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Review paper

SUSTAINABLE COMPOSITE MATERIALS FOR ELECTRIC VEHICLE APPLICATIONS: A COMPREHENSIVE REVIEW

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Abstract. *The shift towards electric vehicles (EVs) plays an essential role in achieving sustainable and eco-friendly transportation. This comprehensive review investigates the incorporation of sustainable composite materials within the realm of electric vehicle applications. Examining a spectrum from biocomposites to recycled polymers, the study thoroughly evaluates thermal and environmental characteristics, alongside a life cycle assessment, providing valuable insights into the potential of these materials to elevate the overall sustainability of EVs. Furthermore, recent steps in manufacturing technologies are highlighted, encompassing the integration of renewable energy sources, implementation of automation, and incorporation of machine learning and artificial intelligence in sustainable composites manufacturing. The application landscape of EVs is thoroughly explored, taking into account various influencing factors. In response to the escalating demand for EVs, a detailed market analysis and trend discussion are included to facilitate a comprehensive understanding. Addressing the multifaceted nature of the review, challenges associated with sustainable composites, innovative solutions, and future prospects are discussed, collectively contributing to the ongoing pursuit of greener and more efficient electric mobility solutions. This review serves as a valuable resource for researchers, policymakers, and industry professionals invested in advancing sustainable practices within the electric vehicle domain.*

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1. INTRODUCTION

A worldwide movement towards sustainability and the reduction of carbon emissions has propelled the electric vehicle (EV) market to the vanguard of the automotive industry's transformation. The increasing popularity of electric vehicles represents a departure from conventional internal combustion engines towards greener options [1]. Nevertheless, there will be difficulties throughout this change. Producing environmentally friendly and lightweight parts that are up to the required standard in terms of performance and safety is an area where the electric vehicle industry really shines. In the electric vehicle industry, sustainable production is important for two reasons [2]. The first is a moral obligation to protect the environment. An important contributor to the total amount of carbon emissions from vehicles is the carbon footprint of their production, which includes the procurement of materials and the manufacturing processes [3]. The second consideration is the element of performance. One of the most important metrics for electric vehicles' competitiveness market and customer acceptability is the efficiency and range of their batteries, both of which are improved by using lightweight materials [4].

One promising approach to these problems is the use of sustainable composites. These materials, which are usually composed of a matrix (such as resin) and fibers (such as carbon or glass), provide the optimal strength-to-weight ratio for electric vehicles. Proper selection of constituents may demand application of multi-criteria decision making methods [5]. When these composites are made using methods that reduce their environmental effect or are sourced from renewable resources, their sustainability is improved. Composites offer great adaptability, performance, and positive impact on the environment. High stiffness and strength for structural components and heat resistance for battery enclosures are two examples of the tailored qualities that composites may offer to various EV components [6,7]. Sustainable composites, produced from renewable sources and recycling, contribute to lowering the overall carbon emissions associated with EV manufacturing. By utilizing agro, forest and oil waste, the automotive industry can reduce its dependence on virgin materials. This resource-efficient approach helps conserve natural resources, contributing to a more circular and sustainable manufacturing model.

Sustainable composites support the principles of a circular economy by repurposing waste materials into valuable resources [8]. This approach minimizes the linear "take-make-dispose" model, promoting the longevity and reusability of materials. Ongoing research and development in sustainable composites aims to enhance their mechanical, thermal, and flammability properties. A crucial aspect of sustainable materials is their life cycle impact (LCA). LCA evaluates the environmental footprint of these composites, considering factors from raw material extraction to end-of-life disposal [9–11]. Sustainable composites showcase a reduced ecological burden compared to traditional materials. As these materials evolve, they are expected to match or exceed the performance of traditional counterparts, ensuring the feasibility of their adoption in critical EV components. In addition, as environmental regulations become more stringent, the use of sustainable materials aligns with compliance requirements. Embracing eco-friendly composites positions automotive manufacturers favorably in the evolving regulatory landscape. Consumers increasingly prioritize environmentally conscious products.

EV manufacturers incorporating sustainable materials in their vehicles can appeal to a growing market segment that values green and ethical choices. The adoption of sustainable composites demonstrates the industry's commitment to innovation and leadership. Companies at the forefront of integrating these materials position themselves as pioneers in sustainable manufacturing practices. While initial costs for sustainable composites may vary, long-term benefits include reduced environmental impact and potential cost savings as manufacturing processes mature and economies of scale are achieved. The automotive industry's increasing recognition of the importance of sustainability fosters a climate of collaboration. Stakeholders across the supply chain collaborate to accelerate the adoption of sustainable composites, contributing to a greener automotive landscape. Thus, sustainable composite materials present a compelling solution for achieving the environmental goals of the EV industry. Their eco-friendly attributes, coupled with ongoing research and collaborative efforts, position these materials as the key contributors to a sustainable and resilient future for electric vehicles. Extensive research is being conducted to explore the potential of different biofiber composites made from various fibers, polymer matrices, and formulations. The demand for biofiber and biodegradable polymer composites in the automotive industry is increasing, driven by their higher specific strength compared to glass fibers and lower energy requirements for production. These composites offer advantages such as higher impact energy absorption, ease of work, and lower health risks [12]. Different manufacturing techniques are being employed for biofiber composites, including compression molding, robotics-assisted molding, resin transfer molding, and vacuum-assisted resin transfer molding. These techniques enable the production of biofiber composites with varying fiber loadings and properties. Leading manufacturers are actively designing and deploying biofiber composite components in the automotive sector, reflecting the global trend towards sustainable materials. This includes the use of biofiber composites in interior panels and exterior parts of automobiles. The ongoing research priorities and global sustainability initiatives are shaping the future trends in biofiber composites, with a focus on enhancing their performance, expanding their applications, and promoting their commercialization and adoption.

Electric vehicles face various challenges in terms of heavy curb weight and fire threats, and the need for sustainable materials with enhanced flame retardancy for lightweight EV components. The use of high-performance sustainable polymer composites can address these challenges by reducing weight, increasing travel ranges, minimizing crash impacts, lowering braking distances, and reducing tire wear and tear [13]. Sustainable composites, such as recycled carbon fibers and advanced biocarbon, offer advantages over traditional plastics in terms of environmental impact and circular economy principles. The transition to EVs requires addressing challenges such as limited range, slow charging, battery damage, and end-of-life issues. Materials research plays a significant role in improving the sustainability of battery vehicles, including mitigating thermal runaway through improved thermal stability and sustainable flame retardants. The integration of renewably resourced, recycled, and waste recovered materials in automotive components enables the circular economy and reduces environmental impact [14,15].

The inclusion of sustainable flame retardants in EV components can improve thermal management and delay thermal runaway, enhancing safety [16,17]. Composites, such as Owens Corning's Advantex glass, offer significant reductions in fluoride, particulate, and

NOx emissions compared to traditional E-glass [18]. The properties of composites enable manufacturers to incorporate sustainable attributes into projects, increasing energy efficiency, durability, and the use of materials with a lower environmental impact. Fiber-reinforced polymeric composites (FRPCs) are widely used in various industries but are flammable, posing a safety risk to humans and property. Flame-retardant treatments are necessary to enhance the fire resistance of FRPCs. A high-quality shield consisting of a strong framework (fibers) and dense fillings (chars) can effectively block heat, oxygen, and degraded volatiles, providing flame protection. The integration of fibers and chars results in a shield with a certain strength. Carbon fibers decorated by polyelectrolyte complexes can be used in epoxy resin composites to enhance fire safety. Biobased layer-by-layer coated ramie fabric-reinforced unsaturated polyester resin composites exhibit improved properties and fire safety. The orientation of natural fiber composites can affect their fire reaction properties, and the kinetics and thermodynamics of thermal decomposition can be determined for polymers containing reactive flame retardants [19]. Various flammability test techniques for composites, such as limiting oxygen index (LOI), UL 94, NBS smoke chamber, OSU test, flame spread tests, cone calorimeter test (CCT), single item burning (SBI) test, room coroner test, and room fire test can be used to measure the flammability [19]. Fire modeling, such as Fire Dynamics Simulator (FDS) developed by NIST and FireFOAM developed by FM Global tools, can be used to assess the fire safety of materials in different realistic fire situations [19].

2. Manufacturing Processes for Sustainable Composites in EVs

Different production methods and technologies are being used nowadays to make sustainable composites for automobile manufacturing [20]. Various manufacturing processes are discussed in this review, from more conventional ones such as Resin Transfer Molding (RTM) to more advanced techniques such as 3D printing using sustainable materials [21]. Environmental effect, efficiency, and viability as an EV production technique are the criteria used to evaluate each approach [22,23]. This review consists of various significant factors which need to be considered by the EV industry. It will provide a comprehensive overview of the status of sustainable composites manufacturing to researchers, policymakers, and experts in the EV sector. This review has the potential to help in speeding the adoption of greener practices in the automobile sector by showcasing the most promising sustainable manufacturing technology and processes. Table 1 presents sustainable materials and their application in the automotive industry [12].

Table 1 Current application of biocomposites in the automotive industry [12]; PP: Polypropylene, PUR: Polyurethane, PLA: Polylactic acid, PBS: Polybutylene succinate, PET: Polyethylene terephthalate, Sorona® EP: Poly trimethylene terephthalate

Company	Model	Biofillers	Matrix	Applications
Audi	A2, A3, A4, A6, A8, Roadster, Coupe, Q7	Wood Fiber, Flax, Sisal	PP, Epoxy, PUR	Seat backs, side and back door panels, boot lining, hat rack, spare tire lining
BMW	3, 5 and 7 series	Kenaf, Flax, Hemp, Wood fiber	PP	Door trim panels, headliner panel, boot lining, seat backs, noise

				insulation panels, dashboard
Citroen	C5	Wood Fiber, Flax	Epoxy	Interior door paneling
Daimler Chrysler	Sebring	Flax, Sisal, Abaca	PP	Door panels, seat cushion, head restraint, door cladding, seatback linings, and floor panels
Fiat	Punto, Brava, Marea, Alfa Romeo 146, 156	Flax, Sisal, Hemp, Cotton, Coconut Fiber	PP	Seat bottoms, back cushions and head restraints
Ford Motors	Ford Flex, Ford Focus BEV, Freestar	Wood fiber, Wheat Straw, Coconut Coir, Soy, Rice Straw	PP, PUR	Interior storage bins, load floor, foam seating, headrests, headliner
General Motors	Cadillac DeVille, Chevrolet Impala, GMC Envoy, Trail Blazer, Terrian, Opel Vectra	Wood, Kenaf, Flax, Cotton	PP, Polyester	Seatbacks, trim, rear shelf, cargo floor, door panels, package trays, acoustic insulator, ceiling liner
Honda	Pilot	Wood Fiber	N/A	Floor area parts
Land Rover	2000, others	Kenaf	PP	Insulation, rear storage shelf/panel, door panels, seat backs
Lotus	Eco Elise 5	Hemp	Polyester	Body panels, spoiler, seats, interior carpets
Mazda	Hydrogen RE Hybrid	Corn	PLA	Console, seat fabric
Mercedes-Benz	A-Class, C-Class, E-Class, M-Class, R-Class S–Class	Abaca/banana, hemp, flax, sisal, Jute	PUR, PP, Epoxy	Door panels, seat cushion, head restraint, underbody panels, seatbacks, spare tire cover, engine and transmission cover
Mitsubishi	Concept Car	Bamboo	PBS	Interior components
Peugeot	406	Hemp, Flax	PP, PUR	Seat backs, parcel shelf
Renault	Clio, Twingo	Jute, Coir	PP, PUR	Rear parcel shelf
SAAB	9S	Flax	PP	Spare wheel, door panels
Toyota	Lexus CT 200h, Prius, Raum	Kenaf, Bamboo, Corn, Starch	PET, Sorona® EP, PP, PLA	Luggage-compartment, speakers, floor mats, Instrument-panel, air-conditioning vent, spare tire cover, shelves
Volkswagen	Golf, Passat, Bora, Touareg	Flax	PP	Door panel, seat back, boot lid finish panel, boot liner
Volvo	C70, V70	Flax	Polyester	Seat padding, natural foams

2.1 Sustainable Composites Manufacturing Techniques for EV Application

2.1.1 Resin Transfer Molding (RTM)

To produce high-performance composite parts, one option is the low-pressure, closed molding method known as resin transfer molding (RTM). To impregnate the fiber reinforcement, resin is injected into a closed mold. The method's capacity to manufacture intricate forms with superior surface treatments, qualities crucial to the aerodynamics and aesthetics of EVs, has propelled it to the forefront of the EV industry. To meet the varied demands of the automobile industry, RTM has progressed with innovations such as Light RTM and High-Pressure RTM (HP-RTM). For example, HP-faster RTM's cycle times make it ideal for mass production. RTM is a greener alternative to open mold methods. During the process less resin overflows, which means less waste and decreased emission of volatile organic compounds (VOCs). This procedure is even more eco-friendly because it can employ natural fibers and resins that come from plants. Structural components such as battery enclosures and chassis elements are the most common uses in electric vehicles [24,25]. Composite materials offer these components a significant advantage due to their excellent strength-to-weight ratio. The usage of RTM in the manufacturing of battery housings for a prominent EV producer is one prime example. To produce a one-piece enclosure that is much lighter than conventional metal enclosures, RTM processes can be used. Both the vehicle’s range and efficiency can be enhanced by reducing the overall weight. The battery container is made safer by incorporating fire-retardant polymers and strengthened fibers throughout the RTM process. In addition, the production method can be in line with the company's sustainability goals due to the reduced waste and lower VOC emissions.

2.1.2 Vacuum Assisted Resin Transfer Molding (VARTM)

The vacuum-assisted resin transfer molding (VARTM) technique is an expansion of the RTM process. The new and enhanced vacuum technology and more efficient resin systems have made VARTM an ideal choice for complicated and large-scale applications. While VARTM and RTM are comparable, the former permits lower injection pressures, which is useful when working with complicated or big molds. When compared to high-pressure options, this method is better for the environment because it uses less energy and produces fewer emissions. The VARTM process is more environmentally friendly since it is controlled, which reduces waste and improves the resin-to-fiber ratio [26]. VARTM is perfect for making lightweight electric vehicle chassis components because of its capacity to construct big, complete structures. These parts help reduce the vehicle's overall weight, which in turn increases the effectiveness of the battery and the distance it can travel. To optimize electric vehicle performance and battery efficiency, a lightweight chassis is essential. Lightweight chassis components have been made possible with the use of VARTM. An integral part of electric vehicles' dynamic performance is their high strength-to-weight ratio, which is made possible by allowing the fabrication of a sophisticated and integrated structure [27]. The vehicle's overall weight can be reduced using VARTM, which leads to better battery efficiency and an increased driving range. By reducing energy consumption and material waste, the approach can lower the environmental footprint compared to standard manufacturing processes [28,29].

2.1.3 3D Printing with Sustainable Materials

A composite part for an electric vehicle can be mass-produced with the help of 3D printing, also known as additive manufacturing. Small-batch production is ideal for this technology because of its waste-minimizing capabilities in creating complex geometries. New developments in 3D printing technology have allowed for the incorporation of continuous fibers into thermoplastics, increasing their strength and stiffness. In keeping with its environmental objectives, the electric vehicle industry uses sustainable materials such as natural fiber reinforcements, bio-based polymers, and recycled plastics [30]. The additive aspect of 3D printing helps to decrease waste and maximize resource utilization, which in turn reduces the carbon footprint of component manufacturing. Without the need for costly mold changes, manufacturers can customize components for individual applications. Prototyping and creating new electric vehicle models rely heavily on this adaptability, which speeds up the innovation process. In addition to drastically cutting down on waste, 3D printing's layer-by-layer construction method guarantees that material is only utilized where it is truly needed [31]. Combining 3D printing with sustainable materials allows for rapid prototyping and customization, making it perfect for designing new EV components. By utilizing bio-based composites and recycled plastics, the EV industry can prove to be environmentally friendly. 3D printing not only reduces the time to design and test vehicles, but it also demonstrates how the automotive industry might reduce its negative effects on the environment. 3D printing with recycled materials demonstrates a circular economy strategy, which supports environmental responsibility in the automotive industry [32].

2.1.4 Autoclave and Out-of-Autoclave Techniques

Autoclave and out-of-autoclave (OOA) are processes used to cure composite materials under controlled temperature and pressure. Autoclaves are essentially pressure vessels that provide a high-quality finish and high fiber volume contents, ideal for structural components of EVs. However, they are energy-intensive and can be costly. OOA techniques, on the other hand, have been developed to reduce energy consumption and process costs, making them increasingly popular for larger components such as body panels. OOA processes are gaining importance in the EV manufacturing sector due to their lower energy requirements and reduced environmental impact. They also offer greater flexibility in terms of the size and shape of components that can be produced, compared to autoclaves. Both autoclave and OOA techniques are crucial in the manufacturing of high-performance composite parts for EVs.

2.2 Technologies Enhancing Sustainable Manufacturing in EV Production

Electric vehicle manufacturers are putting more effort into environmentally friendly production methods by using a range of cutting-edge technologies. Minimizing environmental effects, optimizing resource utilization, and promoting energy efficiency are the goals of these technologies. To improve sustainable manufacturing in the production of electric vehicles, some of the important technologies recently being used are listed below. The integration of these technologies into EV production is a giant leap forward in the direction of greener production methods. In addition to helping the environment, they improve efficiency, cut costs, and encourage new ideas in the automotive business.

2.2.1 Renewable Energy Integration

Solar and wind power are becoming more attractive in powering manufacturing plants. This change is in line with international initiatives to fight climate change and lessen the environmental impact of electric vehicle production. Sustainable production also includes using renewable energy sources during production. To lessen the environmental impact of their factories, more and more EV manufacturers are turning to renewable energy sources including solar, wind, and hydropower. The overall decrease of greenhouse gas emissions linked to EV production is considerably facilitated by this strategy. Sustainable manufacturing in the electric vehicle business is being advanced by integrating AI and automation, developing innovative material technologies, and using renewable energy. In addition to helping achieve the larger environmental objectives of decreasing emissions and increasing the use of renewable resources, these technologies improve the sustainability and efficiency of production operations.

2.2.2 Robotics and Automation

Automated systems and robotics in production lines increase efficiency and precision. By making better use of resources (both material and energy), they lessen waste as well. Better automobiles with less impact on the environment are a result of these technological advancements. Robotic arms, automated cutting systems, and quality control based on sensors are all part of the automation process in composite production. By improving repeatability and decreasing room for human mistakes, these technologies help make production more efficient. To keep up with the ever-increasing demand for EVs while minimizing environmental impact, automation is also crucial.

2.2.3 Machine Learning (ML) and Artificial Intelligence (AI)

ML and AI are utilized for industrial process optimization, quality control, and predictive maintenance. Improved overall sustainability is a result of their contributions to less downtime, higher product quality, and less resource consumption. To improve environmentally friendly production methods, automation and AI are becoming more important. AI algorithms are used in EV composite manufacturing to optimize material utilization, forecast how composite materials will behave under various conditions, and improve the accuracy and efficiency of production lines. Optimization of RTM and VARTM settings is possible with the help of AI-driven systems that sift through numbers of data. These systems provide constant quality while reducing energy consumption and material waste by forecasting the best resin flow pathways, curing durations, and pressure conditions.

2.2.4 Eco-Friendly or Sustainable Components

Electric vehicle manufacturing is increasingly using eco-friendly, recyclable, and lightweight components. Vehicles made with these materials are more efficient and have less effect on the environment [8]. To achieve sustainability in electric vehicle production, it is crucial to create novel composite materials. A lot of people are working on producing materials that are stronger, lighter, and made from renewable or recycled materials. Some of the examples of these advanced composites are natural fiber composites and carbon fiber reinforced plastics (CFRP). The overall weight of electric vehicles can be reduced with the help of CFRPs because of their low weight and strong strength and stiffness [33]. Moreover, natural fiber composites are making a significant impact since they are renewable and have a smaller carbon footprint. Modern advancements in the field have led to bio-based resins and the use of nanomaterials, such as carbon nanotubes and graphene, which improve the mechanical characteristics of composites. To achieve the electric vehicle industry's performance targets while also protecting the environment, these innovations are essential.

2.3 Examining the use of Sustainable Materials in Composite Manufacturing

The electric vehicle industry sees biocomposites as a type of material that combines renewable or biological fibers with a polymer matrix as a viable, eco-friendly substitute for conventional composites. A rising awareness of the need to lessen the negative effects of cars on the environment, both during their usage and their production and disposal, is propelling the incorporation of biocomposites into electric vehicles. A growing number of EVs are being made using biocomposites, a sustainable material that combines natural fibers with a polymer matrix [34]. The reduced environmental effect, increased strength, and reduced weight make these biocomposites highly desirable. Some biocomposites that are being considered for use in electric vehicles are natural fiber-reinforced composites, wood polymer composites, cellulose/lignin-based composites, bio-resin composites, and recycled composites.

Biocomposites are made by combining natural fibers with a polymer matrix. The lightweight, strong, and environmentally friendly nature of these biocomposites makes them highly desirable [35]. Wood plastic composites are manufactured by combining wood fibers or wood grain with polymers. In interior applications such as trim elements and paneling, they are excellent because they offer a good balance between the mechanical qualities and the weight of the material [36]. These composite materials are both durable and lightweight, and they are derived from cellulose fibers. It is possible to utilize them in a variety of interior components, and in some cases, they can even be used in structural applications. Components made of composites can benefit from the utilization of lignin, which is a byproduct of the paper industry. These composites are not harmful to the environment and can be developed for the use in a variety of applications within electric vehicles [31]. These are composites in which the matrix is manufactured from bio-based resins, which are derived from plants or other renewable resources, rather than polymers that are derived from petroleum. They can be used in biocomposites that are completely sustainable when coupled with natural fibers [37,38]. Materials that are both renewable and biodegradable are used for manufacturing EVs. In the case of non-structural components, for instance, a green composite can be created by combining natural fibers with a matrix that is based on starch [39]. The production of EVs is becoming increasingly environmentally friendly, and recycled composites play a crucial part in this. The utilization of recycled composites contributes to the reduction of waste, the reduction of the carbon footprint, and the conservation of resources as the automobile industry moves toward more environmentally friendly methods [40].

Recycled composites are gaining significance in a variety of industries, including the building industry, the aerospace industry, and the automotive industry, because of the environmental benefits they offer and the growing demand for materials that are sustainable. In most cases, these composites are made up of a polymer matrix that is reinforced with recycled fibers or fillers. Recycled CFRP is becoming increasingly popular in the electric vehicle production industry due to the excellent strength-to-weight ratio it possesses. Carbon fibers that have been recovered can be recycled and employed in the production of new composite materials [41,42]. GFRP, which is comparable to carbon fiber reinforced plastic, is capable of being recycled and utilized in a variety of automotive applications. Glass fibers that have been recycled retain a significant amount of strength and are typically more affordable than carbon fibers [43]. When compared to thermosets, thermoplastic composites are more easily recyclable than thermoset composites. As a result of their ability to melt and remold, they are useful for a variety of uses in electric vehicles [44]. To reduce weight without sacrificing strength, recycled composites are utilized in the production of non-structural body panels as well as some structural components. It is possible to construct components of the car, including dashboards, door panels, and seat frames, out of recycled composites, which contributes to the overall sustainability of the vehicle [45]. The use of recycled composites for protective underbody pieces and battery casings helps to reduce the overall weight of the vehicle, which in turn increases its range and efficiency. Certain manufacturers are investigating the possibility of incorporating recycled composites into the construction of wheels and suspension components to lessen their overall weight and improve their overall performance. One of the most important strategies for lowering the environmental effect of the automotive industry is the utilization of recycled composites in the production of EVs [29,46,47]. It is anticipated that these materials will become more widespread as technology continues to evolve, which will contribute to the development of automobiles that are more sustainable and environmentally friendly [48-50]. Fig. 1 illustrates the evolving advanced manufacturing strategy in lightweighting, with a specific focus on EV technology [47].

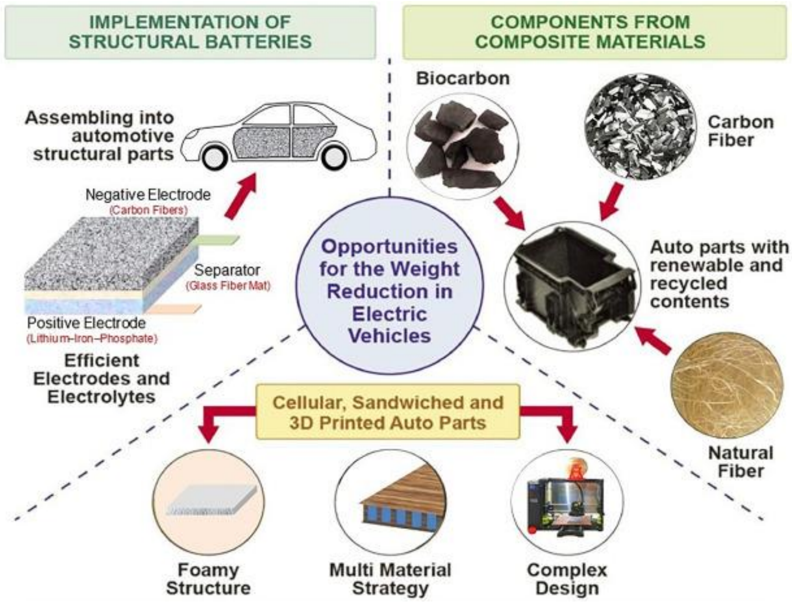

Fig. 1 Illustration of advanced lightweight composites manufacturing strategy for EV components [47]

3. IMPORTANCE OF WEIGHT REDUCTION IN EVS AND THE ROLE OF LIGHTWEIGHT COMPOSITES

Weight reduction in EVs is an essential factor that has a direct impact on the efficiency, performance, and overall sustainability of these vehicles. It is becoming increasingly important that lightweight composites play a part in attaining this weight reduction. This is because these materials give the same level of strength and durability as traditional materials, but at a weight that is far lower. One of the most significant advantages of lowering the weight of an electric vehicle is the increased driving range it provides [51,52]. Considering that bigger vehicles take more energy to move, it follows that a heavier electric vehicle will have its battery depleted more quickly than a lighter one. By decreasing the weight of the vehicle, energy efficiency can be enhanced, which in turn leads to an increase in the number of miles driven on a single charge [53,54].

Decreased weight results in improved acceleration and handling characteristics for the vehicle. This is of utmost significance for EVs, as the instant torque that is supplied by electric motors can be utilized more effectively with a chassis that is lighter, which ultimately results in superior vehicle dynamics. The operation of a lighter vehicle takes less energy, which can lead to the development of battery designs that are both more compact and more efficient. In addition to lowering the price of the battery, this also lessens the negative impact on the environment that is caused by the manufacturing and disposal of electrical batteries. While it is essential to accomplish weight reduction, it is of utmost importance to preserve structural integrity and safety. Composites that are lightweight offer good strength-to-weight ratios, which ensures that the safety of the vehicle is not compromised in the search of reduced weight [55–57]. The components of lighter vehicles, such as brakes and tires, are subjected to less stress, which results in less wear and tear and lower maintenance expenses over the course of the vehicle's lifetime [58,59].

The global lightweight materials market was valued at USD 113.8 billion in 2016 and was expected to grow at a CAGR of 8.9% from 2017 to 2024. Automotive manufacturers are switching to lightweight materials to reduce vehicle weight and fuel emissions, driving market growth. North America is a key market due to the presence of major auto manufacturers and renewable energy equipment manufacturers. The market is segmented by product (aluminum, high strength steel, titanium, magnesium, polymers, composites, others), application (automotive, aviation, energy, other), and region (North America, Europe, Asia Pacific, Latin America, Middle East, Africa) [60]. Fig. 2 shows the market size with respect to the production of lightweight materials in North America from 2013 to 2024 [61].

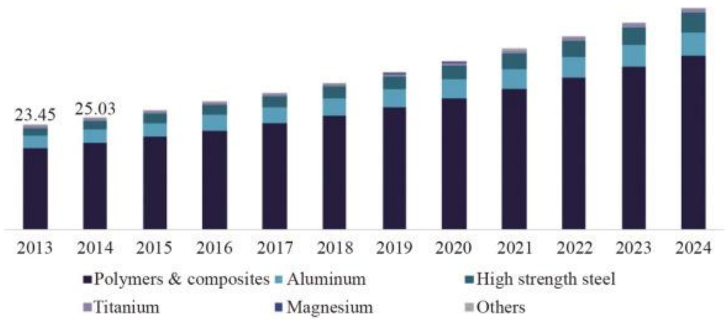

Fig. 2 Market of lightweight materials in North America from 2013 to 2024 [61]

3.1 Role of Lightweight Composites in EVs

The development and production of electric cars are both significantly aided by the utilization of lightweight composites EVs. The performance, efficiency, and general sustainability of electric vehicles can all be significantly improved with the help of these materials [62,63]. Many different aspects can be used to understand the role that lightweight composites play in electric vehicles. Composite materials that are lightweight and used in electric vehicles often consist of high-strength fibers such as carbon or glass that are placed in a polymer matrix. Strength, rigidity, and lightness are all characteristics that these materials possess in remarkable proportions [64,65]. There are several components of electric vehicles that make use of composites. These components include body panels, chassis components, and even structural frames in some cases. By utilizing them, the overall weight of the vehicle is greatly reduced, and this is accomplished without sacrificing either its longevity or its performance [66,67]. Lightweight composites are also utilized in the construction of protective structures and housings for batteries. They offer the essential protection for the battery pack while making a negligible contribution to the overall weight of the vehicle [24,25]. Processes such as RTM, compression molding, and automated layup procedures are being refined for mass production as the fabrication of composite materials continues to undergo technological advancements. Composite components are becoming increasingly practical for broad usage in electric vehicles because of this innovation in manufacturing, which helps to reduce the cost of composite components [61,68]. The thermal properties of composites can be tailored to be advantageous, which is vital for EVs because effective thermal management of electric motors and batteries is essential for achieving maximum possible performance [61,69]. Moreover, the aesthetic and design of EVs affect the overall economy of the vehicle, while the versatility of composites in terms of molding and shaping makes it possible to create unique vehicle designs that are not only visually beautiful but also aerodynamically efficient [70].

4. Applications in Electric Vehicles and Influencing Factors

In EVs, sustainable composite materials made of natural fibers incorporated in a polymer matrix have multiple possible applications. Their meteoric rise to the top of the automotive industry is largely attributable to their low weight, great mechanical features, and acceptance to the environment. Electric vehicles often use sustainable composites for interior components such as door panels, dashboards, and seat frames [71,72]. Because of their reasonable mechanical properties, light weight, and natural look, biocomposites are perfect for various applications. Bumpers, body panels, and other exterior components made of biocomposites are still the subject of active research. Problems with durability, longevity, and weather resistance are being addressed by new materials, hybrid composites as well as nanocomposites [73]. For non-essential construction components, biocomposites offer a strong and lightweight alternative [74,75]. Their application in structural sections is still in its early stages of development, but the present focus is on improving their load-bearing capacity and impact resistance. By decreasing their total weight, biocomposites aid electric vehicles in achieving higher energy efficiency and longer driving ranges. The acoustic and thermal insulation properties of natural fibers are unparalleled. Biocomposites provide a sustainable solution for the electric vehicle sector that is in line with global efforts to reduce environmental impacts throughout the vehicle's lifecycle. Biocomposites have great potential to revolutionize environmentally friendly transportation, even though there are still certain challenges to be solved [76,77]. As a result of continuous research and development and industry collaboration, sustainable composites may one day completely transform the manufacturing process for electric vehicles.

The initial generations of commercial EVs focused mostly on modifying existing vehicle chassis with battery systems. Recent EVs include evolving structural designs that are specifically engineered to operate only on battery power from their inception. This design flexibility has led to new potential for polymer composites, including glass-reinforced polyurethanes as reduced weight substitutes for metal components. EV designs employ predominantly linear components in their structure, making them well-suited for the utilization of polymer composites. The incorporation of novel technology and content continuously enhances the total curb weight of motor vehicles. Thermoplastic materials provide a favorable combination of robust structural integrity and reduced density. The detailed discussion of EV part applications and influencing factors will be presented in the upcoming sections.

4.1 Battery Cell Separators

The enhancement of lithium-ion battery performance is a matter of utmost importance, and there is currently a renewed focus on the development of superior membranes to achieve this goal. The Lithium-ion Battery Separator (LiBS) is a permeable membrane inserted between a battery anode and cathode. The primary purpose of this EV component is to maintain a sufficient distance between the two electrodes to prevent any electrical short circuits, while simultaneously facilitating the movement of ions for the purpose of both charging and discharging. It is the most crucial electric car component in evaluating battery stability as well as safety. UHMW-PE finds its best grade suitable for LiBS in the EV industry.

4.2 High Voltage Battery

High voltage traction batteries are the essential source of power for electric propulsion in the automobile sector. They satisfy numerous criteria to offer dependable lifetime operation, including high voltage/current protection and electrical insulation, thermal propagation protection and flame retardancy, thermal shock and crash resistance. In the present day, batteries in EVs can enhance overall durability, lightweighting, connectivity, safety and range. HTN and PA, polybutylene terephthalate (PBT) and polyphenylene sulfide (PPS) serve as effective polymers for EVs due to their exceptional electrical insulation, together with superior flame retardancy and thermal shock resistance [78]. Various thermoplastic materials are additionally utilized for weight reduction and crash resistance of the battery unit [79]. Continuous fiber reinforced thermoplastics, when combined with long fiber reinforced thermoplastics (LFRT), offer superior toughness, stiffness, and strength while achieving maximum weight loss [68]. Battery components utilize materials that function as electrical insulators or facilitate heat transmission. Hybrid designs integrate materials with distinct qualities into a single component, resulting in reduced weight and cost constraints. Polymeric materials provide the necessary characteristics to meet essential criteria for dependable applications, such as flame retardance and thermal expansion, maintain their shape, exhibit high rigidity even with thin walls, withstand thermal shock and hydrolysis resistance.

Due to the growing interest in hybrid cars, the incorporation of a Battery Management System (BMS) has emerged as a vital component [80]. The objectives of BMS are to optimize the duration of each discharge cycle and maximize the total number of usable battery life cycles. The management of automotive batteries is challenging due to the necessity of real-time operation under rapidly fluctuating charge-discharge circumstances, such as during vehicle acceleration and break, in a hostile and unregulated environment. Furthermore, it is imperative that it establishes a connection with other systems integrated within the vehicle, including the engine management, temperature controls, communications, and safety systems. BMS consists of three primary components: the sensor system, the control unit, and the switching unit. BMS actively maintains uniform voltage or State of Charge across all the battery cells to optimize capacity and prevent localized under-charging or over-charging. This is achieved through a process called balancing. EV battery unit designs have modules that store energy and have their own cooling systems. These modules serve separate purposes, including structural and electrical operations, and are mounted into the vehicle body without prioritizing structural strength. This strategy would effectively tackle issues related to cell cooling, system assembly, chemical bonding performance, safety, and sustainability. A novel prototype of an All-in-one battery module utilizes tab cooling, structural thermoplastic cooling channels, and an electrical connecting plate to accomplish this. This provides advantages in terms of increased range, integration of components, and enhanced thermal management.

4.3 Battery Coolant Hoses and Quick Connectors

A variety of components are specifically engineered to enhance the longevity and safety of EVs and other automobiles by facilitating efficient management of automotive fluids. Polymeric materials exhibit enduring chemical resistance and efficient fluid control, even when exposed to water, glycol, auto gearbox fluids and dielectric fluids. Both internal and exterior EV battery systems need a variety of coolant hoses with different levels of flexibility, ranging from flexible to semi-stiff and stiff. These hoses must be able to function efficiently in under-hood settings with lower temperatures (30-90ºC) and reduced pressure [78]. Thermoplastic vulcanizate (TPV) enables the production of coolant system hoses and tubes for electric vehicles that offer enhanced durability, reduced weight, and cheaper prices compared to systems made from ethylene propylene diene monomer (EPDM) rubber, polyamide (PA) materials, and polyphenylene sulfide (PPS) alternatives [81]. In addition, the utilization of TPV provides distinct sustainability benefits due to its recyclability during the manufacturing process and at the conclusion of its lifespan. Long-chain polyamides have exceptional resistance to hydrolysis at high temperatures. If employed with thermoplastic olefins such as TPV EPDM/PP, they provide significant flexibility for both mono- and multi-layer tubing, serving as substitutes for metal pipes and EPDM rubber cooling lines. Ethylene acrylic elastomers (AEM) are a proven elastomer solution for high-temperature and flexible oil cooler hoses and seals and are compatible with numerous types of oils, including new EV fluids. Fluid management lines can be complemented with quick connections that are constructed using strong materials such as glass fiber reinforced nylon (PA66 GF), high-temperature nylon (HTN), glass fiber reinforced polyphthalamides (PPA GF), or glass fiber reinforced long chain polyamides (LCPA GF). These connectors provide a fully integrated polymer solution.

4.4 Power Electronics

Inverters convert DC, generated by a Lithium-ion battery, into AC to power electric traction motors. High-voltage converters reduce the voltage of the battery to supply power to various systems in the automobile, including entertainment and safety systems. They also convert DC from a high level (e.g. HV Lithium-ion battery) to a lower level (e.g. 12V battery). These processes cause energy losses which are transformed into heat. Plastic insulating components used in power electronics must be able to endure elevated temperatures while maintaining their insulation qualities over the whole temperature range.

PPS and PBT have outstanding electric insulating properties, including dielectric strength, surface and volume resistivity at elevated temperatures. The present process of inversion and conversion generates electromagnetic fields that have the potential to damage delicate onboard devices. Current inverter and converter housings are manufactured of aluminum to hide these electro-magnetic forces. Diverse plastic and plastic/metal composite options are available for electric cars, such as LFRT steel fiber polymers or metal coated polymers. These options meet EMI standards and provide significant reductions in weight.

4.5 HV Connectors

Automotive electric engines work on high electric currents and voltages up to 800V with estimates for even greater voltages in future generations [78]. Connectors utilized in high voltage electrical circuits must include reliable insulation to prevent short circuits and dangerous fires. PA, PPS, and PBT possess exceptional insulating characteristics that fulfil the demands of HV connections, such as elevated CTI, superior dielectric strength, flame resistance, remarkable rigidity, durability, and color persistence. Special grades PA with low acidic content, which avoids corrosion of the soft sealings, is used in connection with high voltage connectors.

4.6 Traction E-Motor

To enhance the comfort and efficiency of existing automobiles, future mobility models need a higher quantity of electric motors. Materials utilized in under-the-hood applications must possess the ability to endure demanding circumstances without compromising safety, quality, or service life. High-performance polymers offer enhanced efficiency, particularly in compact motors, enabling manufacturers to decrease both cost and weight. PPS, PA, and liquid crystal polymer (LCP) grades are components of an extensive range of polymers designed for use in extremely elevated temperature and chemical environments [78].

4.7 Thermal Management

The thermal management system of electric cars is crucial, since it directly impacts the performance and durability of key components, including battery cells, power electronics, and traction motors. The fundamental components of thermal management systems in electric cars closely resemble those found in combustion engines. Hybrid cars incorporate a fusion of both. The need for connections with high-performance engineered materials such as PPS, HTN, and PA is driven by the need to withstand cooling agents, meet extended lifespan requirements, and achieve high accuracy in coolant pumps, impellers, and thermostat housings [78]. TPV is very compatible with tubes and hoses utilized in the thermal management systems of contemporary EVs.

4.8 Noise, Vibration and Hardness (NVH)

EVs offer a smoother and more comfortable journey experience. The issue is in the absence of engine noise, which often serves to conceal the various squeaks, rattles, and buzzes. Consequently, the formerly serene ride becomes increasingly boisterous and disruptive. Efficiently addressing NVH (noise, vibration, and harshness) can effectively mitigate this problem, hence enhancing the overall experience for both the driver and passengers. Many sophisticated materials, such as Zytel NVH Gen 2, which have been demonstrated to effectively diminish noise and vibration in applications such as engine mounts, offer superior dampening properties.

5. Environmental Impact and Life Cycle Assessment

Nowadays automobile industries are focusing on zero-emission transport techniques to combat climate change, which can be achieved using EVs. EVs are considered due to reduced greenhouse gas emission which is directly correlated to the environmental impact. By using EVs powered by renewables, the emission of CO_2 can be reduced by 80 % as compared to fossil-generated electricity [82]. A traditional diesel/petrol-powered vehicle emits 233.5 % more CO_2 when compared to renewables-powered EVs [82]. The electricity mix significantly influences EV emissions, making them carbon-neutral in jurisdictions such as Costa Rica with entirely renewable electricity generation. Despite lower Global Warming Potential (GWP), EVs exhibit higher Human Toxicity Potential (HTP) and Particulate Matter Formation Potential (PMFP) during battery manufacturing and disposal [83]. Factors such as increased vehicle weight, high torque, and accelerated tire wear contribute to environmental concerns, including particulate pollution and ocean plastic waste. Additionally, the disposal of Li-ion batteries poses environmental and safety risks. The life cycle impact of EVs is also influenced by climatic conditions, energy consumption variations due to heating or cooling requirements, assumed lifespan, and the local electricity mix. Therefore, understanding the environmental impacts of EVs requires considering a combination of factors such as jurisdiction-specific conditions, electricity sources, charging times, and lightweight strategies. Table 2 presents the environmental impact of EVs in certain jurisdictions.

Table 2 Environmental impact potential of electric vehicles in substantial jurisdictions [15]; GWP: global warming potential; AP: acidification potential; HTP: human toxicity potential (non-carcinogenic); PMFP: particulate matter formation potential; *kg PM2.5 eq./km

Jurisdiction	Engine power	Vehicle weight, kg	Battery weight, kg	GWP, kg CO_2 eq./ km	AP, kg SO_2 eq	HTP, kg 1,4-DCB eq./ km	PMFP, kg PM10 eq./ km
Germany	100 kW	1615.0	–	0.140	–	0.738	0.0004*
Czech Rep./ Poland	2.1 kWh	1180.22	262.0	0.214	0.001	0.306	0.0004
Canada	–	–	312.0	0.160	0.001	0.260	–
Canada	(petrol)	–	–	0.254	–	0.045	–
Czech Rep./ Poland	1400 cc, petrol	1200.0	–	0.284	0.001	0.085	0.0003

Environmental advantages of eco-friendly composites for EVs can be easily accessed using life cycle analysis. China, as the world's largest carbon dioxide emitter, has been dealing with energy and environmental problems and has implemented policies and financial incentives to promote the development of EVs [84]. Researchers have conducted a comparative life cycle assessment of various fueled vehicles, including internal combustion engine vehicles, hybrid electric vehicles, and electric vehicles, to evaluate their environmental impact [85]. Seven different environmental impact categories were considered, including abiotic depletion, acidification, eutrophication, global warming, human toxicity, ozone layer depletion, and terrestrial ecotoxicity. Electric and plug-in hybrid electric vehicles show higher human toxicity, terrestrial ecotoxicity, and acidification values due to manufacturing and maintenance phases. Hydrogen vehicles are found to be the most environmentally benign option due to their high energy density and low fuel consumption during operation [85]. The Eco-Indicator 99 impact assessment method is used, which includes human health and ecosystem quality as important indicators for decision-making regarding clean transportation vehicles [85]. Another work dealt with the development and utilization of new plant-fiber composite materials and microcellular foam molding processes for lightweight, low-carbon, and sustainable composites for automobiles. Life cycle assessment was conducted to investigate the resource and environmental impacts of plant-fiber composite material automotive components and microcellular foam molding processes. Electricity consumption was the largest influencing factor causing environmental issues throughout the life cycle, accounting for more than 42% of indicators such as ozone depletion, fossil resource consumption, and carbon dioxide emissions [86]. A typical life cycle of a vehicle technology can be divided into two primary stages: the fuel cycle and the vehicle cycle. The fuel cycle involves processes from feedstock production to the utilization of fuel in the vehicle [87]. Fig. 3 illustrates the life cycle analysis along with the environmental impact assessment of fuel and vehicles [13].

Fig. 4 shows an overview of various impacts of internal combustion engine vehicles (ICEVs), hybrid electric vehicles (HEVs), and battery electric vehicles (BEVs) during LCA using the electricity mix of 2015 [88]. The analysis was done considering global warming, ionizing radiation, human carcinogenic toxicity, human non-carcinogenic toxicity, land use, and fossil resource scarcity. Li-ion batteries are one of the major concerns nowadays in the field of EVs. The most influential parameter when it comes to the environment is the use of EVs followed by production and transport.

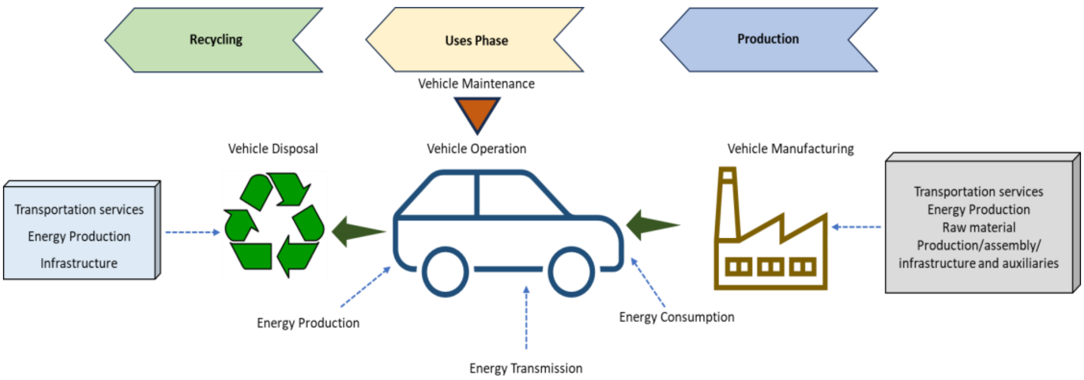

Fig. 3 Life cycle environmental impact assessment of fuel and vehicles

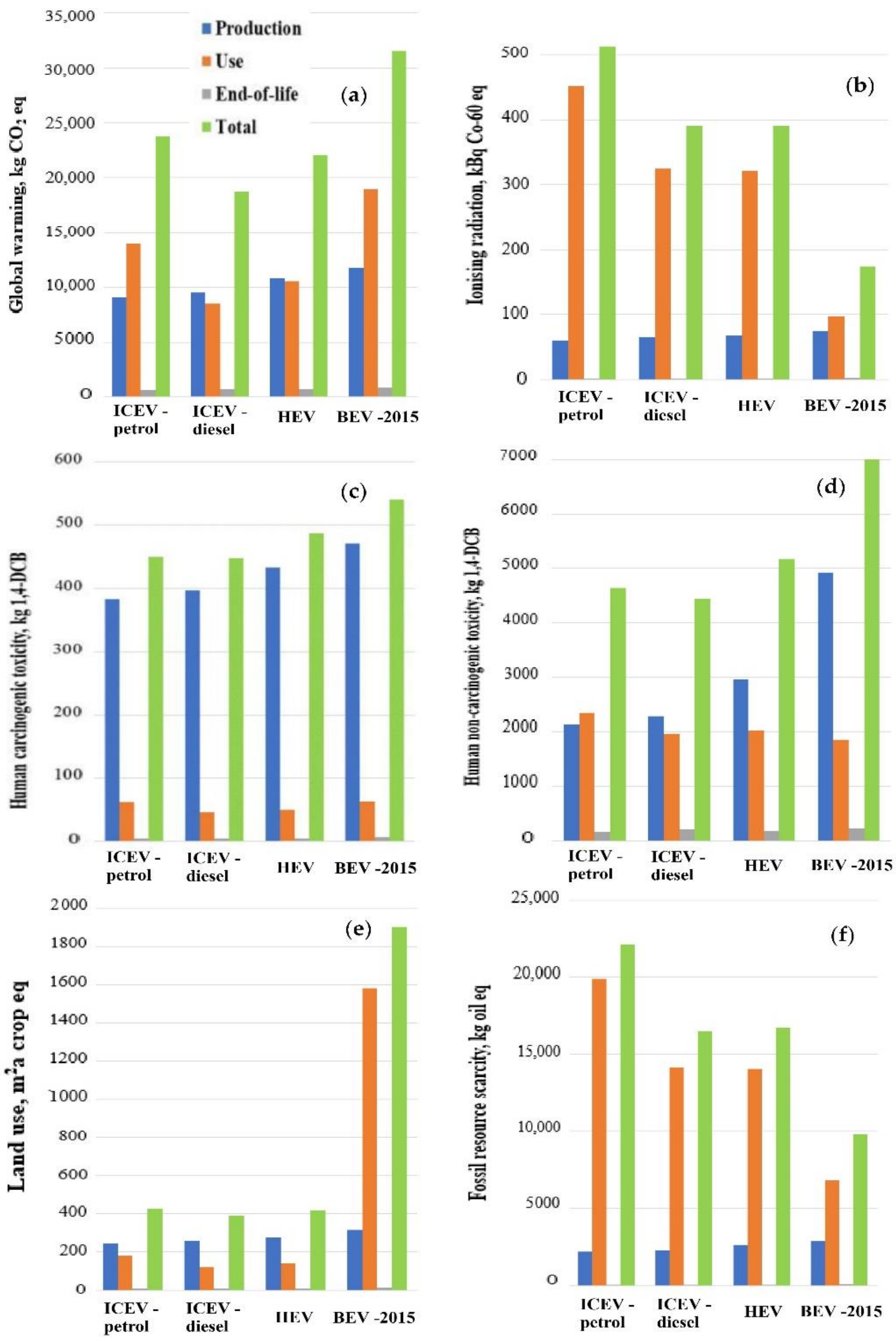

Fig. 4 Impact of (a) global warming, (b) ionizing radiation, (c) human carcinogenic toxicity, (d) human non-carcinogenic toxicity, (e) land use, (f) fossil resource scarcity during LCA (electricity mix of 2015) for ICEVs, HEV, and BEV [88]

6. Market Trends and Economic Viability

The electric vehicle market is a highly dynamic sector within the dominion of clean energy. In 2021, the sales of EVs experienced a remarkable doubling from the previous year, reaching a new record of 6.6 million units. To put this into perspective, back in 2012, the global sales of electric cars amounted to a mere 120,000. Fast forward to 2021, and we now witness over 120,000 electric cars sold each week. This surge in popularity translated into nearly 10% of all global car sales being electric in 2021, a staggering fourfold increase from the market share observed in 2019. Consequently, the number of electric cars traveling the world's roads has soared to approximately 16.5 million, a threefold increase compared to the 2018 figure. The momentum in global electric car sales has not slowed down in 2022, as the first quarter saw a robust performance with 2 million units sold, marking an impressive 75% increase from the same period in 2021 [89].

Several key factors have contributed to the success of EVs. Foremost among them is the consistent support from policies that encourage their adoption. In 2021, public spending on subsidies and incentives for EVs nearly doubled, reaching close to USD 30 billion. Many countries have also committed to phasing out internal combustion engines or have set ambitious targets for vehicle electrification in the coming years. Moreover, numerous car manufacturers have gone beyond policy requirements and are actively electrifying their fleets. Furthermore, the availability of electric vehicle models has significantly expanded, with five times more models on the market in 2021 compared to 2015, enhancing their appeal to consumers. Currently, there are around 450 electric vehicle models available [89,90].

China stands out as a major driving force behind the surge in EV sales in 2021, accounting for half of the global growth. China's 2021 sales alone (3.3 million) exceeded the total global sales in 2020. China included new energy vehicles in its national "863" plan in 2001 and launched the "major science and technology project of EVs" to kickstart EV research and development [91]. The Chinese government has been promoting the use of EVs since the 12th Five-Year Plan (2010-2015) to make travel cleaner. However, the economic crisis has affected people's recognition and acceptance of EVs, hindering their early market diffusion. Europe also witnessed strong growth, with sales increasing by 65% to reach 2.3 million units, following a similar boom in 2020. Even in the United States, where sales had experienced a decline for two consecutive years, there was an uptick, reaching 630,000 units. The trends observed in the first quarter of 2022 closely mirrored these patterns, with China leading global growth with more than a doubling of sales compared to the same period in 2021, a 60% increase in the United States, and a 25% increase in Europe. Despite a challenging year for the car market in 2020, the sales of electric vehicles, including battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs), nearly doubled in 2021, reaching a total of 6.6 million units (Fig. 5). This substantial growth raised the overall number of electric cars in circulation to over 16.5 million. Similar to previous years, BEVs continued to dominate the increase, representing approximately 70% of the total.

On the flip side, electric vehicle sales are lagging in other emerging and developing economies, primarily due to the limited availability of affordable models for mass-market consumers. In countries such as Brazil, India, and Indonesia, electric cars constitute less than 0.5% of total car sales. Nevertheless, there are promising signs of growth in several regions, including India, where EV sales doubled in 2021. With the right investments and supportive policies in place, these regions could potentially experience accelerated EV market uptake by 2030 [89].

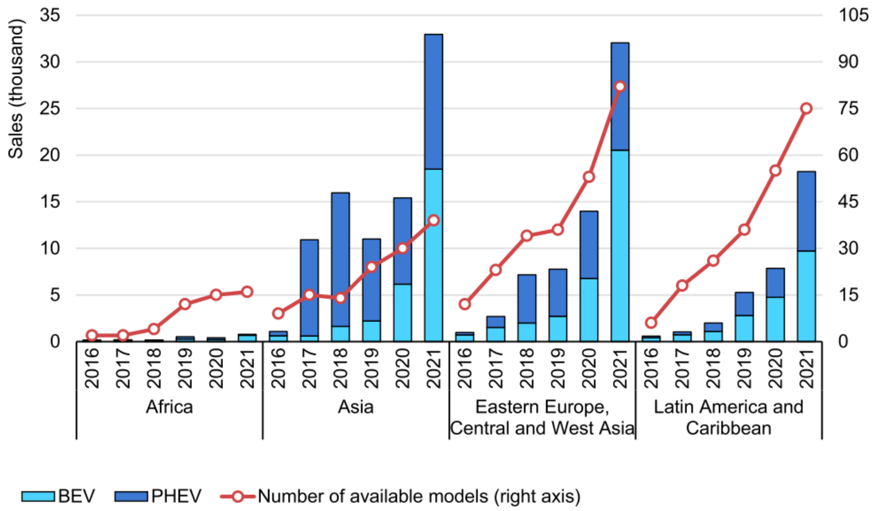

Fig. 5 Growth in EVs sale and model availability from 2016-2021. BEV: Battery Electric Vehicles; PHEV: Plug-in Hybrid Electric Vehicles [89]

The share of global EV battery production capacity reached 57 GWh in 2021. Assessing risks in high-capacity battery supply chains, as mandated by an executive order in early 2021, is highly required. The potential of vehicle-to-grid technologies, which allow EVs to contribute to grid stability and balancing needs, should be particularly exploited in countries falling under the case of increasing EV load with high variable renewables generation. It emphasizes the need for the development and deployment of smart chargers to enable EVs to participate in balancing the system and contribute to grid stability [89]. The automotive sector is facing challenges related to energy consumption and climate change, and reducing vehicle weight is crucial in addressing these challenges. A 10% decrease in curb weight can result in a 6-8% reduction in energy consumption. Composite materials with a high strength-to-weight ratio are considered a viable option for lightweight component design and manufacturing in the automobile sector. The use of composite materials in electric vehicles can reduce weight, improve aerodynamic properties, and decrease fuel consumption, leading to a reduction in harmful emissions and particulate matter [92].

The market trends and demand for sustainable composites in the electric vehicle sector are on the rise. The automotive industry is actively seeking ways to reduce the weight of vehicles in order to minimize energy consumption [92]. Composite materials, particularly fiber-reinforced polymers, have gained attention due to their high performance and lighter weight [93]. The use of composite materials in electric vehicles not only reduces weight but also improves aerodynamic properties, leading to decreased fuel consumption and emissions [94]. The demand for electric vehicles is increasing globally, driven by concerns about the environment and the depletion of fossil fuel reserves [95,96]. As a result, there is a growing need for sustainable materials in the electric vehicle market. The transition from internal combustion engines to electric vehicles is accelerating, creating a demand for efficient and powerful electric motors. Overall, the market for sustainable composites in the electric vehicle sector is expanding due to the push for cleaner and more sustainable transportation options.

7. Challenges and Innovations

Exploration of lightweight materials, such as carbon fiber, sustainable and advanced composites are required to improve energy efficiency and extend driving range. Challenges in EV production include thermal events associated with batteries and the increased overall weight, which can affect various performance factors of EVs. Strategies for addressing these challenges include securing the lithium supply chain, enhancing battery manufacturing hubs, creating new charging infrastructures, and establishing policy mandates towards zero emission transportation. The utilization of high-performance lightweight and sustainable composites with superior flame retardancy can help address the challenges of weight and thermal events in EVs. Lightweighting EV components can increase travel ranges, minimize crash impacts, lower braking distances, and reduce tire wear and tear [97,98]. Despite all these possible advancements, the cost of batteries remains a significant factor in the overall price of EVs, posing a challenge to widespread adoption. Ongoing research aims to enhance energy density, decrease charging time, and increase the lifespan of batteries, contributing to improved overall EV performance. Balancing the power capability and energy density in EVs batteries is equally significant. This has practical implications for EV manufacturers, as they need to optimize battery performance while considering factors such as cost and safety. Battery shortages, rising raw material costs, high demand from affluent buyers, and insufficient charging infrastructure contribute to the high cost of electric cars. For instance, the average price exceeds $66,000, making EVs a luxury item and largely inaccessible to the public in the US. Without price regulation or additional subsidies, widespread adoption remains a challenge [99]. The US government's ambitious goal of having 50% electric cars by 2030 requires a substantial infrastructure investment.

Furthermore, the expansion of the EV market necessitates the development of robust charging infrastructure and supportive government regulations [100]. In the US, the plan to spend $5 billion on 500,000 public charging stations falls short of the estimated 1.2 million needed, with an associated cost of $35 billion. Upgrading the power grid to support a rapid EV shift is another costly endeavor, impacting consumers through potential tax increases. Fig. 6 shows the geographical distribution of mineral resources related to battery manufacturing and its associated companies [101]. Computer simulation can play a crucial role in accelerating systematic battery design, which has practical implications for battery researchers and engineers. By using atomic-scale simulations and machine learning, battery materials can be selected and system designs can be optimized, reducing design cycles and improving battery performance [100]. Measuring and modeling complex material properties accurately in battery cells is useful for practical implications in battery design and testing. Accurate measurement and modeling of material properties are crucial for understanding battery failure mechanisms and improving battery safety. The potential cost reduction in battery technology is also possible by using high energy density materials and replacing expensive materials such as cobalt.

Fig. 6 Geographical distribution of mineral resources related to battery manufacturing and its associated companies. (A) countries with mineral resources, (B) countries with mineral resources and manufacturing companies, and (C) manufacturing countries [101]

The development of the charging infrastructure is another crucial part to address range anxiety and facilitate long-distance travel for EV users. Faster and more widespread charging infrastructure is required, including ultra-fast chargers, to reduce charging times and increase the appeal of EVs [15]. The driving range of EVs on a single charge remains a concern for potential buyers, especially in regions with limited charging infrastructure. Deploying smart energy management systems to optimize charging schedules, incorporate renewable energy sources, and minimize overall energy consumption is highly recommended. Establishing standardized technologies and charging protocols is essential to ensure interoperability and compatibility among various EV models and charging stations. Expanding the range of available EV models on the market is important to address diverse consumer preferences and needs. Standardized technologies and charging protocols are needed to ensure interoperability and compatibility across different EV models and charging stations. There is also a need to convince consumers so that they can shift from traditional internal combustion engine vehicles to EVs. The main concern of the consumers is related to charging accessibility, range, and initial costs. To make EVs more successful, consistent establishment, supportive policies and regulations including incentives, subsidies, and emission standards are required [102]. Also, increased awareness and understanding are also needed among consumers about the benefits, capabilities, and the evolving nature of the EV technology. Lastly, the environmental implications of battery disposal and the establishment of sustainable recycling practices for EV batteries constitute another crucial element of sustainable development that requires attention. Fig. 7 illustrates the model of an EV ecosystem, considering all the factors required for its advancements [103].

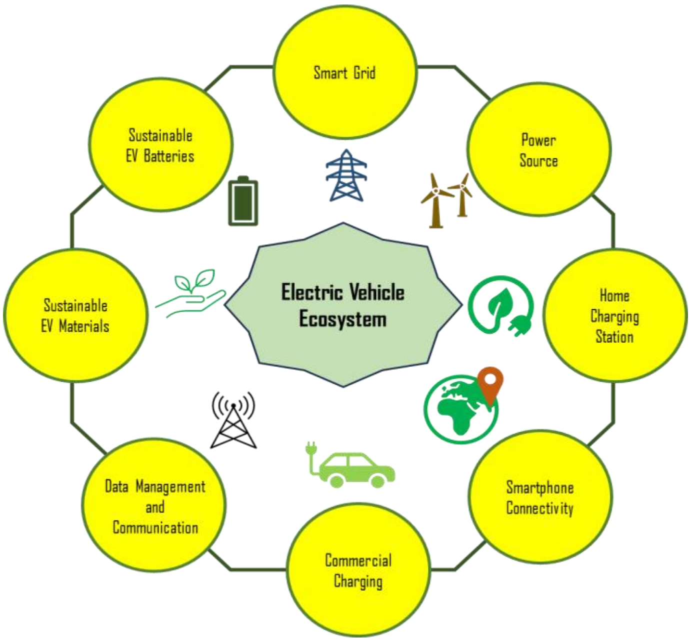

Fig. 7 Model of the EV ecosystem and advancements in the EV ecosystem along with its elements

8. Conclusions and Future Scope

Manufacturing EVs with sustainable composites is an intriguing new frontier that comes with its own set of problems. One reason composites are finding their way into electric vehicles is the demand for lighter materials, which can improve performance while cutting down on fuel usage. Sustainability, performance, and cost-effectiveness are all complicated issues that must be balanced. Several technical challenges remain in the way of sustainable composite manufacturing, notwithstanding considerable progress. Some of these obstacles include the fact that RTM and VARTM are not very scalable when it comes to mass production, maintaining quality across huge batches of products, and incorporating new materials into current production frameworks. One big obstacle is the economics of EVs. There is typically a significant up-front expense associated with sustainable materials and innovative manufacturing technology when contrasted with more conventional options. This may discourage broad use, especially in areas with less economic flexibility or among smaller producers. Another factor is the difficulty with availability and consistent quality due to supply chain complications. This is especially true for novel and inventive materials. It can be difficult for manufacturers and suppliers to work together efficiently due to the absence of industry-wide standards for sustainable materials and production techniques.

Sustainability in the production of EVs is an exciting and ever-changing topic. The production process is becoming more and more focused on sustainability as the demand for electric vehicles increases. We may anticipate that research into novel composite materials will persist, with an eye toward improving performance while decreasing the ecological footprint. Some examples of this include investigating novel material formulations, improving bio-based composites, and incorporating nanomaterials. New developments in manufacturing technology should solve the problems of scalability and cost-effectiveness that exist now. More sustainable and widely available composite components may soon be on the horizon, thanks to the developments in 3D printing, automated assembly, and AI-driven process optimization. Moving towards a model based on the circular economy will be a major trend in sustainable manufacturing going forward. This entails making items in a way that makes them easier to disassemble, recycle, or repurpose when their lifetime comes to a close. Making electric vehicles more recyclable and less harmful to the environment requires research into the development of composite materials and components. Moreover, thanks to major advances in material science and, particularly, in modeling tools [104], the adoption of active/smart structures, involving multifunctional materials such as piezoelectric materials, magnetostrictive materials and shape memory alloys, is expected to grow within the automotive industry, thus enhancing the safety, ergonomics, efficiency, and robustness of vehicle structures.

With the global trend towards more stringent environmental laws, the electric vehicle sector may witness a surge in efforts led by legislation that encourage sustainable behaviors. Incentives for sustainable material use, rules requiring manufacturers to cut emissions, and funding for sustainable technology research and development are all examples of what could fall under this category. Composites will have an even smaller environmental impact in the future as more and more factories switch to renewable energy. In line with the environmentally conscious character of EVs, solar, wind, and geothermal energy have the potential to become the go-to power sources for factories.

There are possibilities and threats at this crossroads in the sustainable composite production for the electric vehicle industry. Even though there are a lot of financial and technological hurdles that need to be overcome, there are some exciting developments coming up that might completely transform the sector. The future of electric vehicle production is looking brighter in terms of sustainability, thanks to the developments in materials science, production technology, energy consumption, the adoption of circular economy ideas, and enabling legislative frameworks. A more environmentally friendly and sustainable automotive future is within reach, thanks to this changing landscape and the thrilling potential it offers to industry stakeholders.

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