Kuwait Journal of Education
ISSN: 2984-7656
Vol 4 Issue 1 (2026)

Hybrid Sugarcane Bagasse–CNSL Bio-Composites: A Review on Developments, Optimization, and Automotive Applications

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Submitted: 01/12/2025 **Revised:** 20/12/2025 **Published:** 30/12/2025

Abstract –

Growing interest in lightweight, economical, and eco-friendly materials has pushed researchers toward natural-fiber-based bio-composites for automotive applications. This review examines recent progress in hybrid sugarcane bagasse composites made with CNSL (Cashew Nut Shell Liquid) resin and discusses how these materials can be refined to serve as practical alternatives to traditional synthetic composites. The main highlights of the sugarcane bagasse which is an agricultural waste product of sugar industry is the good strength to weight ratio, biodegradability, and low density. Hybridization with complementary fibers—either natural or synthetic—has emerged as an effective strategy to improve strength, stiffness, impact resistance, and thermal stability. Parallelly, the incorporation of hardeners into CNSL resin enhances crosslinking, curing behavior, and load transfer efficiency, contributing to more reliable composite structures.

This review synthesizes studies on fiber treatments, hybrid fiber combinations, CNSL–hardener formulations, fabrication processes, and the influence of processing parameters on the resulting composite properties. Studies on mechanical, thermal, and microstructural behavior show that well-designed hybrid bagasse–CNSL composites offer better performance and can be used in several semi-structural and interior automotive parts such as dashboards, door panels, trims, and impact-absorbing sections. However, some issues still need attention, particularly moisture uptake, inconsistency in natural fiber quality, variations in resin behavior, and the lack of uniform testing standards.

Keywords - Bio-resin, Sugarcane bagasse, CNSL, Natural fibers, Composite materials, Automotive applications

I. Introduction

The automotive industry is steadily moving toward material systems that support sustainability, reduced environmental impact, and efficient resource utilization. This transition is driven by increasingly strict emission regulations, the demand for improved vehicle fuel efficiency, and the need to lower the environmental burden associated with manufacturing and end-of-life disposal [1], [10]. While conventional materials such as glass fiber–reinforced polymers and petroleum-based plastics continue to offer high strength and durability, their production and disposal are energy-intensive and raise serious environmental concerns [2]. These limitations have accelerated research into alternative materials that combine lightweight characteristics with ecological compatibility. Natural fiber–reinforced bio-composites have emerged as promising candidates in this context due to their renewable origin, low density, biodegradability, and reduced carbon footprint [4], [15]. Plant-based fibers such as flax, jute, hemp, kenaf, bamboo, and banana have been widely investigated as reinforcements in polymer matrices for automotive components [10], [14]. Among these, sugarcane bagasse has attracted growing attention because it is generated in large quantities as a by-product of sugar and ethanol production, particularly in agrarian economies [9].

Utilizing bagasse fibers in composite materials not only adds value to agricultural waste but also aligns with circular-economy and waste-valorization principles [6]. Despite its advantages, sugarcane bagasse presents several inherent challenges when used directly as a reinforcement material. The presence of lignin, hemicellulose, waxes, and other surface impurities reduces compatibility with polymer matrices, resulting in weak interfacial bonding and inconsistent mechanical performance [3], [12]. Additionally, the hydrophilic nature of bagasse fibers leads to moisture absorption, dimensional instability, and degradation under humid service conditions [8]. To address these issues, various fiber surface modification techniques have been developed to improve fiber–matrix adhesion and enhance long-term performance [12]. In parallel with fiber development, there is a growing emphasis on replacing petroleum-based matrices with bio-derived resin systems. Cashew nut shell liquid (CNSL), a renewable by-product of the cashew processing industry, has emerged as a viable alternative for epoxy resin synthesis [6], [11]. CNSL-based epoxies possess a phenolic molecular structure that enables good thermal stability, chemical resistance, and tunable mechanical properties. When combined with suitable hardeners, these resins can achieve curing behavior and performance characteristics comparable to conventional epoxies, while significantly reducing reliance on fossil resources [5]. Recent studies have shown that hybridization strategies—where sugarcane bagasse is combined with other natural or synthetic fibers—can effectively overcome performance limitations associated with single-fiber composites [13], [15].

Hybrid reinforcement allows improved stress distribution, enhanced impact resistance, and tailored thermal and mechanical properties, making such composites suitable for a range of automotive interior and semi-structural applications [1], [8]. Components such as dashboards, door panels, trims, acoustic panels, and impact-absorbing elements have been identified as promising targets for hybrid bagasse-based materials [10]. Although notable progress has been reported, several gaps remain in the existing literature. These include variability in reported material properties, limited long-term durability data, inconsistent testing methodologies, and fragmented understanding of processing–structure–property relationships [7], [9]. Moreover, the combined influence of fiber treatment, hybrid reinforcement design, CNSL–hardener formulation, and fabrication parameters has not been systematically reviewed. - change this to your preference In this context, the present review consolidates and critically evaluates recent developments in hybrid sugarcane bagasse–CNSL bio-composites for automotive applications. The review focuses on reinforcement strategies, fiber surface treatments, CNSL-based resin systems, processing techniques, and emerging optimization approaches, including machine learning [7]. By identifying key trends, challenges, and future research directions, this work aims to support the development and industrial adoption of sustainable composite materials for next-generation automotive systems.

II. SUGARCANE BAGASSE–BASED HYBRID REINFORCEMENTS

A. Sugarcane Bagasse as a Lignocellulosic Reinforcement

Sugarcane bagasse is a widely available agro-industrial residue obtained after the extraction of juice during sugar and ethanol production [6], [9]. It consists mainly of cellulose, hemicellulose, and lignin, which together impart low density, moderate strength, and inherent biodegradability. These characteristics make bagasse fibers attractive as reinforcements in environmentally friendly polymer composites [3], [14]. The cellulose-rich structure contributes to stiffness and load-bearing capacity, while the naturally porous morphology of bagasse aids in vibration damping and sound absorption—features that are particularly relevant for automotive interior components [8], [10].

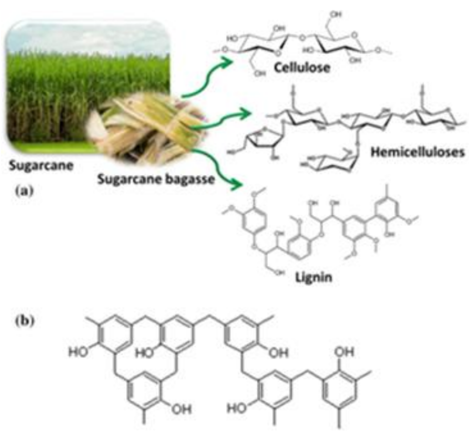

Fig 1. Structure of Sugarcane bagasse

However, bagasse fibers in their untreated form contain surface waxes, residual lignin, and other amorphous constituents that restrict effective bonding with polymer matrices [3], [12]. Moreover, their hydrophilic nature leads to moisture uptake, swelling, and deterioration of mechanical performance when exposed to humid environments [8]. These drawbacks highlight the need for suitable fiber modification and reinforcement approaches to ensure stable and reliable composite behavior [12].

B. Need for Hybrid Reinforcement Strategies

Composites reinforced solely with sugarcane bagasse fibers often do not satisfy the mechanical and thermal requirements of automotive components that experience repeated loading and temperature fluctuations [15]. To address these limitations, hybrid reinforcement has gained prominence as a practical solution [13]. By combining bagasse fibers with other natural or synthetic reinforcements, hybrid composites capitalize on the strengths of different fibers while compensating for individual shortcomings [15].

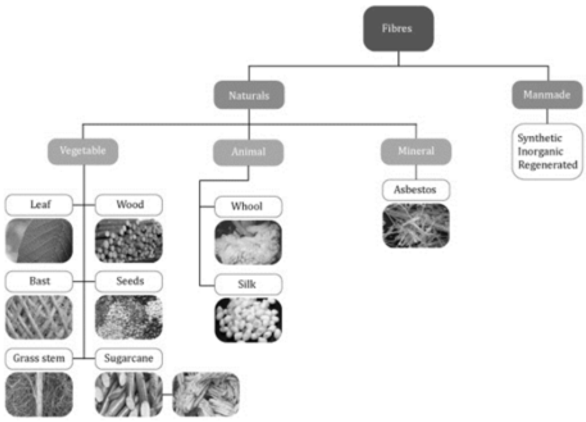

Fig 2. Types of natural fibers for hybrid reinforcement strategies

Hybrid systems generally exhibit improved load transfer, higher resistance to crack propagation, and more controlled failure behavior [13], [15]. Hybrids based entirely on natural fibers—such as bagasse combined with jute, flax, or bamboo—maintain a high level of sustainability while achieving enhanced mechanical performance [8], [14]. Alternatively, partial hybridization with synthetic fibers like glass or basalt significantly improves strength and impact resistance, enabling bagasse-based composites to be considered for semi-structural automotive applications [10], [15].

C. Effect of Hybrid Fiber Configuration and Composition

The effectiveness of hybrid bagasse composites is strongly dependent on fiber arrangement, stacking sequence, volume fraction, and orientation [13]. Research indicates that configurations with stronger fibers positioned on the outer layers and bagasse fibers placed in the core lead to improved flexural strength and impact resistance [15]. Appropriate fiber ratios promote efficient stress sharing and delay damage initiation, whereas poorly designed hybrid layouts may cause localized stress concentration and premature failure [14].

Short, randomly oriented fibers are commonly employed in automotive components with complex geometries due to ease of processing and manufacturing flexibility [10]. In contrast, woven or unidirectional hybrid laminates provide superior mechanical performance and are preferred for components subjected to higher loads [14]. Therefore, hybrid design must be carefully tailored to the intended application, processing route, and service requirements [13].

D. Interfacial Compatibility and Surface Treatment in Hybrid Systems

Interfacial bonding is a key factor governing the performance of hybrid fiber composites [12]. Differences in surface chemistry and stiffness between bagasse fibers and secondary reinforcements can lead to poor stress transfer and interfacial debonding if not properly managed [3]. Surface treatments such as alkali treatment, oxidative modification, silane coupling, and hydrophobic functionalization are commonly used to improve surface roughness, remove weak boundary layers, and introduce functional groups that enhance bonding with polymer matrices [12], [8].

In hybrid systems, improved interfacial compatibility ensures uniform stress distribution across different fiber types and reduces fiber pull-out during loading [3], [15]. This results in enhanced tensile, flexural, and impact properties, along with better resistance to wear and fatigue [7], [15]. Effective interfacial engineering is therefore essential for realizing the full performance potential of hybrid sugarcane bagasse composites [12].

E. Relevance of Hybrid Bagasse Reinforcements in Automotive Applications

Hybrid composites reinforced with sugarcane bagasse meet several key requirements of modern automotive materials, particularly for interior and semi-structural components [1], [10]. Their low density contributes directly to vehicle weight reduction, which in turn supports improved fuel efficiency and reduced emissions [1]. Hybridization also provides flexibility in tailoring mechanical and thermal properties to suit specific component functions, enabling applications in dashboards, door panels, trims, headliners, and impact-absorbing structures [8], [10].

Beyond technical performance, hybrid bagasse composites align strongly with sustainability and circular-economy goals by utilizing agricultural waste and reducing dependence on non-renewable resources [6], [9]. With appropriate hybrid design, surface treatment, and processing control, sugarcane bagasse–based reinforcements offer a realistic pathway toward lightweight, sustainable, and performance-oriented automotive composite materials [15].

III. CNSL-BASED EPOXY RESINS

Cashew nut shell liquid (CNSL) is a renewable by-product obtained during the processing of cashew nuts and has gained increasing attention as a sustainable precursor for polymer resin development [6], [11]. CNSL contains phenolic compounds such as cardanol, cardol, and anacardic acid, which provide reactive functional groups suitable for epoxy synthesis. Owing to this phenolic backbone, CNSL-based resins exhibit inherent thermal stability, chemical resistance, and good adhesion characteristics, making them attractive alternatives to petroleum-derived epoxies [11].

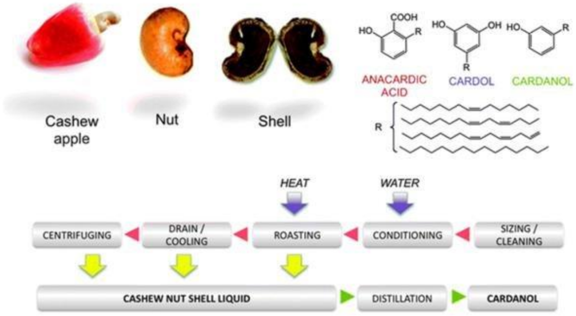

Fig 3. Structure of CNSL

Compared to conventional epoxy systems, CNSL-based resins offer the advantage of high bio-content while maintaining competitive mechanical performance [5]. Their molecular structure allows flexibility in tailoring resin properties through appropriate selection of curing agents and processing conditions. When cured with suitable hardeners, CNSL epoxies can achieve adequate cross-link density, resulting in improved stiffness, strength, and load-transfer efficiency within fiber-reinforced composites [6]. This tunability is particularly beneficial for natural fiber composites, where resin–fiber compatibility plays a critical role in overall performance.

Another important advantage of CNSL-based epoxies is their relatively low viscosity compared to some conventional bio-resins, which facilitates better wetting and impregnation of lignocellulosic fibers such as sugarcane bagasse [5]. Improved wetting reduces void content and enhances interfacial bonding, leading to composites with more consistent mechanical and thermal properties. Furthermore, CNSL resins demonstrate good resistance to thermal degradation and chemical attack, which is essential for automotive components exposed to fluctuating temperatures and service environments [11].

Despite these advantages, CNSL-based epoxy systems still face challenges related to variability in resin composition, curing behavior, and large-scale processing consistency [6]. Ongoing research therefore focuses on optimizing CNSL purification methods, resin formulation, and hardener selection to ensure reproducible performance and compatibility with industrial composite manufacturing processes. With continued development, CNSL-based epoxies are well positioned to serve as sustainable matrix materials for hybrid sugarcane bagasse composites in automotive and related engineering applications [5].

IV. FIBER TREATMENT AND INTERFACIAL OPTIMIZATION

The performance of natural fiber–reinforced composites is strongly influenced by the quality of the interface between the fiber and the surrounding polymer matrix. In the case of sugarcane bagasse, untreated fibers exhibit limited compatibility with polymer resins due to the presence of lignin, hemicellulose, waxes, and other surface impurities [3], [12]. These constituents hinder effective stress transfer and often lead to premature interfacial failure under mechanical or thermal loading. Consequently, fiber surface modification is considered a critical step in enhancing the performance and durability of bagasse-based composites.

Alkali treatment is one of the most employed modification techniques for bagasse fibers. This process removes hemicellulose and surface contaminants, exposes cellulose microfibrils, and increases surface roughness, thereby improving mechanical interlocking with the matrix [12]. In addition to alkali treatment, oxidative methods such as potassium permanganate treatment introduce reactive functional groups that promote chemical bonding with epoxy-based resins [3]. These treatments contribute to improved tensile and flexural properties by strengthening the fiber–matrix interface.

Chemical functionalization methods aimed at reducing the hydrophilic nature of bagasse fibers have also been widely investigated. Treatments involving silane coupling agents or hydrophobic chemicals modify surface polarity and reduce moisture uptake, which is particularly important for automotive components exposed to humid or fluctuating environmental conditions [8]. Improved moisture resistance enhances dimensional stability and helps preserve mechanical integrity during long-term service.

In hybrid composite systems, interfacial optimization becomes even more critical due to differences in surface chemistry and stiffness between bagasse fibers and secondary reinforcements. Effective surface treatment ensures uniform stress distribution across multiple fiber types and minimizes interfacial debonding and fiber pull-out during loading [15]. Microstructural studies using scanning electron microscopy consistently show that treated fibers exhibit reduced voids, improved resin wetting, and cleaner fracture surfaces compared to untreated counterparts [7].

Overall, appropriate fiber treatment and interfacial engineering play a decisive role in improving mechanical strength, wear resistance, and thermal stability of sugarcane bagasse–based composites. Continued efforts to optimize treatment protocols—while minimizing chemical usage and environmental impact—are essential for enabling large-scale adoption of these materials in sustainable automotive applications [12]

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V. FABRICATION TECHNIQUES AND PROCESSING PARAMETERS

The fabrication method plays a crucial role in determining the quality and performance of sugarcane bagasse–based hybrid composites. Processing techniques must ensure uniform fiber distribution, effective resin impregnation, and minimal void formation, particularly when working with natural fibers that exhibit variability in size, morphology, and moisture content [2], [10]. Selection of an appropriate fabrication route therefore depends on component geometry, required mechanical performance, and production scalability.

Compression molding is widely adopted for bagasse-based composites due to its simplicity, cost-effectiveness, and suitability for producing flat or moderately complex automotive components [10]. This technique allows good control over fiber volume fraction and laminate thickness while achieving adequate consolidation under pressure. However, precise control of processing temperature and pressure is required to avoid fiber degradation or incomplete resin curing.

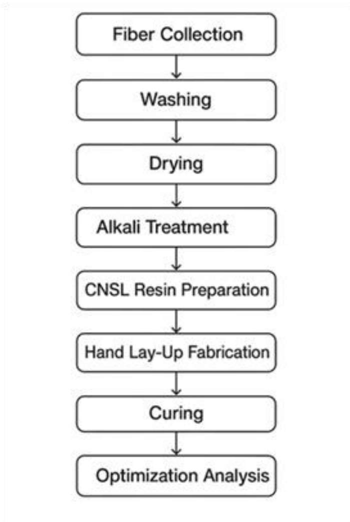

Fig 4. Process flow chart illustrating the sequential steps

Hand lay-up and resin transfer molding (RTM) techniques are commonly used at the laboratory and prototype levels to investigate material behavior and optimize composite formulations [2]. These methods offer flexibility in fiber placement and hybrid configuration, but they are more sensitive to operator skill and may result in higher void content if processing parameters are not carefully controlled. Vacuum-assisted resin transfer molding (VARTM) has been shown to improve resin flow and fiber wetting, particularly for hybrid laminates, leading to improved interfacial bonding and mechanical consistency [10].

Processing parameters such as curing temperature, curing time, applied pressure, and resin viscosity significantly influence the final composite properties. For CNSL-based epoxy systems, optimized curing schedules are essential to achieve sufficient cross-link density while preventing thermal degradation of natural fibers [5]. Inadequate curing can result in poor load transfer and reduced thermal stability, whereas excessive temperatures may damage fiber structure and compromise composite integrity.

Overall, careful optimization of fabrication techniques and processing conditions is essential for translating laboratory-scale sugarcane bagasse–based composites into reliable automotive components. Improved control of processing variables enhances repeatability, mechanical performance, and long-term durability, thereby supporting the broader adoption of sustainable hybrid composites in industrial applications [10].

VI. HYBRIDIZATION AND INSULATION APPLICATIONS

Sugarcane bagasse–based hybrid composites have gained increasing interest for automotive applications where weight reduction, sustainability, and functional performance are key design considerations. These materials are particularly suited for interior and semi-structural components, where mechanical demands are moderate but durability, acoustic comfort, and thermal insulation are critical [1], [10]. By replacing conventional glass fiber–reinforced plastics in such components, bagasse-based hybrids contribute to lower vehicle mass and reduced environmental impact.

Hybridization plays an important role in extending the applicability of bagasse composites to automotive environments. When combined with other natural fibers or functional fillers, bagasse fibers help create composite systems with improved stiffness, impact resistance, and vibration damping [8], [15]. Such hybrid configurations enable tailored material behavior that meets specific component requirements while maintaining a high level of bio-content. Interior panels, door trims, dashboards, and headliners are among the components where hybrid bagasse composites have demonstrated practical feasibility [10].

In addition to structural performance, thermal and acoustic insulation properties are critical for passenger comfort and noise control. The porous structure of sugarcane bagasse contributes naturally to sound absorption and thermal resistance, making it suitable for insulation-oriented applications [8]. Hybridization with materials such as bamboo charcoal, jute, or other low-conductivity reinforcements further enhances these properties by reducing heat transfer and damping sound transmission. These characteristics are particularly valuable for floor panels, roof liners, and firewall insulation components.

From a manufacturing perspective, hybrid bagasse composites are compatible with conventional automotive processing techniques, enabling their integration into existing production lines with minimal modification [10]. Moreover, the use of agricultural waste as a primary reinforcement supports circular-economy goals and aligns with sustainability initiatives adopted by automotive manufacturers. As vehicle design increasingly prioritizes eco-efficiency and passenger comfort, hybrid sugarcane bagasse composites present a viable solution for multifunctional automotive insulation and interior applications [15].

VII. OPTIMIZATION AND MACHINE LEARNING

The growing complexity of bio-composite systems has increased the need for efficient methods to optimize material design and processing parameters. Sugarcane bagasse–based hybrid composites are influenced by multiple interdependent factors, including fiber treatment, hybrid configuration, resin formulation, curing conditions, and operating environment. Conventional trial-and-error approaches are often time-consuming and resource-intensive, particularly when multiple variables interact simultaneously [7]. As a result, optimization techniques and data-driven modeling have emerged as valuable tools for improving composite performance.

Statistical optimization methods such as Taguchi design and response surface methodology have been widely applied to identify key parameters governing mechanical and tribological behavior in natural fiber composites. These approaches help reduce experimental effort while revealing the relative importance of factors such as fiber surface treatment, load conditions, and processing variables [7]. Studies consistently indicate that fiber treatment has a dominant influence on wear resistance and interfacial performance in bagasse-based composites, highlighting the importance of surface engineering.

More recently, machine learning techniques have been introduced to predict composite behavior with higher accuracy and flexibility. Algorithms such as Random Forest, support vector machines, and artificial neural networks have been used to model complex, nonlinear relationships between input parameters and output properties [7]. In the context of sugarcane bagasse composites, machine learning models have demonstrated strong predictive capability for wear rate, mechanical strength, and thermal performance, often outperforming conventional regression-based methods.

Beyond prediction, data-driven models offer opportunities for rapid material screening and design optimization. By reducing reliance on extensive experimental campaigns, machine learning approaches support faster development cycles and more consistent material quality. Although current applications are largely limited to laboratory-scale datasets, continued integration of experimental data with intelligent modeling is expected to play an important role in scaling up sustainable bio-composites for automotive and engineering applications [7]

VIII. CHALLENGES AND FUTURE SCOPE

Despite the encouraging progress reported for hybrid sugarcane bagasse–CNSL bio-composites, several challenges continue to limit their widespread adoption in automotive applications. One of the primary concerns is the inherent variability associated with natural fibers. Differences in fiber morphology, chemical composition, and moisture content—arising from cultivation conditions and extraction processes—can lead to inconsistent composite performance and reduced reproducibility across studies [3], [9].

Moisture sensitivity remains another critical issue for bagasse-based composites. The hydrophilic nature of lignocellulosic fibers promotes water absorption, which can degrade interfacial bonding, reduce mechanical strength, and compromise long-term dimensional stability under service conditions [8]. Although surface treatments and hybridization strategies have shown promise in mitigating these effects, achieving durable moisture resistance without increasing processing complexity or cost remains a significant challenge.

From a materials perspective, the performance consistency of CNSL-based epoxy systems requires further investigation. Variations in CNSL composition, hardener selection, and curing conditions can influence cross-link density and thermal stability, leading to differences in mechanical behavior [5], [11]. Standardization of resin formulations and curing protocols is therefore necessary to ensure reliable composite performance and facilitate industrial-scale implementation.

Looking ahead, future research should focus on establishing standardized testing methodologies and long-term durability assessments that reflect real automotive service conditions, including thermal cycling, humidity exposure, and fatigue loading [7]. Greater emphasis is also needed on understanding processing–structure–property relationships to support predictive material design. In this context, the integration of optimization techniques and machine learning tools offers a promising pathway to accelerate material development, improve consistency, and reduce experimental effort.

In addition, life-cycle assessment and recyclability studies must be incorporated into future investigations to quantify the true environmental benefits of hybrid bagasse–CNSL composites. Addressing these challenges through coordinated experimental, analytical, and data-driven approaches will be essential for advancing these materials from laboratory-scale demonstrations to commercially viable automotive solutions [10].

IX. CONCLUSIONS

This review has critically examined the evolving landscape of hybrid sugarcane bagasse–CNSL bio-composites with specific focus on their suitability for automotive applications. By integrating agricultural waste–derived fibers with bio-based resin systems, these composites present a compelling pathway toward reducing material-related environmental impact while maintaining functional performance. The reviewed studies demonstrate that appropriate fiber treatment, hybrid reinforcement design, and optimized CNSL–hardener formulations can significantly enhance mechanical, thermal, and interfacial properties.

Hybridization emerges as a key strategy for bridging the performance gap between conventional synthetic composites and fully bio-based materials. When properly engineered, bagasse-based hybrid composites exhibit characteristics that are well aligned with the requirements of automotive interior and semi-structural components, including weight reduction, impact resistance, and acoustic and thermal insulation. The growing compatibility of these materials with established manufacturing processes further supports their practical viability.

Despite notable progress, the transition from laboratory research to industrial adoption requires greater emphasis on material standardization, long-term durability assessment, and processing consistency. The integration of optimization techniques and data-driven approaches offers a promising direction for accelerating material development and improving reliability. Overall, hybrid sugarcane bagasse–CNSL bio-composites represent a technically credible and environmentally responsible material class with strong potential to contribute to next-generation automotive design. Continued interdisciplinary research and industry collaboration will be essential to fully realize their impact.

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