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A systematic review on hybrid composite materials for enhancing fuel efficiency and reducing emissions in automobiles

Joseph Bamidele Awotunde[1], Abidemi Emmanuel Adeniyi[2*], Peace Busola Falola[3], Segun Adebayo[4], Oluwasegun Julius Aroba[5]

[1]Department of Computer Science, University of Ilorin, Ilorin, Kwara State, Nigeria.
[2]Department of Computer Science, Bowen University, Iwo, Osun State, Nigeria.
[2]Chitkara University Institute of Engineering and Technology, Chitkara University, Punjab, India.
[3]Computer Science Unit, Distance Learning Center, University of Ibadan, Ibadan, Oyo State, Nigeria.
[4]Department of Operations and Quality Management, Durban University of Technology, Durban, South Africa.
[5]Operations and Quality Dept. Faculty of Management Science, Durban University of Technology, South Africa, 4001.
[5]Center for Ecological Intelligence, Faculty of Engineering and Built In Environment, University of Johannesburg, Gauteng ,APK Campus, Johannesburg , South Africa, 2006.
Corresponding author: Abidemi Emmanuel Adeniyi (*Email: abidemi.adeniyi@bowen.edu.ng*)

Abstract

The growing concern over environmental impacts and the need for sustainable practices have prompted research into innovative materials that can improve vehicle performance while minimizing ecological footprints. Hybrid composite materials combine lightweight, high-strength components such as carbon fiber and polymers with metal alloys to reduce vehicle weight, improve fuel efficiency, and lower emissions while maintaining structural integrity and performance in automobiles. Therefore, this systematic review explores the role of hybrid composite materials in enhancing fuel efficiency and reducing emissions in the automotive sector. The review synthesizes existing literature on various hybrid composites, examining their mechanical properties, weight reduction potential, and overall impact on fuel consumption and emissions. Key findings highlight the advantages of integrating multiple materials to optimize performance characteristics and the challenges associated with manufacturing and recycling these composites. The study concludes with recommendations for future research directions, emphasizing the importance of interdisciplinary approaches to develop effective hybrid materials that meet the evolving demands of the automotive industry.

Keywords: Automobiles, Carbon fiber, Fuel efficiency, Hybrid composite materials, Hybrid powertrains, Lightweight materials, Reduce emissions, Reinforcements.

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1. Introduction

Hybrid composite materials in automobiles combine two or more different types of reinforcements or matrix materials to optimize performance [1, 2]. These materials blend properties like strength, stiffness, durability, and lightweight characteristics [1]. Commonly used reinforcements include carbon fiber, glass fiber, or natural fibers, embedded in polymer, metal, or ceramic matrices. In automotive applications, hybrid composites enhance fuel efficiency by reducing vehicle weight while maintaining safety and performance [3]. They are used in body panels, interiors, and structural components, offering superior corrosion resistance and design flexibility. Their sustainable attributes, such as recyclability and lower energy use during production, support greener vehicle manufacturing practices. Fuel efficiency in automobiles refers to optimizing energy use to travel further on less fuel, achieved through advanced engine technology, lightweight materials, and aerodynamics [4, 5]. Reducing emissions involves minimizing pollutants like CO_2 and NO_x using innovations such as electric or hybrid powertrains, improved combustion, and emission control systems [6]. Together, these approaches lower environmental impact, conserve resources, and meet stringent global sustainability standards in transportation.

Hybrid composite materials are emerging as key enablers for improving fuel efficiency and reducing emissions in the automotive industry [7, 8]. These materials combine different components, such as natural fibers, synthetic fibers, and lightweight metals, to create composites that are both lightweight and strong [9]. By replacing traditional steel and cast iron, hybrid composites can significantly reduce vehicle weight, which is directly linked to improved fuel efficiency and reduced greenhouse gas emissions. The automotive industry is undergoing a transformative shift driven by the dual imperatives of fuel efficiency and emission reduction. Hybrid composite materials are increasingly recognized for their potential to enhance fuel efficiency and reduce emissions in the automotive sector. By integrating various materials, these composites achieve a balance of lightweight design and superior mechanical properties, which are crucial for modern vehicle performance.

Hybrid composite materials, which combine multiple types of fibers (natural, synthetic, or metallic) with polymer, ceramic, or metal matrices, are emerging as critical enablers in this evolution. These materials enhance vehicle performance by reducing weight while maintaining or even improving structural integrity, thermal resistance, and durability. The resultant lightweight vehicles demand less energy for propulsion, translating to improved fuel efficiency and reduced greenhouse gas emissions. Natural fibers, such as hemp, jute, and flax, are gaining popularity due to their renewable nature, cost-effectiveness, and recyclability. When incorporated into polymer matrices, these fibers not only reduce the weight of automotive components but also lower manufacturing costs and improve sustainability. For example, hybrid composites combining natural fibers with carbon fibers have demonstrated superior tensile and flexural strength, making them suitable for critical applications in vehicle body structures and interiors [10, 11].

Moreover, advancements in hybrid materials, including aluminum-based and multi-layered composites, are being tailored for both conventional and electric vehicles. These materials achieve mass reductions of up to 50% compared to traditional counterparts, significantly enhancing energy efficiency [12]. However, challenges remain, such as the environmental impacts of material production, which need to be addressed through better life cycle assessments and sustainable manufacturing practices [12]. Overall, hybrid composites are crucial for meeting stricter emission standards and addressing sustainability goals in automotive design. With ongoing innovation, they are likely to play an even greater role in shaping the future of green mobility [10, 11].

Vehicle weight is directly proportional to fuel consumption and emission levels. Traditional materials like steel and aluminum, while robust, often fail to meet the lightweighting goals essential for modern automotive applications. Hybrid composites bridge this gap, offering a blend of properties tailored to specific applications, such as improved energy absorption in crash scenarios, corrosion resistance, and adaptability to intricate designs. For instance, aluminum-based hybrid composites have been extensively used due to their strength-to-weight ratio and thermal stability. Hybrid composites significantly reduce vehicle weight, which directly correlates with improved fuel efficiency. For instance, aluminum-based hybrid composites have shown remarkable mechanical properties, making them suitable for lightweight applications [13-15].

The use of friction stir processed hybrid composites (FSPHC) allows for the combination of different materials, enhancing strength while minimizing weight [16]. The incorporation of both natural and synthetic fibers in hybrid composites leads to improved strength-to-weight ratios and better dimensional stability. The addition of ceramic particulates in aluminum-based composites enhances wear resistance and overall mechanical performance, making them ideal for automotive applications [14]. The shift towards bio-based fibers in hybrid composites promotes sustainability, as these materials are derived from renewable resources, contributing to reduced environmental impact [17]. While hybrid composites offer numerous advantages, challenges such as cost and manufacturing complexities remain. Addressing these issues is essential for broader adoption in the automotive industry. Hence, the review of literature on hybrid composite materials become necessary for the enhancing fuel efficiency and reducing emissions in automobiles. Therefore, this study aims to explore the following key research questions:

1. What are the various application areas of hybrid composite materials?
2. What are the Significances of Hybrid Composite Materials in automobiles?
3. What are the limitations of existing Hybrid Composite Materials for automobiles?
4. What other methods used in automobiles apart from Hybrid Composite Materials for the enhancing fuel efficiency and reducing emissions?

What influence will the findings have on the future direction of Hybrid Composite Materials in automobiles research?

This study addresses the most current state-of-the-art research in hybrid composites for January 2019-October 2024. It also presents a comparative analysis of most current studies on hybrid composites combine lightweight, high-strength components like carbon fiber and polymers with metal alloys to reduce vehicle weight, improve fuel efficiency, and lower emissions. The study also discusses their concepts in relations to automobiles, challenges, and future research directions. Therefore, this study has the following key contributions:

i. it explores the role of hybrid composite materials in enhancing fuel efficiency and reducing emissions in the automobiles;
ii. the investigation on various hybrid composites to examines their mechanical properties, weight reduction potential, and overall impact on fuel consumption and emissions;
iii. this study can help solve immediate and the challenges associated with manufacturing and recycling these composites; and
iv. the study inspiring researchers to build upon the current work and interdisciplinary approaches to develop effective hybrid materials that meet the evolving demands of the automotive industry.

2. Hybrid Composite Materials in Automobiles

Hybrid composite materials are increasingly pivotal in modern automotive engineering due to their ability to enhance vehicle performance, reduce weight, and improve sustainability. These materials, formed by combining two or more different constituent materials, offer unique mechanical, thermal, and environmental benefits, making them essential in meeting current demands for lightweight, fuel-efficient, and eco-friendly vehicles [18]. Hybrid composite materials are revolutionizing the automotive industry by offering a balance of performance, weight reduction, and sustainability. These materials combine different types of fibers, such as glass, carbon, or natural fibers, with polymers or metallic matrices to achieve properties unattainable by individual materials alone. Their lightweight nature contributes significantly to reducing vehicle weight, enhancing fuel efficiency, and lowering emissions, which are critical for both conventional and electric vehicles (EVs) [19, 20].

Recent advancements emphasize the integration of bio-based and recycled materials into hybrid composites to enhance their environmental benefits. For instance, natural fiber composites, often combined with thermoplastics, are gaining traction for their biodegradability and lower energy consumption during production [21]. These materials are particularly valuable in lightweight structural applications, where they help achieve fuel savings and reduced greenhouse gas emissions across the vehicle's lifecycle. Moreover, hybrid composites are playing a pivotal role in EVs by addressing challenges like battery weight and range efficiency [22]. Their application in components such as battery enclosures, underbody panels, and structural reinforcements enhances vehicle performance while supporting sustainability goals. However, the production of some advanced composites still poses environmental challenges due to the energy-intensive nature of manufacturing processes and raw material sourcing.

Innovations in hybrid composites also focus on enhancing mechanical properties, such as impact resistance and thermal stability, ensuring safety and durability. For example, multi-material combinations, such as carbon fiber with thermoplastic polymers, offer high strength-to-weight ratios, crucial for high-performance vehicles. Overall, hybrid composite materials are integral to modern automotive strategies aimed at sustainability and efficiency. By leveraging their unique properties, automakers are creating vehicles that are lighter, more efficient, and environmentally friendly, aligning with global trends in reducing carbon footprints and advancing green technologies [23].

2.1. The Significance of Hybrid Composite Materials in Automobiles

Vehicle weight is directly proportional to fuel consumption and emission levels [24]. Traditional materials like steel and aluminum, while robust, often fail to meet the lightweighting goals essential for modern automotive applications [25, 26]. Hybrid composites bridge this gap, offering a blend of properties tailored to specific applications, such as improved energy absorption in crash scenarios, corrosion resistance, and adaptability to intricate designs [27, 28]. For instance, aluminum-based hybrid composites have been extensively used due to their strength-to-weight ratio and thermal stability [29].

Hybrid composite materials have revolutionized the automotive industry by addressing the pressing demand for lightweight, durable, and sustainable solutions [30]. These materials, formed by combining two or more distinct constituents at a macroscopic level, offer superior mechanical properties, such as high strength-to-weight ratios, enhanced corrosion resistance, and improved energy absorption capabilities [31, 32]. Their adaptability allows for tailored performance characteristics, making them ideal for applications in automotive components like chassis, body panels, and suspension systems.

The use of hybrid composites contributes significantly to vehicle weight reduction, which improves fuel efficiency and reduces greenhouse gas emissions [33]. For example, replacing traditional steel parts with hybrid composites can achieve up to a 60% weight reduction, enhancing overall vehicle performance [34]. Additionally, these materials support innovative designs, enabling manufacturers to integrate functionality with aesthetics without compromising safety standards. The growing emphasis on sustainability has further boosted the adoption of hybrid composites, especially those reinforced with natural fibers or recycled materials. Such advancements align with global regulatory policies aimed at reducing the carbon footprint of the automotive sector. Hybrid composite materials, a blend of two or more distinct materials, have become pivotal in revolutionizing automobile manufacturing. They combine the mechanical strengths of their constituents to address key challenges in modern automotive design, particularly weight reduction, sustainability, and enhanced performance.

Lightweight Design: Lightweight design in automobiles leverages hybrid composite materials, combining materials like glass, carbon fibers, and bio-based polymers to achieve reduced weight, enhanced strength, and improved fuel efficiency [35]. These composites, widely used in EVs, optimize energy use and sustainability. However, production challenges, including high environmental costs for material manufacturing, remain significant [36]. Advancements in hybrid designs offer potential but require careful life-cycle assessments [11]. One of the most compelling advantages of hybrid composites is their ability to significantly reduce vehicle weight without compromising structural integrity. Lighter vehicles demand less energy for propulsion, improving fuel efficiency in internal combustion engine (ICE) vehicles and extending the range of battery electric vehicles (BEVs) [37]. For instance, carbon fiber-reinforced plastics and glass fiber composites are increasingly used for components like chassis, doors, and seat frames, replacing heavier metals such as steel and aluminum [38, 39]. This contributes to improved handling and lower emissions.

Enhanced Fuel Efficiency and Emissions Reduction: Hybrid composite materials enhance automobile fuel efficiency and reduce emissions by combining lightweight design with superior mechanical properties [40]. These materials, such as glass fiber-polymer hybrids, reduce vehicle mass, improving mileage and decreasing energy demand. Their use also supports sustainability by integrating natural fillers. However, production impacts must be managed to optimize lifecycle benefits. Hybrid composites play a critical role in meeting stringent global emissions standards. The combination of materials such as polymers with metal reinforcements enables the design of energy-efficient components. Reduced vehicle weight directly decreases greenhouse gas emissions during operation. This synergy is especially vital for electric and hybrid vehicles, where weight-saving translates into reduced battery load and better overall efficiency [41].

Improved Strength and Durability: Hybrid composite materials significantly enhance the strength and durability of automotive components by combining lightweight construction with robust mechanical properties. These materials, such as carbon fiber-reinforced plastics and aluminum-based hybrids, reduce vehicle weight while maintaining high impact resistance and wear protection. This improves fuel efficiency, durability, and safety in electric and conventional vehicles. Advances in manufacturing, like faster resin curing and thermoplastic lattice structures, further optimize performance and production efficiency [42]. Hybrid composites offer superior strength-to-weight ratios, corrosion resistance, and impact resistance. Their use in safety-critical components like crash structures and battery enclosures enhances vehicle safety while reducing lifecycle costs due to less maintenance. For example, aluminum-based hybrid composites are favored for their excellent mechanical properties in high-performance applications.

Sustainability and Recycling: Hybrid composite materials are increasingly significant in the automotive industry due to their potential to enhance sustainability. They combine materials like natural fibers and synthetic resins, offering reduced vehicle weight and improved fuel efficiency, which helps lower greenhouse gas emissions [43]. However, recycling these composites is challenging because of their mixed material composition, which complicates separation and reuse. Recent innovations include biodegradable composites and bio-resin use to address these concerns, aligning with circular economy goals and reducing environmental impact. With a growing focus on sustainability, hybrid composites incorporate eco-friendly materials, such as natural fibers and recycled components, to reduce the environmental footprint. However, challenges remain in recycling composite materials due to the complexity of separating their constituents. Advancements are being made in recyclable thermoplastic resins and bio-based composites, contributing to a circular economy for automotive manufacturing [43].

Applications in Electric and Autonomous Vehicles: Hybrid composite materials are transforming the automotive industry, particularly in EVs and autonomous vehicles (AVs), by addressing weight reduction, efficiency, and safety. Their unique combination of lightweight properties and high strength significantly reduces vehicle weight, enhancing range and performance in EVs. For instance, using composites in battery enclosures has enabled up to 90% weight reduction compared to traditional metals while improving thermal management and flame retardancy, crucial for fast-charging systems [44]. In autonomous vehicles, lightweight composites help offset the additional weight of sensors and computing equipment. This balance is critical to maintain fuel efficiency and performance. Hybrid composites also offer enhanced design flexibility, enabling the integration of components such as A-pillars and underbody panels, further streamlining vehicle architecture [44].

Despite their advantages, challenges remain. The high cost of composite production and scalability issues limit their widespread adoption. However, innovations like thermoset polymer composites for motor enclosures and bio-based composites for EV modules indicate growing potential [11]. These materials also improve environmental sustainability by reducing overall life-cycle emissions.

Future applications are expected to focus on reducing production costs and expanding their role in critical components like battery systems and structural frames. As industry collaborations and technology mature, hybrid composites will play an essential role in advancing the next generation of vehicles [45]. Hybrid composites are particularly beneficial for the evolving EV market. Lightweight materials are used for battery housings and thermal insulation systems, ensuring safety and efficiency. Moreover, as autonomous vehicles require additional sensors and electronic systems, hybrid composites help offset the weight of these technologies, maintaining performance and efficiency [45]. Despite their benefits, the production of hybrid composites is energy-intensive and costly. Scaling their use to mass-market vehicles requires innovations in manufacturing techniques, such as advanced molding processes and additive manufacturing. Research is also focused on enhancing their recyclability and reducing the environmental impact of production. Hybrid composite materials are reshaping the automotive industry, driving advancements in lightweighting, sustainability, and safety. While challenges in cost and recycling remain, continued innovation and adoption promise to accelerate their integration into mainstream automotive manufacturing, aligning with global trends toward greener, more efficient mobility solutions.

Natural Fiber Composites: Recent trends include the integration of natural fibers such as hemp, flax, and jute into composite matrices. These materials not only reduce reliance on synthetic fibers but also contribute to sustainability by lowering the carbon footprint and enabling recyclability [46]. For example, a hybrid of hemp and carbon fibers has demonstrated excellent tensile and flexural strength while being lightweight. Hybrid composite materials incorporating natural fibers, such as hemp or flax, play a significant role in modern automotive applications [1]. They offer environmental benefits by reducing reliance on non-renewable resources, lowering carbon footprints, and being recyclable. Additionally, these materials enhance vehicle performance by reducing weight, improving fuel efficiency, and decreasing emissions. Despite these advantages, challenges like durability, water absorption, and adhesion with polymer matrices persist. Recent innovations, such as combining natural and synthetic fibers, aim to address these issues while maintaining cost-effectiveness and sustainability [10].

Thermal and Fire Resistance: Hybrid composites are crucial in EVs for applications like battery casings and structural components. Advanced designs enhance thermal stability and fire resistance, protecting the battery pack and improving safety standards. Hybrid composite materials are crucial in modern automobiles due to their enhanced thermal and fire resistance properties. They address the growing need for lightweight, durable materials capable of withstanding high temperatures, making them ideal for critical applications like electric EV batteries and structural components. For instance, materials such as carbon and glass fibers combined with thermoplastics improve strength, thermal stability, and resistance to thermal runaway, critical for EV safety. Innovations like Quantix® ULTRA showcase remarkable fire resistance, withstanding flames over 1,200°C for extended durations, while maintaining structural integrity [47]. Hybrid composites also contribute to sustainability by integrating bio-based fibers and advanced nanotechnologies, reducing environmental impact. Their versatility supports complex designs and lightweight construction, critical for improving vehicle performance and energy efficiency [48]. These advancements position hybrid composites as indispensable in creating safer and more efficient automobiles.

Cost and Efficiency: While hybrid composites, particularly those incorporating carbon fibers, can be expensive, their long-term benefits reduced fuel consumption, enhanced durability, and fewer maintenance needs often outweigh the initial investment [49]. Hybrid composite materials are vital in modern automobiles, especially for balancing cost and efficiency. These materials, combining natural fibers (like hemp) and synthetic components (e.g., carbon fiber), reduce vehicle weight, improving fuel efficiency and lowering emissions [50]. Natural fibers are cost-effective and environmentally friendly, yet their mechanical properties can be limited. Combining them with synthetic fibers enhances durability and performance while maintaining affordability. However, cost concerns arise due to high initial production and integration expenses, particularly for advanced composites used in EV components [51]. These materials require specialized manufacturing processes and economies of scale to reduce costs. Despite these challenges, innovations, such as lightweight composites in EV battery enclosures, have demonstrated significant weight reductions and improved thermal safety, essential for EV adoption [52]. Future developments aim to optimize manufacturing techniques, enhance recyclability, and lower costs, driving broader adoption across vehicle types.

3. Review of Related Works

Hybrid composite materials have become a key focus of research in the automotive sector because of their potential to improve fuel efficiency and reduce emissions. In this section, some of the major works are reviewed with analyses of the advantages, applications, and the disadvantages/shortcomings of hybrid composites for automotive applications. Ravishankar, et al. [53] have presented a critical review on hybrid composites specifically tailored for automotive applications; such a review has underlined how weight reduction and mechanical performance improvement go hand in hand, with cost efficiency. There was a lack of experimental validation and scalability solutions for wider industrial usage. The review by Patel, et al. [54] was concerned with lightweight composite materials, with a focus on their potential for vehicle energy efficiency by weight reduction. This review identified materials such as carbon fiber and polymer matrices as enablers of fuel efficiency. However, lifecycle assessments and sustainability impacts were not comprehensively addressed in this review. Agarwal, et al. [55] investigated new environmentally friendly composite materials, with a focus on lightweighting developments for sustainable automotive solutions. The analysis underlined bio-based material sources and newer processing methodologies; however, two significant critical gaps in the study involved real-world testing and scalability. Pervaiz, et al. [34] explored wider automotive lightweighting trends, with particular attention to the advantages of composite materials in achieving high strength-to-weight ratios. While the review provided insight into material advantages, its focus on conventional composites meant that hybrid material innovations were less discussed. Togun, et al. [56] traced recent developments in FCHEVs and identified the role of hybrid composites in the enhancement of energy management and emission reduction. This study presented the strategic incorporation of advanced materials into FCHEVs, but detailed discussion on specific hybrid composites was beyond its scope.

Material efficiency strategies are discussed by Hertwich, et al. [57] encompassing all industries from automotive to many others. While the environmental advantages of lightweighting are emphasized, specific automotive applications are minimally developed within hybrid composite materials; rather, general material efficiency frameworks are provided. Johnson and Joshi [58] summarized the technological changes in engine efficiency and emission reduction. Their conclusions highlighted the complementary nature of lightweight materials in mitigating emissions, though material-level innovation was a peripheral part of the study. Skosana, et al. [50] discussed natural fiber-reinforced composites for automotive lightweighting in an ecofriendly alternative. The study did review the sustainability-related advantages of natural fibers, their renewability, and the low environmental impact; however, challenges related to the durability and industrial scalability of natural fibers remain unresolved. Zhang and Xu [20] reviewed advanced lightweight materials for automotive manufacturing. Their review listed state-of-the-art materials that have the ability to bring down emission and enhance mechanical properties. The study lacked comprehensive details on cost and challenges faced in implementing hybrid composites. Islam, et al. [27] on one hand, highlighted some advances in natural fiber-reinforced hybrid composites and their potential to balance sustainability with mechanical performance. Key areas identified for future research involve durability and cost-effectiveness. Rajak, et al. [59] reviewed applications of composite materials in the automotive sector, focusing on lightweight, energy efficiency, and structural aspects. This review study provided more detailed information about conventional composites, while hybrid material development had scant coverage. Adesina, et al. [60] investigated hybrid natural fiber-reinforced polymeric composites, which were assessed for automotive bumper beams. Their results showed that natural fibers are feasible for use in hybrid composites; however, they require up-scaled, industrialized production methods. Suriani, et al. [61] presented a critical review on natural fiber-reinforced hybrid composite, discussing their processing techniques, applications, and cost benefits. Although the review was invaluable, it did not specifically focus on integrating hybrid composites with automotive systems.

In fact, this collective body of work underscores the transformative potential of hybrid composites in addressing automotive challenges such as lightweighting, fuel efficiency, and emission reduction. The gaps in scalability, cost analysis, and real-world validation persist; hence, further research is needed to optimize these materials for widespread automotive use.

3.1. Motivation for the Review

The increasing demand for sustainable and energy-efficient automotive solutions has strategically positioned hybrid composite materials at the focal point of modern automotive research. This review highlights their potential to transform important challenges, such as fuel efficiency, emission reduction, and lightweighting, but equally offers significant gaps that motivate further exploration. The primary advantages of hybrid composites are the superior strength-to-weight ratio and improvement in thermal and electrical properties. Some recent experiments have shown their effectiveness in structural uses, thermal management, and energy storage systems in electric and fuel-cell vehicles. In addition, it suffers from barriers to widespread diffusion owing to high production costs, scalability challenges, and a need for long-term durability assessment.

In addition, the review has highlighted the important contribution of hybrid composites with an ecofriendly and biobased matrix towards fulfilling international goals concerning sustainability. Although good progress is being witnessed, trade-offs between mechanical performance and environmental benefits still need further optimization; further, there is a scope for real-world validation and lifecycle assessment. This SLR is, therefore, motivated by the need to close these gaps through a systematic review of existing research on hybrid composite materials. This review intends to consolidate knowledge regarding their applications, performance, and limitations, and to identify future directions for research that will definitely advance their integration into the automotive industry. In addressing these challenges, the SLR hopes to contribute to the creation of novel materials capable of meeting the twin demands of sustainability and performance. Table 1 summarize the related works of the reviews.

Table 1.
Summary of the State-of-the-art related works reviews.

Authors	Topic	Objectives
Ravishankar, et al. [53]	Hybrid composites for automotive applications	The study discussed the overview of the performance and cost benefits of hybrid composites in automotive applications.
Patel, et al. [54]	Lightweight composite materials for automotive	The author discussed the role of lightweight composites in fuel efficiency improvement and vehicle weight reduction.
Agarwal, et al. [55]	Eco-friendly composite materials for light weighting	To find out about eco-friendly composites in light automotive manufacturing and their processing techniques.
Pervaiz, et al. [34]	Trends in automotive light weighting	Understand the use of composite materials for lightweighting and high strength-to-weight ratios.
Togun, et al. [56]	Fuel economy and performance in FCHEVs	The aim is to explore the role of hybrid composites in energy management and emission reduction in FCHEVs.
Hertwich, et al. [57]	Material efficiency for reducing GHG emissions	To identify material efficiency strategies that could reduce GHG emissions in the automotive sector and beyond.
Johnson and Joshi [58]	Engine efficiency and emissions reduction	The study reviews developments in engine efficiency and relates them to emission reduction.
Skosana, et al. [50]	Natural fiber-reinforced	Assess the sustainability and performance

	composites for automotive	of natural fibre-reinforced composites in automotive parts.
Zhang and Xu [20]	Advanced lightweight materials in automotive	Overview of state-of-the-art lightweight materials for weight and emission reduction in road transport vehicles.
Islam, et al. [27]	Natural fiber-reinforced hybrid composites	To underline the progresses, challenges, and potentials of natural fibre-reinforced hybrid composites for automotive applications.
Rajak, et al. [59]	Composite materials in the automotive sector	The presentation will discuss application and advantages of composite materials with respect to energy efficiency and lightweighting.
Adesina, et al. [60]	Hybrid natural fiber composites for bumper beams	The evaluation of mechanical properties and feasibility of hybrid natural fiber composite materials for automotive structural components.
Suriani, et al. [61]	Natural fiber hybrid composites: Processing and cost	To present a critical review of the processing techniques, applications, and cost implications of natural fiber hybrid composites.

4. Method and Materials

This section includes the search strategy, eligibility criteria, information source and search, study selection, data collection processes, data extraction, and analysis.

4.1. The Study Selected and Data Gathering Procedures

Each article's title, keywords, and abstract were checked after the initial exploration of the literature, and the potentially relevant articles were retrieved further to be tested for suitability for literature search and selection. Identification, screening, eligibility, and inclusion were the four stages of this procedure. During the identification stage, 303 papers were collected from from various reputable repositories (Scopus, IEEE Xplore, WoS, ScienceDirect and SprigerLink). After eliminating duplicate ones, the remaining papers numbered 253. Then, two independent reviewers did a coarse-to-fine evaluation regarding the eligibility of the manuscripts, one screening the title, keywords, and abstracts; the other independent one read the complete texts. The exclusion criteria included unpublished thesis and dissertation studies, conference papers not published in a peer-reviewed journal, papers not in English, and those not applying composite materials for fuel efficiency. Therefore, screening excluded 118 articles and full-text assessment excluded 99 papers. 36 papers remained out of the 303 papers. Thus, 36 studies were identified for the eligibility phase. After these processes, 36 publications were considered eligible for inclusion in this study.

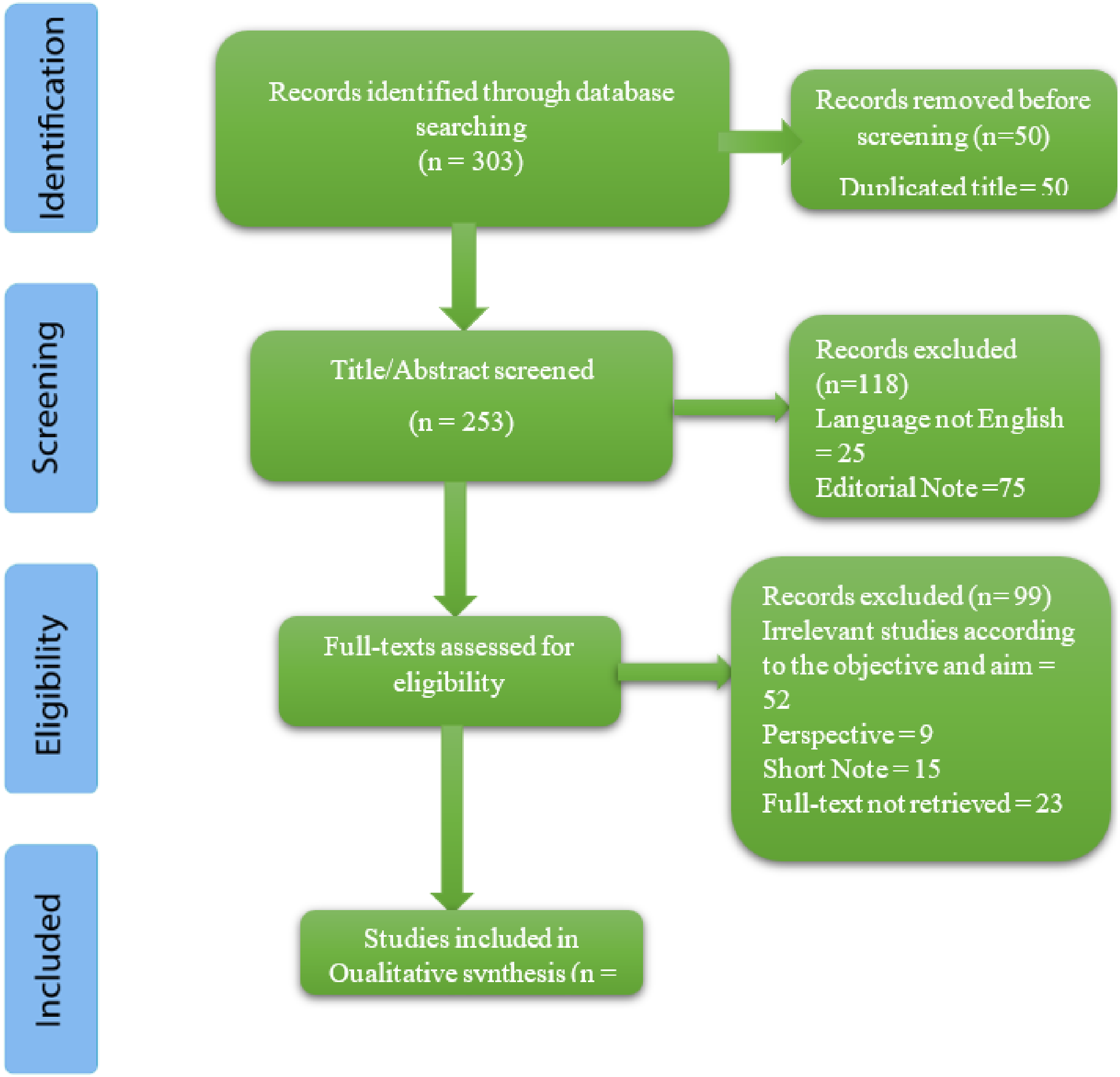

Figure 1.
PRISMA Diagram.

4.2. Search Strategy

The authors have conducted an electronic search using five publishing databases: IEEEXplore, Taylor and Francis, Sage, Springer, and WoS. The language of the search was restricted to the English language. The publishing date was set as the time of the search, November 2024, with a lower limit of January 2019. Table 2 lists the terms in the search. The AND was used as a logical operator. A targeted search was carried out to complement the computerized search. This included an online search using Google Scholar and a manual search of the cited references of relevant publications identified through the search strategy. The relevant papers were then set on the ISI Web of Science-on (December 2024) to identify any other publications that cited them (forward citation search).

Table 2.
Databases and Keywords used for Study Search.

1. Search Sources	2. Search Queries
3. Scopus	"hybrid AND composite AND materials AND for AND enhancing AND fuel AND efficiency AND reducing AND emissions AND in AND automobiles AND PUBYEAR > 2018 AND PUBYEAR < 2025 AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (DOCTYPE , "ar"))
4. Web of Science	hybrid AND composite AND materials AND for AND enhancing AND fuel AND efficiency AND reducing AND emissions AND in AND automobiles AND PUBYEAR > 2018 AND PUBYEAR < 2025 AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (DOCTYPE , "ar"))
5. Science Direct	hybrid AND composite AND materials AND for AND enhancing AND fuel AND efficiency AND reducing AND emissions AND in AND automobiles" [Publication Date: (01/01/2019 TO 11/30/2024)]

4.3. Eligibility Criteria

All the papers which scrutinized Hybrid Composite Materials for Enhancing Fuel Efficiency and Reducing Emissions in Automobiles were taken into consideration for this review. The inclusion criteria include: (i) Published between 2019 and 2024, (ii) Paper written in English language and, (iii) In a Peer-reviewed Scientific Journal. Unpublished thesis and dissertation studies were excluded. The review eliminated studies that are not within the inclusion criteria: for being only studies, or conference papers, not in English, and not using Composite materials and Reducing emissions in Automobiles.

4.4. Information Source and Search

Literature exploration was achieved via Scopus, ScienceDirect, and Web of Science (WoS). Numerous explorations in the stated e-databases were accomplished during November 2024 using the following search terms: ("hybrid AND composite AND materials AND for AND enhancing AND fuel AND efficiency AND reducing AND emissions AND in AND automobiles AND PUBYEAR > 2018 AND PUBYEAR < 2025 AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (DOCTYPE , "ar")) OR hybrid AND composite AND materials AND for AND enhancing AND fuel AND efficiency AND reducing AND emissions AND in AND automobiles AND PUBYEAR > 2018 AND PUBYEAR < 2025 AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (DOCTYPE , "ar")) OR hybrid AND composite AND materials AND for AND enhancing AND fuel AND efficiency AND reducing AND emissions AND in AND automobiles" [Publication Date: (01/01/2019 TO 11/30/2024)]) The keywords used in the database searching is shown in Table 3 and distribution per publication year is shown in Figure 2. Figures 2–4 show the outcomes of these processes. In the next section, the mentioned headings are used to summarize the recognized studies and their distribution in research.

Table 3.
The keywords used in the database searching.

Keywords	**Search String**
Hybrid Composite Materials, Enhancing Fuel Efficiency, Reducing Emissions, Automobiles	hybrid AND composite AND materials AND for AND enhancing AND fuel AND efficiency AND reducing AND emissions AND in AND automobiles AND PUBYEAR > 2018 AND PUBYEAR < 2025 AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (SUBJAREA , "ENGI") OR LIMIT-TO (SUBJAREA , "ENVI") OR LIMIT-TO (SUBJAREA , "ENER") OR LIMIT-TO (SUBJAREA , "CENG") OR LIMIT-TO (SUBJAREA , "MATE") OR LIMIT-TO (SUBJAREA , "CHEM") OR LIMIT-TO (SUBJAREA , "MATH")) AND (LIMIT-TO (EXACTKEYWORD , "Performance") OR LIMIT-TO (EXACTKEYWORD , "Article") OR LIMIT-TO (EXACTKEYWORD , "Diesel Engines") OR LIMIT-TO (EXACTKEYWORD , "Fuel Economy") OR LIMIT-TO (EXACTKEYWORD , "Energy Efficiency")) AND (LIMIT-TO (EXACTSRCTITLE , "Energy") OR LIMIT-TO (EXACTSRCTITLE , "Energies") OR LIMIT-TO (EXACTSRCTITLE , "Journal Of Environmental Chemical Engineering") OR LIMIT-TO (EXACTSRCTITLE , "Thermal Science And Engineering Progress"))

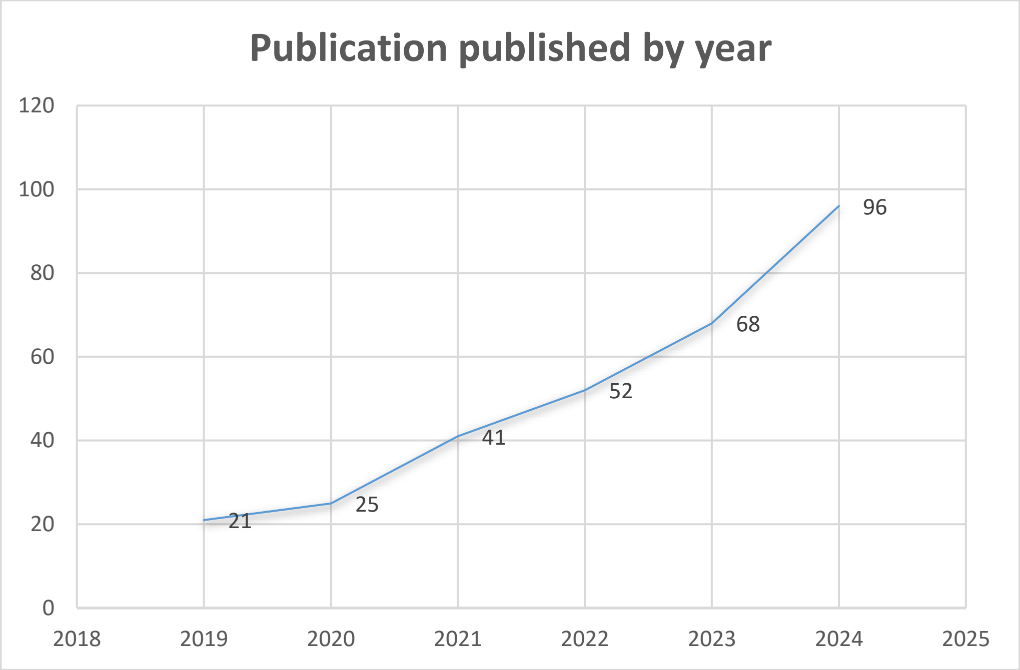

Figure 2.
Distribution of publication per year.

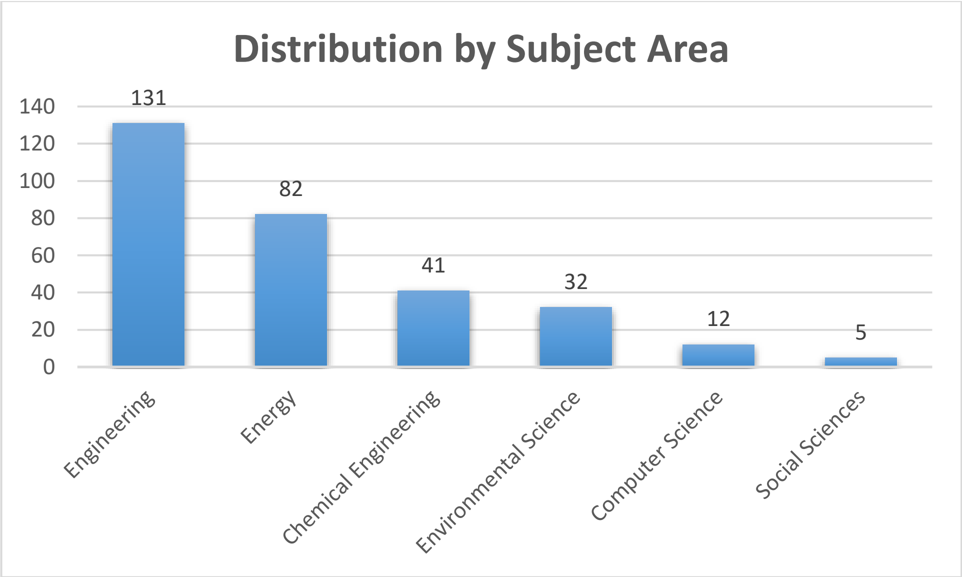

Figure 3.
Distribution of publication per subject Area.

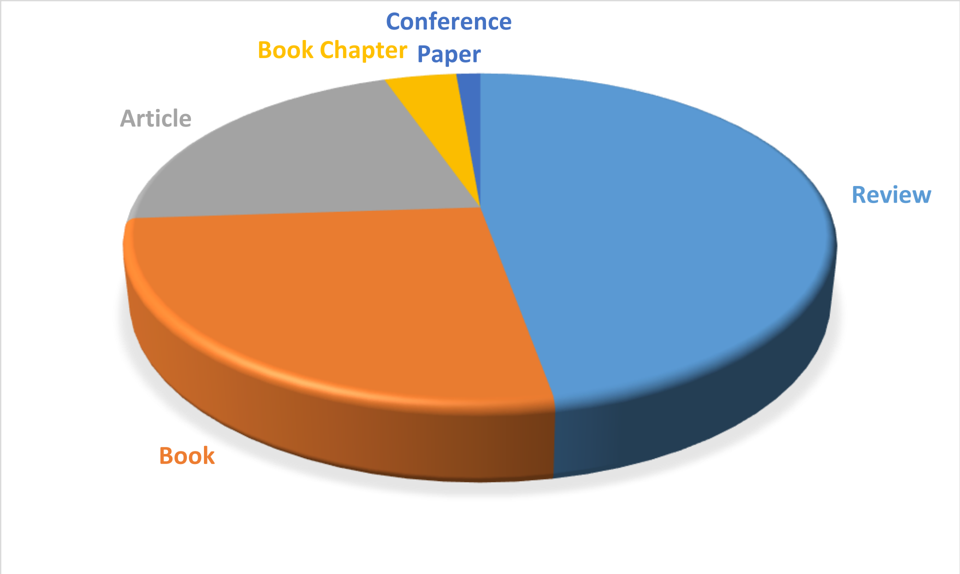

Figure 4.
Distribution of publications pertinent to the document category.

Table 4.
State-of-the-art review.

Author	Application Domain	Key Findings	Contribution	Gap Identified
Sadeq, et al. [62]	Hydrogen Energy Systems	It has a high energy density, 120 MJ/kg, which could drastically reduce CO_2 emissions. However, the present electrolysis techniques are inefficient at 60–80% and expensive at approximately $5/kg. The storage options also require ultra-high pressures up to 700 bar or very low temperatures below −253 °C.	This work has stressed that strategic developments are necessary to enhance electrolysis efficiency and lower costs; likewise, developing advanced materials and infrastructure is a dire need for storing hydrogen.	Challenges at various steps, from production efficiency and storage conditions to economic viability, suggest that wide strategic planning and interdisciplinary efforts are required to overcome the barriers.
Khanna, et al. [63]	Nano-Hybrid Composites	The nano-hybrid composites address the pressing need felt in several industries for multifunctional materials-from electronics to aerospace, energy to biomedical engineering-fueled innovation.	The study provides a critical roadmap of nanocomposites, covering their design and fabrication techniques, as well as characterization methods. Applications ranging from shape memory materials to energy harvesting among other broad areas make this a useful resource for both academia and industry.	Whereas the study covers many aspects of various applications and theoretical considerations, practical deployment challenges or large-scale production feasibility has probably yet to be explored.
Kumar [64]	Nano-Coating Technologies	Nano-coating confers many advantages, such as very high corrosion and wear resistance, coupled with improved adhesion.	The study summarizes the corrosion performances of various coatings-namely, ceramic, metallic, and nanocomposite-on metallic substrates, emphasizing the effectiveness of nano-coatings in ensuring durability and efficiency within a wide range of applications.	The study has not mentioned ongoing challenges or limitations in nano-coatings applications that might suggest further research on durability, long-term performance, and cost-effectiveness in industrial scale-up.
Nivedhitha, et al. [65]	Hydrogen Energy	This transition signifies an increasing role of hydrogen in the field of	The review systematically covers the evolution of hydrogen technology-from its	The review fail to discuss in greater detail the economic impediments

		sustainable energy solutions, from nickel-metal hydride batteries to advanced hydrogen engines.	application in batteries to its use in state-of-the-art engines-emphasizing both technological advancement and the increasingly important position of hydrogen in the energy sector.	and the infrastructural challenges that have to be addressed in order to facilitate the wider diffusion of hydrogen technologies.
Praveena, et al. [66]	Biofuel Production	It points out the potential of algae and waste feedstocks for the production of biofuel in the circular economy, highlighting their sustainability and environmental benefits.	This paper presents the systematic review of existing technologies and methodologies using algae and different kinds of waste for biofuel conversion, underlining the efficiency and circularity of such processes.	While noting various advancements, the review indicate further scalability and economic viability to increase these technologies' practical use in the biofuel industry.
Durlik, et al. [67]	Sustainable Shipping and Green Ports	It highlights that there is a big potential of AI for improvements in efficiency and sustainability within shipping and port operations.	Current technologies are analyzed, with their applications to the shipping and ports sector, highlighting optimisation in logistics, emission reduction, and improved operational efficiency.	The study enumerates the absence of uniform protocols and difficulties in integrating different systems and regions as major challenges in the universal adoption of AI solutions in the maritime industry.
Bakhchin, et al. [68]	Environmental and Pollution	The study has shown that integrated catalytic systems have the capability of simultaneously reducing NOx and particulate matter, hence an overall increase in emission control.	The paper discusses catalytic technologies applied in after-treatment systems and their synergy on emissions reduction, detailing the performance of the catalytic systems and their relative efficiency in waste energy utilization from combustion processes.	The research may point out that substantial development is still pending in catalyst durability and cost for wider industrial application and regulatory compliance.
Hsu, et al. [69]	Energy Conversion	The paper underlines the crucial position of waste-to-energy technologies in attaining sustainability, hence waste management and energy generation in urban areas.	Current WtE technologies in the study are reviewed with a broader perspective on efficiency, environmental impact, and relevance to sustainable urban development.	Notwithstanding successes recorded so far, the research indicates that scalability challenges, economic viability, and public acceptance remain important drawbacks to WtE solutions.
Alabtah, et al. [70]	Composite Materials	Bio-inspired structures can enhance the energy absorption capabilities of carbon fiber crash boxes under quasi-static axial compression, the study illustrates.	The paper quantitatively investigates the performance improvement of bio-inspired structures in prepreg carbon fibers, showing that it allows for better energy absorption compared with the designs without the structure.	The investigation point to the need for further optimization of the bioinspired patterns to maximize material efficiency and cost-effectiveness in real-world applications.
Mu [71]	Flame Retardant Composites	The review identifies that non-halogenated flame retardants work very effectively in enhancing the fire safety of fiber-reinforced epoxy composites used in the aviation and automotive sectors.	The contribution of this work lies in specifying how such composites are formulated, together with their performance metrics with a focus on their mechanical strength, thermal stability, and flame retardancy.	While the composites are promising, regarding fire resistance, the study indicate further improvements that could be made for long-term durability and cost-effectiveness, as well as assessments of environmental impacts during manufacture and disposal.

Chen, et al. [72]	Thermoelectric Generators	This work recognizes that further efficiency in thermoelectric generators may be considerably improved by optimizing the designs of heat exchangers and using advanced thermoelectric materials.	This study furthers the understanding of the interaction of heat exchanger efficiencies and material properties for thermoelectric generators and provides a new framework for designing more efficient systems.	Despite improvements, this study points to limitations within current material science that restrict further efficiency gains, thus the need for continued research into new materials and technologies.
Elkaee, et al. [73]	Environmental Engineering	Various reducing agents that have been used in different SCR technologies are reviewed, pointing out the efficiencies and limitations in bringing down the NOx emission.	This review consolidates current knowledge on SCR technologies and undertakes a critical assessment of the effectiveness and practicality of various reducing agents applied in industrial applications.	The review points out the development gap in more powerful, less expensive reducing agents that could function under broader sets of environmental conditions and emission sources.
Kausar [74]	Polymer Engineering	It also emerges from the study that the addition of nano-reinforcements in epoxy composites expands their shape memory capabilities for higher structural diversity and innovation.	The paper makes a significant contribution to the field by describing the mechanism through which nano-reinforcements have given effect to the thermal and mechanical properties of shape memory polymers, hence affording insight into new applications and design possibilities.	Long-term stability and environmental impact of such nano-reinforced materials possibly provide paths for further investigation, as well as scalability regarding their commercial production.
Jiaqiang, et al. [75]	Automotive Emissions	It highlights the main mechanisms ruling soot formation in modern automobile engines, while different technologies and strategies for the reduction of soot emissions are evaluated.	This paper is helpful because it systematically summarizes the current understanding of soot formation processes and points out in detail the effective techniques of reduction, including both technological improvement and fuel modification.	The review probably indicates the need for further development of universally applicable soot reduction technologies that are cost-effective and can be incorporated into existing automotive systems without significant modifications.
Pirouzfar, et al. [76]	Petroleum Processing	The study outlines the main types of gasoline, to wit: straight-run, cracked, reformed, synthetic, and those containing additives. Each of these types is derived through various processes that contribute differently to the entire gasoline market.	This overview helps establish how various types of gasoline are produced and utilized within both the automotive and aviation industries by showing their origin and chemical properties.	It would be interesting to hear an in-depth discussion on the environmental impact of each type of gasoline and how each one stands in efficiency and performance on different types of engines.
Wei, et al. [77]	Materials Science	The review outlines efficient techniques for the conversion of machining chips into	This paper consolidates current knowledge on the ball milling technique for recycling metal chips, emphasizing	The review points to a lack of understanding of the chips-generated metal powders' long-term

		metal powder by the ball milling process and its feasibility and efficiency.	recent efforts in process optimization and their possible industrial applications.	performance and structural integrity; it calls for further investigation in powder consistency and properties relating to specific applications.
Hasan and Karmakar [78]	Environmental Science	It points out the efficiency of activated carbons in heavy metals removal from wastewater, particularly those coming from car batteries.	This paper presents a review of different types of activated carbon materials and their adsorption performance, compiling the current state of research and developments with regard to heavy metal-contaminated wastewater treatment.	The review fails to show the areas that require more effective means of economical production and regeneration processes, aside from improved efficiency in the adsorption characteristics for various industrial uses.
Aguilar Esteva, et al. [79]	Industrial Ecology	The study, therefore, proposes a holistic circular economy framework for the automobile industry, focusing on maximum resource efficiency and waste reduction through the reuse, recycling, and remanufacturing of materials and components.	This paper contributes by highlighting actionable strategies and principles that could guide automobile manufacturers in transitioning toward a more sustainable, circular economy model.	It points to deficiencies in existing regulatory and market mechanisms that are barriers to the full deployment of circular economy practices in the automotive sector and hence indicate areas for policy improvement and industry collaboration.
Luo, et al. [80]	Energy Research, Automotive Engineering	This review identifies areas of recent improvement in the optimization and design of FCHEVs with a focus on energy efficiency, power management, and system integration	The paper gives an in-depth overview of the current status of state-of-the-art technologies in FCHEVs-innovative fuel cell design, optimisation and design hybrid powertrain architecture, and energy recovery systems-that will help map out the future road of development.	The research has pointed out the need for furthering the cost-effectiveness and durability of fuel cell systems, with challenges also identified in developing robust infrastructure that will support the wide adoption of FCHEVs.
Cherevotan, et al. [81]	Materials Chemistry	This review discusses the efficiency of porous silica-immobilized amines for direct CO_2 capture from the air, considering their high adsorption capacity and thermal stability.	The mechanisms, advantages, and challenges related to the application of silica-amine composites are discussed in the paper, with an emphasis on their scalability for CO_2 capture in mitigating climate change.	It points out that further research is needed on improving regeneration efficiency, reducing energy consumption, and overcoming the economic barriers to large-scale implementation.
Jayakumar, et al. [82]	Materials Science and Sustainability	This demand has developed to increase across industries such as automotive, aerospace, and construction in an environmentally and efficiency-driven world.	The paper reviews current improvements in developing lightweight composites and sustainable materials, focusing on their potential to reduce energy consumption and carbon footprints in industrial applications.	The study has identified gaps in production process scalability, material cost-effectiveness, and composite material recycling or reuse, which may provide avenues for further research to respond to the challenges at hand
Alarifi and Asmatulu [83]	Materials Science and Engineering	The book describes advanced hybrid composites' design, fabrication, and application, focusing on their superior mechanical properties	The book offers a comprehensive overview of hybrid composite materials, covering their structural advantages, performance benefits, and innovations in processing techniques, along	The book, therefore, calls for further research into the environmental impact of the hybrid composite, including recycling challenges, cost efficiency, and long

		and multifunctionality in aerospace, automotive, and biomedical applications.	with real-world application examples.	performance in extreme environmental conditions.
Yang, et al. [84]	Machine Learning in Automotive Engineering	This work illustrates that reinforcement learning algorithms can be effectively used for the class imbalance problem in the classification of vehicle booming noise and improves the detection performance accordingly.	The paper proposes a novel application of reinforcement learning for imbalanced datasets within the automotive noise domain by proposing an adaptive framework for enhancing the performance of a classifier with reduced false negatives.	The study identifies the need for scalability in real-world applications and further exploration of optimization techniques for the computational efficiency of reinforcement learning models for edge deployment in vehicles.
Dericiler, et al. [85]	Nanotechnology and Automotive Engineering	Properties including high strength, thermal conductivity, and a lightweight structure make graphene highlight the transformation in automotive parts; this is the point noted by this study.	The authors analyze numerous applications of graphene in motor vehicles with regard to improving battery performance and durability and a light total weight of the vehicle in order to improve energy and environmental sustainability in the auto-motive industry.	The study points out that graphene production has yet to be scaled up for widespread automotive use, and further research is needed on cost-effective manufacturing processes and long-term material stability
Hooshmand Zaferani, et al. [86]	Thermal Management and Energy Recovery	Results from this study have pointed out the potential of thermoelectric generators in effectively converting wasted heat into useful energy, therefore helping in the development of better thermal management systems.	The paper outlines an overview of advances in TEG materials, design, and integration methods, with emphasis on applications related to waste heat conversion for usable energy in automotive, industrial, and electronic systems.	The study identifies some gaps in the cost-effectiveness of TEG materials and challenges in optimizing performance for diverse operating environments, hence suggesting further material innovations and scalable solutions.
Khanna, et al. [63]	Nano-Hybrid Composite	Nanomaterials hybrid reinforced are critical in these aspects, offering multifunctionality and adaptability; therefore, they have major potential to revolutionize industries pertaining to electronics, aerospace, energy, and biomedical engineering.	It is a comprehensive book on detailed explanation, design principles, fabrication techniques, and the application of nanocomposites to connect academic and industrial issues towards solving challenges in understanding and deploying such materials in various working sectors.	While the applications and potential of nano-hybrid composites are discussed in detail, there is little focus on the challenges of large-scale manufacturing, cost-efficiency, and long-term environmental impacts of these materials.
Pirouzfar, et al. [76]	Petroleum Chemistry	The study will look into the chemical composition, performance enhancement, and environmental impact of gasoline additives, underlining their contribution to fuel efficiency and a decrease in emissions	This book covers a wide range of gasoline additives, explaining their mechanisms, benefits, and possible trade-offs, while also considering challenges in regulatory compliance and environmental safety	The study points out certain lacuna in the development of cost-effective and eco-friendly additives and the long-term effect research of additives on durability and emissions from engines.
Aguilar Esteva, et al. [79]	Circular Economy and Automotive Industry	The paper therefore presents a comprehensive framework for a circular economy in the automotive industry,	This paper contributes to incorporating the principles of the circular economy into automotive design and production; it shows how material and energy loops can	It highlights the challenges to scaling up circular strategies, which concern economic viability, a shift in consumer behavior, and a

		focusing on resource recovery, recycling, and sustainable manufacturing practices to enhance energy and material efficiency	be closed with the help of advanced technologies and policy suggestions.	strong infrastructure to support recycling and reuse.
Zhai, et al. [87]		It draws the attention of the study towards the advancement in the designing and development of wear-resistant materials by improving durability, hardness, and thermal stability concerning applications in industries.	This work is a review of wear-resistant materials on new design methodology, improvement technique, and performance applications that are used in the fields of aeronautics, automotives, and manufacturing industries.	Thus, the present study throws up challenges for future research investigations on cost-effective methods for manufacture, eco-friendly materials, and enhancement of performance under severe operating conditions.
Nivedhitha, et al. [65]	Energy Storage and Conversion	It draws the attention of the study towards the advancement in the designing and development of wear-resistant materials by improving durability, hardness, and thermal stability concerning applications in industries.	This work is a review of wear-resistant materials on new design methodology, improvement technique, and performance applications that are used in the fields of aeronautics, automotives, and manufacturing industries.	Thus, the present study throws up challenges for future research investigations on cost-effective methods for manufacture, eco-friendly materials, and enhancement of performance under severe operating conditions
Praveena, et al. [66]	Renewable Energy and Circular Economy	The study systematically reviews biofuel production from algae and waste feedstocks, emphasizing their role within a circular economy framework. Attention is drawn to progress regarding conversion technologies and environmental advantages of using waste materials for biofuels production.	Current technologies and methodologies for producing biofuels from wastes and algae are critically analyzed, pointing out their efficiency, scalability, and integration within energy systems.	Issues raised deal with scaling up the process, economic viability, or requirements for further research into optimized use of feedstock and increase of conversion efficiencies to help their viability in a circular economic perspective.
Durlik, et al. [67]	Maritime Industry and Artificial Intelligence	The study will investigate the integration of AI in promoting sustainability in the maritime sector, focusing on shipping and port operations, and how AI can contribute to reducing emissions, optimizing energy use, and improving the overall efficiency of operations.	The authors give a detailed review of the AI applications in fuel optimization, predictive maintenance, route planning, and smart energy management. Case studies presented from Maersk Line and the Port of Rotterdam highlight considerable improvements in fuel efficiency, emission reduction, and environmental monitoring.	Challenges include high costs of implementation, data privacy, and regulatory complexities. It therefore requires further development of AI technologies through collaborative efforts and public–private.
Bakhchin, et al. [68]	Pollution Control	This research deals with some of the state-of-the-art aftertreatment technologies for internal combustion engines. Low-temperature combustion strategies, integrated with post-	The authors of this review provide a broad overview of new catalyst formulations and system configurations that are being investigated for improving low-temperature performance and durability. Energy conversion and	The study has pinpointed a number of challenges with regard to optimization of complex interactions between engine operating parameters, combustion kinetics, and emission

		combustion purification systems, may have a role to play in the near-term introduction of vehicles that achieve major reductions in NOx and PM emissions. In fact, three technologies hold a bright future in this direction: SCR, LNT, and DPF.	recovery techniques have been explored, like thermoelectric generators and organic Rankine cycles, which utilize waste heat from exhaust gases with the goal of further enhancing overall efficiency.	formation. It calls for further research to overcome some of the current aftertreatment systems' limitations, especially at low-temperature conditions, which will lead to superior performance in emission reduction for advanced combustion engines.
Alarifi and Asmatulu [83]	Materials Science and Engineering	The book provides an overview of hybrid composite materials, including their basic principles, properties, chemistry, fabrication techniques, and various applications in different engineering fields.	It is a single-source reference on different types of engineering materials, with detailed information on recent research results and new technologies from synthetic processes to recent applications in various industrial sectors.	This book identifies that a basic understanding of the fundamentals is needed in choosing the right combination of materials that will provide the required unique properties and also to understand which fabrication techniques will be used.
Elkaee, et al. [73]	Environmental Engineering and Catalysis	It also presents a comprehensive review of the advances in SCR technologies for NOx reduction using different reducing agents, including ammonia, urea, hydrocarbons, hydrogen, and carbon monoxide. The efficiency and applicability of these agents in different SCR systems are highlighted.	The performance analysis, mechanisms, and influencing factors of each reducing agent in the SCR process are in-depth discussed by the authors. Catalyst components are introduced, and the critical role of SCR in mitigating NOx emission is discussed, emphasizing that environmental impacts should be reduced while industrial processes are to be improved.	The study identifies the optimization challenges of SCR technologies in the need for research to address several challenges, future directions, and innovations of SCR technologies with an emphasis on the reduction of environmental impacts and enhancement of industrial processes.

5. Current Challenges of Hybrid Composite Materials in Automobiles

the automobile industry, composite materials are often more expensive to produce and repair compared to conventional materials like steel or aluminum. Consequently, reducing manufacturing costs while maintaining high quality remains a persistent challenge. Sustainability has become increasingly important for automobile manufacturers, but recycling composite materials presents difficulties [88]. Developing efficient recycling methods and sourcing sustainable composite materials will be critical for the industry's future. Meeting the large-scale production demands of the automotive sector requires optimized manufacturing processes for composite materials, which remains a significant hurdle. Additionally, adopting new materials is complicated by global regulations and stringent safety requirements. Repairs to composite components can also be more complex and costlier than for traditional materials, necessitating the development of affordable and effective repair techniques.

Scaling production to meet industry needs while ensuring a secure and efficient supply chain for composite materials, especially during periods of disruption, is another key challenge. Developing innovative composite materials with enhanced properties such as greater strength, durability, and heat resistance is an ongoing necessity. As vehicles become increasingly advanced with features like electric propulsion and autonomous systems, integrating composite materials into these designs requires thoughtful adaptation. Balancing weight reduction for improved fuel efficiency and lower emissions while maintaining or enhancing vehicle performance, safety, and handling is a continuous challenge. To prevent production bottlenecks, it is essential to maintain a steady and reliable supply of high-quality composite materials and components. Furthermore, standards and regulations for composite materials are less established than those for traditional materials, complicating efforts to ensure quality and safety. Hybrid composite materials are increasingly used in the automotive industry due to their potential for lightweight construction, improved fuel efficiency, and sustainability. However, they face several challenges:

High Production Costs: Manufacturing hybrid composites is often expensive due to the complexity of combining different materials, such as natural and synthetic fibers, or metals and polymers. The production stage, especially for advanced composites, has a significant environmental and economic impact, making cost reduction a critical focus area [88, 89]. Hybrid composite materials, while advantageous for reducing weight and improving performance in automobiles, face challenges with high production costs [61]. These materials often require complex manufacturing processes, such as precise layering and curing of fibers and resins, which can result in slower cycle times compared to traditional metal components [89]. The lack of scalability and automation in composite production adds to the costs, making them less competitive for mass-market vehicles. Additionally, the need for specialized equipment and expertise further increases capital investments for manufacturers. Although advances in thermoplastic composites and streamlined production techniques are helping to reduce costs, these savings are not yet sufficient to meet the economic demands of large-scale automotive production [90]. Composites remain more feasible for premium or specialized vehicles, such as electric vehicles, where weight reduction offsets battery mass. Economies of scale and further technological advancements are necessary for broader adoption in the automotive industry

Environmental Concerns: While hybrid composites reduce vehicle weight and emissions during use, the production of these materials can have a high carbon footprint. Factors such as the extraction of raw materials and energy-intensive processes limit the environmental benefits of hybrid composites in some cases. Hybrid composite materials in automobiles pose environmental challenges, primarily during production. These materials, despite reducing vehicle weight and improving fuel efficiency, have a significant environmental impact due to energy-intensive manufacturing and the extraction of raw materials. Recycling these composites is complex, leading to disposal issues and potential waste accumulation. Life Cycle Assessments (LCAs) reveal mixed results, with high Global Warming Potential (GWP) and energy demands offsetting operational emissions benefits, especially in electric vehicles where emissions during use are minimal [11].

Recycling and End-of-Life Management: Hybrid composites pose significant recycling challenges due to the difficulty in separating their constituent materials. This complexity hinders the adoption of circular economy practices in the automotive sector, especially as regulations increasingly demand sustainable end-of-life strategies. Recycling and end-of-life (EOL) management of hybrid composite materials in automobiles face significant challenges [91]. These materials, such as carbon fiber-reinforced polymers, are difficult to recycle due to their heterogeneity and bonding methods. Mechanical, thermal, and chemical recycling methods exist but are often costly, energy-intensive, and yield low-quality recyclates, limiting market adoption. Additionally, hybrid composites' complex structures hinder efficient separation during dismantling [92, 93]. Regulatory frameworks like the EU's Waste Framework Directive promote circularity but require advancements in design for recyclability, sorting technologies, and infrastructure. Collaboration between industries is vital to improve EOL processing efficiency and develop viable markets for recycled composites [93].

Performance Trade-offs: Achieving the desired mechanical properties, such as strength, durability, and thermal resistance, while minimizing weight remains a challenge. For example, natural fibers enhance sustainability but often require treatment to match the performance of synthetic alternatives. Hybrid composite materials in automobiles face performance trade-offs that present challenges. While these materials reduce weight and enhance fuel efficiency, critical for electric and hybrid vehicles, they often sacrifice durability or structural integrity under extreme conditions [80]. Complex designs also increase manufacturing costs and complexity. Additionally, balancing strength, recyclability, and lightweight properties remains difficult, especially when integrating natural fibers or thermoplastics. Despite advancements, limited scalability and supply chain issues hinder widespread adoption [94]. Addressing these challenges requires innovative design and production methods.

Compatibility with Existing Systems: Hybrid composites must integrate seamlessly with current manufacturing processes and vehicle architectures. Adjustments in tooling, joining techniques, and quality assurance systems are often required, adding to implementation barriers. A significant challenge with hybrid composite materials in automobiles is ensuring compatibility with existing manufacturing systems and vehicle designs. These materials often differ in mechanical, thermal, and chemical properties compared to conventional steel or aluminum, complicating integration into production lines. For instance, issues like bonding with dissimilar materials, thermal expansion mismatches, and difficulty in recycling due to multi-material compositions hinder their widespread adoption. Advanced composites also require specialized processing techniques and equipment, increasing initial costs and limiting their feasibility for high-volume production. Furthermore, the need for lightweighting in electric vehicles adds complexity, as achieving desired strength and durability while meeting sustainability goals often involves trade-offs.

Design and Performance Prediction: Predicting the behavior of hybrid composites under various loading conditions is complex due to the interplay between different materials. Accurate modeling and simulation techniques are essential for designing hybrid composites with the desired properties, but these models are often still in development. Design and performance prediction for hybrid composite materials in automobiles pose significant challenges, particularly due to their complex material behavior and manufacturing processes. One key issue is accurately modeling the mechanical properties, as the fibers' orientation and matrix materials often vary during production, influencing the final part's strength and durability [95, 96]. Simulating manufacturing processes, such as injection molding and thermoforming, requires precise predictions of fiber orientations and their effects on the material's performance. Moreover, hybrid composites, which combine natural and inorganic fillers, can enhance properties like tensile strength and modulus, but their behavior can be highly dependent on filler content and distribution [97]. Developing reliable performance models and ensuring manufacturability are critical for optimizing automotive applications, especially when aiming for lightweight yet strong components [98].

Material Compatibility: Hybrid composites often involve different materials with distinct physical, chemical, and thermal properties. Ensuring compatibility between the constituents is challenging and crucial for optimizing performance and avoiding issues like delamination or material failure. Material compatibility remains a significant challenge in the development of hybrid composite materials for automotive applications. This is particularly evident when combining different fibers, such as carbon and natural fibers, with resin matrices. The primary concerns include issues with fiber-matrix bonding, the dispersion of fibers within the matrix, and differences in thermal and mechanical properties. For example, natural fibers can absorb moisture, affecting the composite's durability and performance, while carbon fibers are often prone to delamination due to poor adhesion with certain matrix materials [10]. Additionally, maintaining uniform mechanical properties across hybrid composites is difficult due to variations in fiber types and orientations, leading to inconsistent strength and flexibility [27]. Addressing these issues is key to improving the structural integrity and cost-effectiveness of composite materials for automotive applications [40].

Despite these challenges, composite materials are expected to play a growing role in the future of automotive design as technological advancements and consumer demand drive the industry toward more sustainable and fuel-efficient vehicles. Researchers must address issues such as the relatively fragile nature of composites and their limited load-bearing capacity over extended use. Accidental damage can be significant, highlighting the need to identify and synthesize optimal material combinations to enhance performance and reliability. Addressing these challenges will involve advances in material science, cost-efficient production technologies, and enhanced recycling methods, alongside policy support for sustainable materials.

6. The Future Prospects of Hybrid Composite Materials in Automobiles

Hybrid composite materials, which combine two or more distinct materials to leverage their respective advantages, have shown immense potential in the automotive industry. Their use in vehicles is growing as manufacturers aim to reduce weight, improve fuel efficiency, and enhance safety while also meeting increasingly stringent environmental regulations. Hybrid composites typically combine fibers such as carbon, glass, or aramid with resins like epoxy or polyester, resulting in a material that offers a blend of desirable properties such as strength, durability, and lightweight characteristics.

Hybrid composite materials are gaining significant traction in the automotive industry due to their potential for reducing vehicle weight, enhancing fuel efficiency, and supporting the shift toward EVs. These composites combine materials like natural fibers with synthetic fibers to optimize mechanical properties, offering better energy absorption, strength, and thermal resistance. As environmental regulations push for lower emissions, hybrid composites play a critical role in lightweighting vehicles while maintaining safety standards. Their use in parts such as body panels, battery enclosures, and structural components is expected to grow, driven by advancements in production technologies and recycling options. There innovations focus on integrating bio-based fibers, which can improve sustainability without sacrificing performance.

Composites offer superior mechanical, thermal, impact, and adhesion properties compared to conventional materials. However, developing structural combinations that also possess qualities like biodegradability and recyclability remains challenging and requires further research to enhance these properties. Composites require large quantities and can be costly to produce, with high production costs being the most significant challenge. Polymerization relaxation can be pre-optimized during composite preparation to achieve maximum efficiency at a reduced cost. Additionally, further research is needed to better understand how the composition of composites affects the development of enhanced microstructures during the preparation process [95]. The growing global demand for fiber in the automobile sector is expected to decline in the near future. Along with the development of additional preparative techniques, challenges related to modeling and assembly remain. As a result, there is a critical need for further research and practical application of composite manufacturing methods within the automobile industry [44].

The future of hybrid composite materials in automobiles looks promising, driven by the demand for energy-efficient vehicles and the shift towards sustainability. Lightweight materials are critical for reducing vehicle weight, improving fuel efficiency, and extending the range of EVs, and hybrid composites are at the forefront of this trend. Their strength-to-weight ratio is superior to traditional materials like steel, making them ideal for use in body panels, structural components, and interior parts of vehicles. As manufacturers move toward designing electric and autonomous vehicles, which require lightweight, durable, and high-performance materials, hybrid composites can significantly contribute to achieving these objectives. Moreover, hybrid composites can help automakers meet environmental goals. These materials are not only lighter but can also be manufactured with reduced energy consumption compared to metals. Additionally, they can be tailored to offer enhanced properties such as thermal resistance, impact strength, and corrosion resistance, which are crucial for improving vehicle safety and longevity.

In terms of research, efforts are focused on improving the manufacturing processes for hybrid composites, such as resin transfer molding, vacuum infusion, and 3D printing. These methods can help lower costs and improve the scalability of production. However, challenges remain, such as optimizing the interface between different materials in hybrid composites and ensuring their recyclability. Hybrid composites often face difficulties in bonding different fibers and resins together, which can affect their mechanical properties. Another area of research is the development of bio-based composite materials. Researchers are exploring renewable, biodegradable fibers and resins to make hybrid composites more sustainable. By integrating natural fibers like hemp or flax with bio-based resins, hybrid composites could contribute to the development of eco-friendly automobiles. Hybrid composites are poised to play a significant role in the future of the automotive industry, offering opportunities for vehicle weight reduction, energy efficiency, and sustainability. While challenges in manufacturing and material integration remain, ongoing research is likely to resolve these issues, paving the way for broader adoption in the coming decades.

7. Results and Discussion

The purpose of this section is to present a summarized review of the study's yielded search strategy and its respective analysis, as well as any limitations to the review study.

7.1 Data Extraction and Analysis

The results of each research question of this study are discussed in the following sections, along with an evaluation of the strengths and limitations of the existing works.

RQ1: What are the various application areas of hybrid composite materials?

Hybrid composite materials are versatile and find applications across diverse sectors because of their tailored mechanical, thermal, and environmental properties [99]. The automotive industry is one of the major industries that use HCMs for structural components, body panels, and interior parts for lightweight design with improved safety and fuel efficiency. In aerospace, they reduce weight and enhance thermal resistance. In the construction industry, they are used for load-carrying structures and for applications that require corrosion resistance. Besides, HCMs play a vital role in renewable energy systems, such as wind turbine blades and fuel-cell enclosures, where high strength-to-weight ratios are paramount. Biomedical engineering also incorporates these materials into prosthetics and implants due to their strength and biocompatibility. Recent developments have focused on the use of bio-based and recycled materials for sustainability, extending their applications in green technologies such as electric vehicles and battery casings.

Application Area	Description
Automotive Industry	HCMs are finding application in structural components, body panels, and interiors due to their weight-reduction potential, which would eventually provide better fuel economy Link, et al. [96]. As an example, carbon fiber-reinforced polymers have applications in high-performance vehicles to realize such goals.
Aerospace Sector	The addition of HCMs in aircraft manufacturing contributes to the reduction of weight, thereby offering improved thermal resistance to enhanced fuel efficiency and performance Xiao, et al. [100].
Construction Industry	HCMs find application in load-bearing applications and are also used for corrosion-resistant functions that give durability and life to the building materials Singh, et al. [101].
Renewable Energy Systems	HCMs in wind turbine blades and fuel-cell enclosures provide critical strength-to-weight ratios that are crucial to efficiency and performance Chandel, et al. [14].
Biomedical Engineering	HCMs are used for prosthetics and implants because of their durability and biocompatibility, which enhance patient outcomes [102].

RQ2: What are the Significances of Hybrid Composite Materials in Automobiles?

Hybrid composite materials are crucial to the development of automotive design in reducing vehicle weight, improving fuel efficiency, and reducing emissions [99]. Their high strength-to-weight ratios enable the replacement of conventional metals such as steel and aluminum, reducing energy demand for propulsion [20]. This directly enhances the range of electric vehicles and fuel efficiency in internal combustion engine vehicles. HCMs contribute to crash safety by offering superior energy absorption and impact resistance. Their resistance to corrosion means longevity, reducing maintenance needs and lifecycle costs. Besides, the possibility of HCMs to combine different materials, such as natural and synthetic fibers, meets the requirements of sustainability and helps car manufacturers comply with global emission regulations. Their application in thermal management systems, such as battery casings for EVs, further enhances safety and efficiency in modern vehicles.

Application Area	Description
Weight Reduction	HCMs possess superior strength-to-weight ratios that enable the replacement of traditional metals such as steel and aluminum, thus reducing vehicle weight and improving fuel economy Link, et al. [96].
Improved Safety	HCMs are characterized by superior energy absorption and resistance to impacts, hence contributing to improved crash safety Xiong, et al. [103].
Corrosion Resistance	The inherent corrosion resistance of HCMs leads to durability and lower maintenance and lifecycle costs.
Sustainability	To incorporate various materials into its formulation, such as natural and synthetic fibers, has met the trends of sustainability and assisted automakers in complying with the various global emission regulations.
Thermal Management	HCMs are used in thermal management systems, including battery casings for electric vehicles, enhancing safety and efficiency.

RQ 3: What are the limitations of Existing Hybrid Composite Materials for automobiles?

Despite their advantages, HCMs have some drawbacks. The high cost of production and integration inhibits their widespread adoption [104]. Energy-intensive manufacturing processes and raw material sourcing affect environmental sustainability [105]. Recycling of HCMs is still difficult because it is hard to separate the different materials that constitute them. Long-term durability and performance in extreme conditions, like high temperatures or impact scenarios, are still under research. Another limitation is scalability for mass-market vehicles because advanced composites require specialized fabrication techniques. Other limitations also include problems with hybrid composites, including natural fiber moisture absorption and poor adhesion with polymer matrices, which affect mechanical performance. Such limitations need to be overcome through innovations in cost-effective manufacturing, enhanced recyclability, and improvement in material formulation.

Application Area	Description
High Production Costs	The cost of producing and integrating HCMs is very high, hence, it cannot be widely spread.
Environmental Impact	Manufacturing processes and sourcing of raw materials that are energy-intensive have raised concerns over environmental sustainability.
Recycling Challenges	It is difficult to recycle the HCMs due to the inability to separate the constituent materials.
Durability Concerns	Long-term durability and performance under extreme conditions remain a subject of research in cases of high temperatures or impact.
Scalability Issues	Scaling up for mass-market vehicles is difficult because advanced composites require specialized fabrication techniques.
Natural Fiber Limitations	Some of the problems hybrid composites with natural fibers could face are moisture absorption and poor adhesion with polymer matrices, which eventually affect mechanical performance.

RQ4: What other methods are used in automobiles apart from Hybrid Composite Materials in automobile research?
Apart from HCMs, the automotive sector increases fuel efficiency and reduces emissions through a variety of methods.

Application Area	Description
Advanced Powertrains	Hybrid and fully electric powertrains reduce fuel consumption and resultant emissions by adding electric motors and energy recovery.
Lightweight Materials	The use of lightweight materials such as aluminium, magnesium alloys, and high-strength steels maintains structural integrity.
Aerodynamic Design	Drag is reduced with the optimization of vehicle shapes for improved fuel efficiency.
Nanotechnology in Lubricants	Nanolubricants improve friction and wear to a minimum, which means increased performance and lower emissions.
Emission Control Systems	Catalytic converters, SCR systems, and DPFs are some of the efficient ways to reduce NOx and particulate emissions.
Alternative Fuels	Biofuel, hydrogen, and synthetic fuel will decrease the carbon footprint of conventional engines
Waste Heat Recovery	Technologies such as thermoelectric generators transform exhaust heat into usable energy, thereby enhancing the overall energy efficiency.

7.2. Summary of the Review

The systematic review on hybrid composite materials for enhancing fuel efficiency and reducing emissions in automobiles explores how integrating these advanced materials can contribute significantly to reducing the environmental footprint of the automotive sector. Hybrid composites combine two or more materials, often combining natural fibers with synthetic materials like glass fibers or thermoplastics, to optimize performance while maintaining sustainability. Key advantages of hybrid composites include their potential for weight reduction in vehicles, which directly influences fuel consumption and emission reductions. By replacing heavier traditional materials such as steel with lighter composites, automakers can achieve significant efficiency gains. These materials also contribute to improved safety, durability, and resistance to wear, making them suitable for various automotive applications including structural components, interior panels, and body parts [11].

Furthermore, hybrid composites, which utilize a blend of natural and synthetic fibers, not only promote fuel efficiency through lightweighting but also enhance recyclability, offering an environmental edge. However, the production processes for these materials can have environmental impacts, particularly concerning the extraction and processing of raw materials. Despite these challenges, advancements in material technology are continually addressing such issues, with researchers focusing on optimizing production methods to reduce energy consumption and improve the overall sustainability of hybrid composites. The review underscores the importance of developing materials with a lower environmental impact during production while maintaining their performance in the automotive applications that drive fuel efficiency and emissions reductions.

This systematic review explores hybrid composite materials in automobiles, focusing on their role in improving fuel efficiency and reducing emissions. It highlights advancements, material properties, and applications driving sustainable, lightweight automotive design. Our review study included 36 articles in our systematic review, which have been analyzed based on aspects of hybrid composite materials, Fuel efficiency, and application areas. A summary of our investigation can be viewed in Figure 2. The study reviewed some interesting and valuable articles on the state of the art in hybrid composite materials. This article is organized based on fuel efficiency and reducing emissions in automobiles. Figure 2 displays the

PRISMA flow diagram of how the systematic review was conducted. Table 1 shows the summary of the related pieces of literature reviewed and finally, Table 2: Databases and keywords used for the study search.

References

[1] S. Chandgude and S. Salunkhe, "In state of art: Mechanical behavior of natural fiber-based hybrid polymeric composites for application of automobile components," *Polymer Composites,* vol. 42, no. 6, pp. 2678-2703, 2021.

[2] R. K. Behera, B. Samal, S. Panigrahi, and K. Muduli, "Microstructural and mechanical analysis of sintered powdered aluminium composites," *Advances in Materials Science and Engineering,* vol. 2020, no. 1, p. 1893475, 2020.

[3] B. De, M. Bera, D. Bhattacharjee, B. C. Ray, and S. Mukherjee, "A comprehensive review on fiber-reinforced polymer composites: Raw materials to applications, recycling, and waste management," *Progress in Materials Science,* vol. 146, p. 101326, 2024.

[4] A. Candela, G. Sandrini, M. Gadola, D. Chindamo, and P. Magri, "Lightweighting in the automotive industry as a measure for energy efficiency: Review of the main materials and methods," *Heliyon,* vol. 10, no. 8, p. e29728, 2024.

[5] R. K. Behera, B. P. Samal, S. C. Panigrahi, K. Muduli, A. Mohamed, and A. Samal, "Evaluation of magnesium recovery in Al-Mg alloys produced by modified stir casting method using genetic algorithm optimisation technique," *International Journal of Materials Engineering Innovation,* vol. 12, no. 2, pp. 134-148, 2021.

[6] S. Kasiński and M. Dębowski, "Municipal solid waste as a renewable energy source: advances in thermochemical conversion technologies and environmental impacts," *Energies,* vol. 17, no. 18, p. 4704, 2024.

[7] H. Abedsoltan, "Applications of plastics in the automotive industry: Current trends and future perspectives," *Polymer Engineering & Science,* vol. 64, no. 3, pp. 929-950, 2024.

[8] R. K. Behera *et al.*, "Experimental analysis on machinability aspects of sintered aluminium metal matrix (Al+ Si+ Mg+ Cu+ SiC) composite-a novel product produced by powder metallurgy method," *International Journal of Materials Engineering Innovation,* vol. 13, no. 1, pp. 1-22, 2022.

[9] S. Panthapulakkal, L. Raghunanan, M. Sain, B. KC, and J. Tjong, *Natural fiber and hybrid fiber thermoplastic composites: advancements in lightweighting applications*. Elsevier, 2017, pp. 39-72.

[10] D. Malkapuram, "Development of hybrid natural fiber reinforced composite material for automotive applications," SAE Technical Paper. No. 2023-28-0131, 0148-7191, 2023.

[11] M. Delogu, L. Zanchi, C. A. Dattilo, and M. Pierini, "Innovative composites and hybrid materials for electric vehicles lightweight design in a sustainability perspective," *Materials Today Communications,* vol. 13, pp. 192-209, 2017.

[12] X. Wang, W. Li, Z. Luo, K. Wang, and S. P. Shah, "A critical review on phase change materials (PCM) for sustainable and energy efficient building: Design, characteristic, performance and application," *Energy and buildings,* vol. 260, p. 111923, 2022.

[13] B. R. Moharana, S. K. Sahoo, D. K. Biswal, and K. Muduli, "Influence of fusion welding processes on microstructure and mechanical properties of dissimilar metal (AISI 304 SS-Copper) weldment," *Materials Today: Proceedings,* 2023.

[14] R. Chandel, N. Sharma, and S. A. Bansal, "A review on recent developments of aluminum-based hybrid composites for automotive applications," *Emergent Materials,* vol. 4, no. 5, pp. 1243-1257, 2021.

[15] A. Mohamed, W. Doaemo, and K. Muduli, "A review on fly ash as a sustainable material to reinforce the mechanical properties of concrete," *International Journal of Materials Engineering Innovation,* vol. 13, no. 1, pp. 58-72, 2022.

[16] K. F. Hasan, S. Chen, G. Török, L. Xiaoyi, P. G. Horváth, and T. Alpár, *Natural/Synthetic polymer hybrid composites in automotive applications*. Singapore: Springer, 2023, pp. 97-112.

[17] N. Norizan, A. Atiqah, M. Ansari, and M. Rahmah, "Green materials in hybrid composites for automotive applications: Green materials," *Implementation and Evaluation of Green Materials in Technology Development: Emerging Research and Opportunities,* pp. 56-76, 2020.

[18] N. Sahu and A. Rizwan, "Multifunctional composite materials: Innovations and applications," *International Journal of Composite Materials and Matrices,* vol. 10, pp. 28-34p, 2024.

[19] A. K. Mohanty *et al.*, "Sustainable composites for lightweight and flame retardant parts for electric vehicles to boost climate benefits: a perspective," *Composites Part C: Open Access,* vol. 12, p. 100380, 2023.

[20] W. Zhang and J. Xu, "Advanced lightweight materials for Automobiles: A review," *Materials & Design,* vol. 221, p. 110994, 2022.

[21] V. Prasad, A. Alliyankal Vijayakumar, T. Jose, and S. C. George, "A comprehensive review of sustainability in natural-fiber-reinforced polymers," *Sustainability,* vol. 16, no. 3, p. 1223, 2024.

[22] S. Palanisamy, K. Vijayananth, T. M. Murugesan, M. Palaniappan, and C. Santulli, "The prospects of natural fiber composites: A brief review," *International Journal of Lightweight Materials and Manufacture,* vol. 7, no. 4, pp. 496-506, 2024.

[23] A. Zahoor *et al.*, "A systematic study involving patent analysis and theoretical modeling of eco-friendly technologies for electric vehicles and power batteries to ease carbon emission from the transportation industry," *Energy Conversion and Management,* vol. 321, p. 118996, 2024.

[24] J. Moradi, I. Banagar, S. Mehranfar, A. M. Andwari, J. Könnö, and A. Gharehghani, "Advancing combustion technologies and alternative fuels in hybrid electric vehicles: A pathway to high-efficiency, low-emission propulsion systems," *Future Technology,* vol. 3, no. 4, pp. 42-54, 2024.

[25] N. Busarac, D. Adamovic, N. Grujovic, and F. Zivic, "Lightweight materials for automobiles," presented at the IOP Conference Series: Materials Science and Engineering (Vol. 1271, No. 1, p. 012010). IOP Publishing, 2022.

[26] V. K. Patel, N. Patel, M. D. Patel, H. A. Shukla, A. Patel, and N. J. Parmar, "Innovations in lightweight materials for automotive engineering," *Journal of Electrical Systems,* vol. 20, no. 10s, pp. 2121-2133, 2024.

[27] T. Islam *et al.*, "Advancements and challenges in natural fiber-reinforced hybrid composites: a comprehensive review," *SPE Polymers,* vol. 5, no. 4, pp. 481-506, 2024.

[28] H. Z. Hassan and N. M. Saeed, "Advancements and applications of lightweight structures: a comprehensive review," *Discover Civil Engineering,* vol. 1, no. 1, p. 47, 2024.

[29] E. W. A. Fanani, E. Surojo, A. R. Prabowo, and H. I. Akbar, "Recent progress in hybrid aluminum composite: Manufacturing and application," *Metals,* vol. 11, no. 12, p. 1919, 2021.

[30] D. K. Rajak, D. D. Pagar, R. Kumar, and C. I. Pruncu, "Recent progress of reinforcement materials: a comprehensive overview of composite materials," *Journal of Materials Research and Technology,* vol. 8, no. 6, pp. 6354-6374, 2019.

[31] G. Sun, D. Chen, G. Zhu, and Q. Li, "Lightweight hybrid materials and structures for energy absorption: A state-of-the-art review and outlook," *Thin-Walled Structures,* vol. 172, p. 108760, 2022.

[32] J. Yang, Z. Zhu, S. Han, Y. Gu, Z. Zhu, and H. Zhang, "Evolution, limitations, advantages, and future challenges of magnesium alloys as materials for aerospace applications," *Journal of Alloys and Compounds,* vol. 1008, p. 176707, 2024.

[33] S. P. Subadra, S. Yousef, P. Griskevicius, and V. Makarevicius, "High-performance fiberglass/epoxy reinforced by functionalized CNTs for vehicle applications with less fuel consumption and greenhouse gas emissions," *Polymer testing,* vol. 86, p. 106480, 2020.

[34] M. Pervaiz, S. Panthapulakkal, M. Sain, and J. Tjong, "Emerging trends in automotive lightweighting through novel composite materials," *Materials Sciences and Applications,* vol. 7, no. 01, p. 26, 2016.

[35] D. Carvalho *et al.*, "Advancing sustainability in the automotive industry: Bioprepregs and fully bio-based composites," *Composites Part C: Open Access,* vol. 14, p. 100459, 2024.

[36] M. Ramesh, M. T. Selvan, and A. Saravanakumar, *Evolution and recent advancements of composite materials in structural applications*. Elsevier, 2025, pp. 97-117.

[37] F. Leach, G. Kalghatgi, R. Stone, and P. Miles, "The scope for improving the efficiency and environmental impact of internal combustion engines," *Transportation Engineering,* vol. 1, p. 100005, 2020. https://doi.org/10.1016/j.treng.2020.100005

[38] G. Marmol, D. P. Ferreira, and R. Fangueiro, *Automotive and construction applications of fiber reinforced composites*. Elsevier, 2021, pp. 785-819.

[39] S. A. Pradeep *et al.*, "A perspective on the evolution of plastics and composites in the automotive industry," *Applied Plastics Engineering Handbook,* pp. 705-748, 2024.

[40] H. Guo, X. Zhou, and Z. Liu, "Advanced lightweight structural materials for automobiles: Properties, manipulation, and perspective," *Science of Advanced Materials,* vol. 16, no. 5, pp. 563-580, 2024. https://doi.org/10.1166/sam.2024.4686

[41] P. Gupta, B. Toksha, B. Patel, Y. Rushiya, P. Das, and M. Rahaman, "Recent developments and research avenues for polymers in electric vehicles," *The Chemical Record,* vol. 22, no. 11, p. e202200186, 2022. https://doi.org/10.1002/tcr.202200186

[42] A. Choudhury, J. Nanda, S. N. Das, K. Muduli, and S. Bathula, "The physico-mechanical and morphological characterisation of polycrystalline Al/Al2O3 composites at different process parameters," *International Journal of Materials Engineering Innovation,* vol. 15, no. 3, pp. 242-263, 2024. https://doi.org/10.1504/IJMATEI.2024.140198

[43] N. Ninduwezuor-Ehiobu *et al.*, "Exploring innovative material integration in modern manufacturing for advancing us competitiveness in sustainable global economy," *Engineering Science & Technology Journal,* vol. 4, no. 3, pp. 140-168, 2023. https://doi.org/10.51594/estj.v4i3.558

[44] A. Wazeer, A. Das, C. Abeykoon, A. Sinha, and A. Karmakar, "Composites for electric vehicles and automotive sector: A review," *Green Energy and Intelligent Transportation,* vol. 2, no. 1, p. 100043, 2023. https://doi.org/10.1016/j.geits.2022.100043

[45] M. Yoon, "Composite material application forecast in light of future mobility trends," *International Journal of Automotive Technology,* vol. 26, no. 1, pp. 13-22, 2025. https://doi.org/10.1007/s12239-024-00131-6

[46] K. Amulya, R. Katakojwala, S. Ramakrishna, and S. V. Mohan, "Low carbon biodegradable polymer matrices for sustainable future," *Composites Part C: Open Access,* vol. 4, p. 100111, 2021. https://doi.org/10.1016/j.jcomc.2021.100111

[47] K. S. Varun, S. R. Swamy, and C. Darshan, "Thermal and mechanical properties of hybrid composite materials for high-performance engineering applications," *Library of Progress-Library Science, Information Technology & Computer,* vol. 44, no. 3, pp. 19228–19241, 2024.

[48] N. Saba, M. Jawaid, M. T. H. Sultan, and O. Alothman, "Hybrid multifunctional composites—recent applications," *Hybrid Polymer Composite Materials,* pp. 151-167, 2017. https://doi.org/10.1016/B978-0-08-100785-3.00005-X

[49] D. K. Rajak, P. H. Wagh, and E. Linul, "Manufacturing technologies of carbon/glass fiber-reinforced polymer composites and their properties: A review," *Polymers,* vol. 13, no. 21, p. 3721, 2021. https://doi.org/10.3390/polym13213721

[50] S. J. Skosana, C. Khoathane, and T. Malwela, "Driving towards sustainability: A review of natural fiber reinforced polymer composites for eco-friendly automotive light-weighting," *Journal of Thermoplastic Composite Materials,* vol. 38, no. 2, pp. 754-780, 2025.

[51] F. Un-Noor, S. Padmanaban, L. Mihet-Popa, M. N. Mollah, and E. Hossain, "A comprehensive study of key electric vehicle (EV) components, technologies, challenges, impacts, and future direction of development," *Energies,* vol. 10, no. 8, p. 1217, 2017.

[52] H. Togun *et al.*, "A critical review on the efficient cooling strategy of batteries of electric vehicles: Advances, challenges, future perspectives," *Renewable and Sustainable Energy Reviews,* vol. 203, p. 114732, 2024.

[53] B. Ravishankar, S. K. Nayak, and M. A. Kader, "Hybrid composites for automotive applications–A review," *Journal of Reinforced Plastics and Composites,* vol. 38, no. 18, pp. 835-845, 2019.

[54] M. Patel, B. Pardhi, S. Chopara, and M. Pal, "Lightweight composite materials for automotive-a review," *Carbon,* vol. 1, no. 2500, p. 151, 2018.

[55] J. Agarwal, S. Sahoo, S. Mohanty, and S. K. Nayak, "Progress of novel techniques for lightweight automobile applications through innovative eco-friendly composite materials: A review," *Journal of Thermoplastic Composite Materials,* vol. 33, no. 7, pp. 978-1013, 2020.

[56] H. Togun *et al.*, "A review on recent advances on improving fuel economy and performance of a fuel cell hybrid electric vehicle," *International Journal of Hydrogen Energy,* vol. 89, pp. 22-47, 2024.

[57] E. G. Hertwich *et al.*, "Material efficiency strategies to reducing greenhouse gas emissions associated with buildings, vehicles, and electronics—a review," *Environmental Research Letters,* vol. 14, no. 4, p. 043004, 2019.

[58] T. Johnson and A. Joshi, "Review of vehicle engine efficiency and emissions," *SAE International Journal of Engines,* vol. 11, no. 6, pp. 1307-1330, 2018.

[59] D. K. Rajak, D. Pagar, A. Behera, and P. L. Menezes, *Role of composite materials in automotive sector: Potential applications*. Singapore: Springer, 2021, pp. 193-217.

[60] O. Adesina, T. Jamiru, E. Sadiku, O. Ogunbiyi, and L. Beneke, "Mechanical evaluation of hybrid natural fibre–reinforced polymeric composites for automotive bumper beam: a review," *The International Journal of Advanced Manufacturing Technology,* vol. 103, no. 5, pp. 1781-1797, 2019.

[61] M. Suriani *et al.*, "Critical review of natural fiber reinforced hybrid composites: processing, properties, applications and cost," *Polymers,* vol. 13, no. 20, p. 3514, 2021.

[62] A. M. Sadeq *et al.*, "Hydrogen energy systems: Technologies, trends, and future prospects," *Science of The Total Environment,* vol. 939, p. 173622, 2024.

[63] V. Khanna, P. Sharma, and P. Mahajan, *Technological applications of nano-hybrid composites*. IGI Global, 2024.

[64] S. Kumar, *Combating Hot Corrosion of Metallic Substrate by Nano-Coating*. Bentham Science Publishers, 2024, pp. 75-103.

[65] K. Nivedhitha *et al.*, "From nickel–metal hydride batteries to advanced engines: A comprehensive review of hydrogen's role in the future energy landscape," *International Journal of Hydrogen Energy,* vol. 82, pp. 1015-1038, 2024.

[66] V. Praveena, L. J. Martin, J. Matijošius, F. Aloui, A. Pugazhendhi, and E. G. Varuvel, "A systematic review on biofuel production and utilization from algae and waste feedstocks–a circular economy approach," *Renewable and Sustainable Energy Reviews,* vol. 192, p. 114178, 2024.

[67] I. Durlik, T. Miller, E. Kostecka, A. Łobodzińska, and T. Kostecki, "Harnessing AI for sustainable shipping and green ports: Challenges and opportunities," *Applied Sciences,* vol. 14, no. 14, p. 5994, 2024.

[68] D. Bakhchin, R. Ravi, O. Douadi, M. Faqir, and E. Essadiqi, "Integrated catalytic systems for simultaneous NOx and PM reduction: A comprehensive evaluation of synergistic performance and combustion waste energy utilization," *Environmental Science and Pollution Research,* vol. 31, no. 34, pp. 46840-46857, 2024.

[69] H.-W. Hsu *et al.*, "Toward sustainability of waste-to-energy: An overview," *Energy Conversion and Management,* vol. 321, p. 119063, 2024.

[70] F. G. Alabtah, E. Mahdi, and M. Khraisheh, "Energy absorption characteristics of a bio-inspired prepreg carbon fiber crash box under quasi-static axial compression," *Composites Part C: Open Access,* vol. 14, p. 100487, 2024.

[71] X. Mu, "Flame retardant fiber-reinforced epoxy composites for aviation and automotive applications," *Non-Halogenated Flame-Retardant Technology for Epoxy Thermosets and Composites,* pp. 401-435, 2024.

[72] C.-Y. Chen, K.-W. Du, Y.-C. Chung, and C.-I. Wu, "Advancements in thermoelectric generator design: Exploring heat exchanger efficiency and material properties," *Energies,* vol. 17, no. 2, p. 453, 2024.

[73] S. Elkaee, A. D. Phule, and J. H. Yang, "Advancements in (SCR) technologies for NOx reduction: A comprehensive review of reducing agents," *Process Safety and Environmental Protection,* vol. 184, pp. 854-880, 2024.

[74] A. Kausar, "Incipient shape memory featuring nano-reinforced epoxy nanocomposites—structural diversity and innovations," *Polymer-Plastics Technology and Materials,* vol. 63, no. 9, pp. 1209-1226, 2024. https://doi.org/10.1080/25740881.2024.2326133

[75] E. Jiaqiang *et al.*, "Soot formation mechanism of modern automobile engines and methods of reducing soot emissions: A review," *Fuel Processing Technology,* vol. 235, p. 107373, 2022.

[76] V. Pirouzfar, M. Narimani, A. F. Bakhsh, C.-H. Su, and M. Gharebaghi, *Gasoline additives*. Walter de Gruyter GmbH & Co KG, 2022.

[77] L. K. Wei *et al.*, "Producing metal powder from machining chips using ball milling process: A review," *Materials,* vol. 16, no. 13, p. 4635, 2023.

[78] M. S. Hasan and A. K. Karmakar, "Removal of car battery heavy metals from wastewater by activated carbons: a brief review," *Environmental Science and Pollution Research,* vol. 29, no. 49, pp. 73675-73717, 2022.

[79] L. C. Aguilar Esteva, A. Kasliwal, M. S. Kinzler, H. C. Kim, and G. A. Keoleian, "Circular economy framework for automobiles: Closing energy and material loops," *Journal of Industrial Ecology,* vol. 25, no. 4, pp. 877-889, 2021.

[80] Y. Luo, Y. Wu, B. Li, J. Qu, S. P. Feng, and P. K. Chu, "Optimization and cutting-edge design of fuel-cell hybrid electric vehicles," *International Journal of Energy Research,* vol. 45, no. 13, pp. 18392-18423, 2021.

[81] A. Cherevotan, J. Raj, and S. C. Peter, "An overview of porous silica immobilized amines for direct air CO 2 capture," *Journal of Materials Chemistry A,* vol. 9, no. 48, pp. 27271-27303, 2021.

[82] A. Jayakumar, S. Radoor, J. T. Kim, J.-W. Rhim, J. Parameswaranpillai, and S. Siengchin, *Lightweight and sustainable materials—a global scenario*. Elsevier, 2023, pp. 1-18.

[83] I. M. Alarifi and R. Asmatulu, *Advanced hybrid composite materials and their applications*. Elsevier, 2023.

[84] J. Yang, D. S. Kunte, B. Cornelis, and D. A. Clifton, "Reinforcement learning for imbalanced vehicle booming noise classification," presented at the 2023 2nd International Conference on Machine Learning, Control, and Robotics (MLCR), 2023.

[85] K. Dericiler, N. Aliyeva, H. M. Sadeghi, H. S. Sas, Y. Z. Menceloglu, and B. S. Okan, *Graphene in automotive parts*. Elsevier, 2022, pp. 623-651.

[86] S. Hooshmand Zaferani, M. Jafarian, D. Vashaee, and R. Ghomashchi, "Thermal management systems and waste heat recycling by thermoelectric generators—an overview," *Energies,* vol. 14, no. 18, p. 5646, 2021.

[87] W. Zhai *et al.*, "Recent progress on wear-resistant materials: designs, properties, and applications," *Advanced Science,* vol. 8, no. 11, p. 2003739, 2021.

[88] F. Khan *et al.*, "Advances of composite materials in automobile applications–A review," *Journal of Engineering Research,* vol. 13, no. 2, pp. 1001-1023, 2025.

[89] R. A. Witik, F. Gaille, R. Teuscher, H. Ringwald, V. Michaud, and J.-A. E. Månson, "Economic and environmental assessment of alternative production methods for composite aircraft components," *Journal of Cleaner Production,* vol. 29, pp. 91-102, 2012.

[90] G. V. Mahajan and V. S. Aher, "Composite material: A review over current development and automotive application," *International Journal of Scientific and Research Publications,* vol. 2, no. 11, pp. 1-5, 2012.

[91] M. Y. Khalid, Z. U. Arif, W. Ahmed, and H. Arshad, "Recent trends in recycling and reusing techniques of different plastic polymers and their composite materials," *Sustainable Materials and Technologies,* vol. 31, p. e00382, 2022. https://doi.org/10.1016/j.susmat.2021.e00382

[92] A. E. Krauklis, C. W. Karl, A. I. Gagani, and J. K. Jørgensen, "Composite material recycling technology—state-of-the-art and sustainable development for the 2020s," *Journal of Composites Science,* vol. 5, no. 1, p. 28, 2021. https://doi.org/10.3390/jcs5010028

[93] R. Hossain, M. T. Islam, A. Ghose, and V. Sahajwalla, "Full circle: Challenges and prospects for plastic waste management in Australia to achieve circular economy," *Journal of Cleaner Production,* vol. 368, p. 133127, 2022. https://doi.org/10.1016/j.jclepro.2022.133127

[94] M. Harun-Ur-Rashid and A. B. Imran, "Emerging trends in engineering polymers: A paradigm shift in material engineering," *Recent Progress in Materials,* vol. 6, no. 3, pp. 1-37, 2024.

[95] M. Sen, *Nanocomposite materials in nanotechnology and the environment*. London, UK: IntechOpen, 2020.

[96] T. Link *et al.*, "Hybrid composites for automotive applications-development and manufacture of a system-integrated lightweight floor structure in multi-material design," in *Proceedings of the SPE 19th Annual Automotive Composites Conference & Exhibition*, 2019.

[97] H. Abdul Khalil *et al.*, "Enhancement of basic properties of polysaccharide-based composites with organic and inorganic fillers: A review," *Journal of Applied Polymer Science,* vol. 136, no. 12, p. 47251, 2019. https://doi.org/10.1002/app.47251

[98] J. Plocher and A. Panesar, "Review on design and structural optimisation in additive manufacturing: Towards next-generation lightweight structures," *Materials & Design,* vol. 183, p. 108164, 2019. https://doi.org/10.1016/j.matdes.2019.108164

[99] A. Khan, S. Sapuan, E. Zainudin, and M. Zuhri, "Hybridization and its transformative role in bamboo fiber reinforced polymer composites: A review," *Advanced Composites and Hybrid Materials,* vol. 7, no. 5, p. 164, 2024. https://doi.org/10.1007/s42114-024-00974-8

[100] H. Xiao, M. T. H. Sultan, F. S. Shahar, M. Gaff, and D. Hui, "Recent developments in the mechanical properties of hybrid fiber metal laminates in the automotive industry: A review," *Reviews on Advanced Materials Science,* vol. 62, no. 1, p. 20220328, 2023. https://doi.org/10.1515/rams-2022-0328

[101] P. Singh, R. M. Singari, R. Mishra, and G. Bajwa, "A review on recent development on polymeric hybrid composite and analysis of their enhanced mechanical performance," *Materials Today: Proceedings,* vol. 56, pp. 3692-3701, 2022.

[102] R. Kolluru, P. Prasanthi, and A. S. Kumari, "Mechanical characterization of natural hybrid composites for automotive applications," *Journal of the Brazilian Society of Mechanical Sciences and Engineering,* vol. 45, no. 10, p. 511, 2023.

[103] J. Xiong, Y. Zhang, L. Su, F. Zhang, and C. Wu, "Experimental and numerical study on mechanical behavior of hybrid multi-cell structures under multi-crushing loads," *Thin-Walled Structures,* vol. 170, p. 108588, 2022. https://doi.org/10.1016/j.tws.2021.108588

[104] H. Hegab, N. Khanna, N. Monib, and A. Salem, "Design for sustainable additive manufacturing: A review," *Sustainable Materials and Technologies,* vol. 35, p. e00576, 2023. https://doi.org/10.1016/j.susmat.2023.e00576

[105] S. Ma, W. Ding, Y. Liu, S. Ren, and H. Yang, "Digital twin and big data-driven sustainable smart manufacturing based on information management systems for energy-intensive industries," *Applied Energy,* vol. 326, p. 119986, 2022. https://doi.org/10.1016/j.apenergy.2022.119986