Furthermore, the literature base will be expanded and corrected to situate this work within broader research on bamboo composites, hybrid structures, and electro-mobility systems. Finally, a quantitative life cycle assessment (LCA) comparing laminated bamboo to conventional materials will be undertaken to more precisely quantify sustainability impacts.

This study provides an initial prototype-level demonstration of laminated bamboo as a viable material for sustainable transport applications. While further validation is essential, the present findings establish a foundation for advancing laminated bamboo from material-scale feasibility toward reliable, safe, and scalable applications in urban mobility.

Acknowledgment

This paper was made possible through the support of the Initiative Project titled *"Peningkatan Publikasi Mahasiswa Teknik Industri dengan Program Konversi Skripsi to Paper"* with project code 2025 - PP0030031. The authors gratefully acknowledge the funding and facilitation provided by this initiative, which has significantly contributed to the successful completion and publication of this work.

AUTHOR CONTRIBUTIONS

Safarudin Gazali Herawan: Writing – concepts – original draft & review. Ismail Azizi Martalogawa, Azqy Nur Farenzy Saputra, Ahmad Hanif: Data collection - writing. Ihwan Ghazali: Review – writing.

DATA AVAILABILITY

The data that support the findings of this study are openly available in zenodo at https://zenodo.org/records/16730592.

DECLARATION OF GENERATIVE AI IN SCIENTIFIC WRITING

During the preparation of this work, the authors used ChatGPT to enhance the clarity of the writing. After using the ChatGPT, the authors reviewed and edited the content as needed and take full responsibility for the publication's content.

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 EISSN: 2961-872X ● PISSN: 2961-8924 ● DOI: 10.56741/ IISTR.esl.001314