Review Article

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Applications of Nanotechnology in Electric Vehicles: Enhancing Energy Efficiency and Reducing Environmental Impact

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ABSTRACT

With an immediate global transition towards electric vehicles (EVs) to promote sustainable mobility, electronics has gained importance, which not only improves car performance but also mitigates people-induced environmental damage in the form of vehicular emissions. Nanotechnology has come forth as one of the transformative solutions, providing immense advancements in energy storage, structural materials, power electronics, and sustainable manufacturing technologies. This review aims to look into the diversified roles of nanomaterials in EV design and development, with a strong emphasis on lithium-ion batteries, as well as solid-state counterparts, supercapacitors and nanocomposites for weight reduction. It further emphasizes on the incorporation of nanotechnology in powertrain cooling systems, green synthesis processes and recycling mechanisms. In addition, this work covers safety, toxicity, and regulatory aspects, as well as the environmental advantages of nanotechnology as far as carbon attenuation is concerned. Real-world applications and future directions are illustrated through recent industry advances, case studies, and ongoing research. In summary, the review highlights the main challenges and opportunities in the journey towards energy-saving and eco-friendly electric vehicles of next generation, which are the focus of nanotechnology.

Keyword: Nanotechnology; Electric Vehicles (EVs); Energy storage; Nanomaterials; Sustainable transportation.

1. INTRODUCTION

1.1 Background on Electric Vehicles (EVs)

As there is a raise in fossil fuel dependency and in their environmental implications, electric vehicles (EVs) emerged as a possible remedy (Wang, 2023a). Improvement of energy density of batteries has become an ongoing agenda in order to increase the driving range of vehicles powered by batteries (Madrid, 2023; Sun *et al.* 2019). However, EVs also have some limitations including small range, long charging-duration, high prices etc. (Gnanavendan *et al.* 2024; Wang, 2023b). Researchers are working on other new materials to address these issues, including silicon anodes and solid-state electrolytes (Somashekarappa, 2019). The establishment of charging infrastructures and fast charging technologies is strongly acknowledged as a necessity for the mass adoption of EVs (Alperen and Erdal, 2023; Sanguesa *et al*. 2021). Battery production and disposal continue to present environmental concerns, emphasizing the need for sustainable solutions (Madrid, 2023). However, EVs have a great opportunity to mitigate greenhouse gas (GHG) emissions and tackle air pollution. Addressing these issues necessitates collaboration among industry stakeholders, governments, and researchers to facilitate the shift towards sustainable transportation (Alperen and Erdal, 2023).

1.2 Need for Sustainable and Efficient Technologies in EVs

Electric vehicles provide environmental benefits, but their sustainability is complicated throughout their lifecycle. Important concerns include the ecotoxicology of battery production, resource extraction, and energy usage (Chaudhari, 2024; Balaji *et al.* 2024; Narisetty and Maddineni, 2024). With the increasing demand for lithium-ion batteries, concerns about raw material supply as well as end-of-life management have been raised (Rajaeifar *et al.* 2022; Tang, 2024). Nanotechnology provides a potential approach to enhance battery performance and sustainability (Ellingsen *et al.* 2016). Strategies for recycling and a circular economy are important to minimize environmental burdens and to secure the supply of materials (Jose *et al.* 2024; Celadon *et al.* 2024). There is an emphasis on the environmental footprint of the EV supply chain covering aspects like

raw material extraction and manufacturing which must be addressed to minimize negative consequences (Esiri *et al*. 2023). An overview of key challenges that still need to be addressed through technology innovation, policy development and industry collaboration to enhance the sustainability of EVs and continue making progress towards a cleaner transportation landscape.

1.3 Role of Nanotechnology in Addressing Current EV Challenges

Nanotechnology is transforming the development of EVs, particularly concerning batteries and lightweight materials. Nanomaterials (e.g., graphene, carbon nanotubes, nanostructured silicon) can improve the capacity, charging speed and lifespan of batteries (Meng, 2024; Zheng, 2024a). Nanocoating enhances the stability of the electrode and addresses degradation problems (Meng, 2024). The nanomaterials in cathodes and anodes solve the problems of fading capacity and poor conductivity polymer (Zhao, 2023). Car-body nanocomposites, for example carbon fiber reinforced composites, offer reduced vehicle mass and enhanced body strength (Sun, 2023). Nanotechnology contributes to enhance safety *via* better thermal management as well as crash resistance (Chen, 2024). Sustainable nanomaterial technologies in EVs are guided by environmental life-cycle assessments (Ellingsen *et al.* 2016). The development of fast charging technology will allow EVs to charge in less time and increase their efficiency (Somashekarappa, 2019). However, environmental, health, and safety issues still challenge the wider scale deployment of nanotechnology in transportation (Shafique and Luo, 2019).

1.4 Scope and Objectives of the Review

This review paper aims to study the applications of nanotechnology in EVs, with a special emphasis on what part do they play in efficient energy usage and environmental sustainability. This review aims to address the following objectives: exploring the application of nanotechnology in the manufacturing and enhancement of sustainability for EV batteries, lightweight materials, power electronics, and thermal management, synthesizing recent advancements and innovations in nanomaterial applications to promote sustainability in EVs. It also discusses environmental challenges in implementing nanotechnology for EV sustainability, and its impact and tries to identify future perspectives and research directions for the application of nanotechnology in EV manufacturing and performance enhancement.

By focusing on these aspects, this paper emphasizes the transformative potential of nanotechnology in transforming the EV industry, while keeping the environmental impact low.

2. NANOTECHNOLOGY IN EV ENERGY STORAGE

Energy storage is a vital setpoint in EVs, as it establishes their range, effectiveness and sustainability. Lithium-ion (Li-ion) batteries, which are the most common type of battery used in contingency on vast majority EVs today, have several disadvantages, particularly related to energy density, charging time, lifespan, and environmental impact. Nanotechnology offers a very good potential to improve the performance of batteries, overcome limitation of alternative energy storage systems and thermal management issues in EVs (Kan, 2024; Miao, 2024).

2.1 Nanomaterials in Lithium-ion Batteries

Lithium-ion batteries represent the primary energy storage technology in EVs because of their high energy density, efficiency, and reliability. Nevertheless, they experience loss of capacity, low charging rates and safety risks like overheating. Meanwhile, the use of nanomaterials in Li-ion batteries plays an important role in enhancing the performance, rate capability and cycle life of Li-ion battery electrodes (Zheng, 2024a).

2.1.1 Nanostructured Cathodes and Anodes

The specific capacity of Li-ion batteries also relies heavily on the efficiency of their cathodes and anodes as the storing and transferring lithium-ions during charge and discharge cycles. Nanotechnology permits the alteration of these electrode materials in order to improve their conductivity, capacity, and structural performance.

- Nanostructured cathodes: Traditional cathode material like such as ($LiCoO_2$), can be combined with nanoparticles of lithuim iron phosphate ($LiFePO_4$) or nickel-manganese-cobalt oxides (NMC) to improve charge retaining capacity as well as stability (Zhang, 2023). Nanocoatings on cathodes also prevent material degradation during multiple cycles (Huang *et al.* 2020).

- Nanostructured anodes: As new anode types, silicon nanowires, graphene-based materials and carbon nanotubes (CNTs) are emerging as substitutes for traditional graphite anodes in Li-ion batteries, which can provide much higher lithium-ion storage capacity and faster transportation in rapid charge batteries (Sun and Wang, 2014; Roy and Srivastava, 2015)

2.1.2 Enhancing Battery Capacity and Lifespan

Nano-doping, nanocoating, and tailored nanostructures can be applied to solve the cathode problems, such as lattice distortion, ion dissolution, and electrolyte decomposition, for cathode materials like

lithium manganese oxide (LMO), nickel manganese cobalt oxide (NMC), and nickel cobalt aluminum oxide (NCA) (Wang, 2023; Zhao, 2023). Nanotechnology meets requirements for anodes in substances such as lithium titanium oxide (LTO) and silicon (Kan, 2024; Zhao, 2023), especially in relation to conductivity management and volumetric expansion. These improved characteristics increase EV battery energy density, lifespan, and rate of charge (Zheng, 2024b). However, hurdles such as scalability, production costs, and environmental impacts, require further studies to assess commercial viability (Omata *et al.* 2024; Kan, 2024).

2.2 Alternative Battery Technologies Using Nanomaterials

Although Li-ion batteries dominate the EV market, there is a need to find the alternative battery technologies that could be either less resource intensive, more safe or more efficient in terms of energy storage. These alternatives to energy storage using nanotechnology contribute to the development of these well-studied solutions.

2.2.1 Solid-state Batteries

Solid-state batteries (SSBs) are a likely replacement for conventional lithium-ion batteries, which possess improved safety, energy density, and longevity (Li, 2024; Xu, 2024). Nanotechnology thus becomes an important tool for SSB technology and development, such as solid electrolytes improvement, along with the interface between electrode and electrolyte and finally energy density (Zhang *et al.* 2023; Xin *et al.* 2017). Nanostructured materials, like ceramic oxides and polymer composites, enhance ionic conductivity and thermal stability (Cui, 2024). Recent advances are linked with ultrathin electrolyte membranes, nanofabricated materials for conductivity enhancement, and new fabrication technologies (Shah *et al.* 2024). Further studies are still being done on new nanostructures, nanocomposite materials, interfacial engineering, etc., to overcome issues such as high production costs and interfacial resistance to provide better performance and safety (Abniel *et al.* 2024). The global SSB production capacity is expected to grow at a compound annual growth rate of over 118% until 2035 (Thomas *et al.* 2024).

2.2.2 Nanotechnology in Sodium-ion and Hydrogen Fuel Cells

The declining availability of lithium has driven for research into alternative energy storage technologies, including sodium-ion (Na-ion) batteries and hydrogen fuel cells. In recent years, due to the rapid development of nanotechnology, the performance of sodium-ion batteries (SIBs) and hydrogen fuel cell has been effectively developed. Sodium ion batteries (SIBs) have gained significant attention due to the high natural abundance of sodium, rendering them as a cost-effective option over traditional lithium-ion batteries (Kumar and Kundu, 2024; Palomares *et al.* 2012). The limitation of SIBs, such as relatively low conductivity and volume change, has been gradually overcome using nanocomposite materials in recent years (Liang *et al.* 2018). In this regard, various nanostructured electrode materials from layered oxides to polyanionic compounds have shown remarkable performance in terms of energy density and cycling stability for Li-ion as well as Na-ion batteries (Kan, 2024). Various nanocatalysts (e.g., platinum (PtNPs) and CNTs have shown advanced hydrogen oxidation and oxygen reduction reactions when applied in hydrogen fuel cell systems (Manthiram *et al.* 2008; Guo *et al.* 2008). Both SIBs and fuel cells contain nanostructured materials which have high surface area and higher kinetics (Shukla and Kumar, 2013; Hwang *et al.* 2017). Nanotechnology is paving the path for the commercialization of alternative battery and fuel cells in order to provide sustainability of next generation EVs and their environmental impact.

2.3 Nanotechnology for Fast Charging and Thermal Management

Some of the biggest barriers to EV adoption include long charging times, heat generation, and degradation that impacts battery life and safety. Nanotechnology is offering novel solutions to these challenges.

2.3.1 Nanomaterials for Ultra-fast Charging

Nanomaterials push ultrafast charging technology to the next level. For instance, Nanostructured electrodes such as silicon nanowires and graphene-based materials, enable quick lithium-ion diffusion and thus allow for superfast charging without loss of battery lifetime (Wang *et al.* 2019). Nanotechnology also enhances efficiency in hybrid energy storage systems consisting of supercapacitors. Using nanomaterials, supercapacitors can provide quick bursts of energy when needed, thereby minimizing the battery wear.

2.3.2 Nanofluids for Battery Cooling and Thermal Management

Advanced nanofluids having metal and carbon-based nanoparticles serve as efficient coolants for thermal management by regulating the battery temperature as well as dissipating heat for hybrid and electric vehicles (HEVs and EVs). When charging and discharging, phase-change nanomaterials absorb and release heat to maintain an optimal battery temperature (Wiriyasart *et al.* 2020). Moreover, nano-coating cool plates enhance thermal conductivity, ensuring the safety and longevity of the battery. These advancements have

significantly enhanced the efficiency, lifetime, and reliability of EV batteries (Olabi *et al*. 2022).

The following section covers how the usage of nanotechnology allows us to resolve EV performance and efficiency problems through creating lightweight and super strong materials.

3. NANOTECHNOLOGY IN LIGHTWEIGHT AND HIGH-STRENGTH MATERIALS FOR EVS

Reducing the weight of the EVs to improve the efficiency, range and performance, is one of the biggest considerations in the design process. Additionally, lighter-weight materials help reduce energy consumption and promote battery efficiency while improving overall durability within the vehicle. Though traditional materials like steel and aluminum are strong, they add unnecessary mass to the vehicle. Nanocomposites and nanocoatings, have the potential to create lightweight, high-strength, durable, and environmental-resistant materials.

3.1 Nanocomposites for Lightweight Vehicle Structures

Nanocomposites are materials created by adding nanoscale reinforcements to polymers, metals, or ceramics, thereby enhancing their mechanical, thermal, and structural performance. For example, in EVs, nanocomposites are lightweight but possess high strength and impact resistance compared to their conventional counterparts, making them suitable for automotive applications such as vehicle chassis, body panels, and structural reinforcements (Sun, 2023; Gutowski *et al.* 2017).

3.1.1 Carbon Nanotubes and Graphene-based Composites

Due to their exceptional strength-to-weight ratio and electrical conductivity, carbon-based nanomaterials, such as carbon nanotubes (CNTs) and graphene, are new high-performance reinforcements for lightweight vehicle structures. These composites are offering higher strength, stiffness, and impact resistance, which makes them suitable for chassis parts and structural reinforcements of EVs (Choudhary *et al.* 2022). The improved electrical conductivity also provides both electromagnetic shielding (protection against electromagnetic waves) and self-sensing functions for smart structures in new generation vehicles (Rimamnya *et al.* 2023; Chen *et al.* 2016).

Because of their excellent tensile strength and fracture toughness, graphene-based composites can be used to manufacture lightweight body panels as well as a durable body structure (Pandey *et al*. 2022). Graphene enhances heat dissipation and inhibits thermal expansion problems in the structure of electric vehicles (Wang *et al.* 2009). Integrating CNTs and graphene allows EV manufacturers to create lighter, stronger, and more energy-efficient vehicles, leading to extended battery life and better performance.

3.1.2 Polymer Nanocomposites for Body Panels

Polymer nanocomposites for automotive applications, especially in EVs, provide unique properties. As these materials are lightweight and have good mechanical properties, they are suitable for structural and body panels (Naskar *et al.* 2016). Nanofillers like clay, silica, and carbon nanotubes in polymer matrices cause increased stiffness, thermal stability, and impact resistance (Bhattacharya, 2016). Nanoclay and nanocellulose are commonly used as reinforcements in polymer composites, where they have shown positive results in enhancing their mechanical properties and minimizing their environmental footprint (Hussin *et al.* 2020). Recent developments encompass self-healing nanocomposite materials which can recover from small-scale damage, thus extending the life of components (Sun, 2023). These lightweight nanocomposites contribute to lower overall vehicle weight in EV manufacturing, better energy efficiency, and increased structural integrity (Shah *et al*. 2022). However, limitations exist in processing and accessing structure-property relationships for widespread commercial realization (Naskar *et al.* 2016).

3.2 Nanocoatings for Corrosion and Wear Resistance

Similar to conventional vehicles, EVs are operating in extreme environmental conditions of moisture, temperature, and road debris resulting in corrosion and gradual deterioration of materials. As an advanced means of protecting EV components, nanocoatings form a barrier from ultra-thin, durable and resilient layers that can protect against corrosion and wear, and even prolong the lifetime of the parts.

3.2.1 Anti-corrosion Nanocoatings

Graphene nanocoatings function as barriers to oxygen and moisture, preventing rust on surfaces, and protecting metallic elements such as chassis (Malhotra *et al.* 2020). Nanoceramic coatings (e.g., titanium dioxide (TiO_2), aluminum oxide (Al_2O_3)) provide a high oxide resistance, which makes them suitable for active high-temperature components such as battery enclosures and exhausts (Fengbo *et al.* 2023). Superhydrophobic nanocoatings successfully repel both water and dirt, inhibiting corrosion and maintaining the vehicle's appearance (Jurak *et al.* 2020). By applying these anti-corrosion nanocoatings, EV manufacturers can cut maintenance costs and enhance the durability and longevity of structural components.

3.2.2 Wear-resistant Nanocoatings

Wear resistance is especially important for EV components such as bearings, suspension systems and brakes. Nanotechnology enables improvements in these parts, increasing strength and reducing friction. Diamond-like carbon (DLC) nanocoatings with high hardness, low friction coefficient and excellent wear resistance are used to lower friction in moving components and prolong their lifespan (Goti *et al.* 2023).

Low-friction layers of solid lubricants with nanoparticles such as molybdenum disulfide (MoS_2) and tungsten disulfide (WS_2) enhance the efficiency of electric drivetrains (Srinivas *et al.* 2017). Nano-self-lubricating nano-coatings protect gears, axles, and motors by lowering wear and increasing energy efficiency (Summèra Banday *et al.* 2021). Polymer-based composites, transition metal dichalcogenides (TMDs) and MXene nanosheets have also become effective solid lubricants (Ren *et al.* 2020).

Nanocoatings benefit EVs by reducing friction, increasing part life, and improving energy efficiency. In summary, nanotechnology can achieve lighter, stronger and more sustainable vehicles with materials such as CNTs, graphene and polymer nanocomposites. The need to improve the efficiency and safety of nanotechnology in EV electronics, sensors and smart systems will be addressed in the following section.

4. NANOTECHNOLOGY IN ENERGY EFFICIENCY AND POWER ELECTRONICS

Electric vehicles will continue to evolve on energy efficiency, determined by advancements in supercapacitors, power electronics, and cooling systems. The integration of nanotechnology is expected to further enhance the overall performance of EVs. These technologies enhance energy storage, minimize energy loss, and improve thermal management which results in greater efficiency, longer driving range, and enhanced reliability.

4.1 Nanomaterials in Supercapacitors for Regenerative Braking

Electric vehicles utilize regenerative braking to recover energy that is otherwise wasted during braking. Supercapacitors are an integral part of the system because they can provide high power while also charging and discharging rapidly. Nanomaterials enhance supercapacitor performance through these aspects by improved energy storage, durability, and charge retention

Graphene-based supercapacitors utilize graphene's high surface area and efficient electrical conductivity to achieve a higher energy storage with fast charging (Manoharan *et al.* 2021). With the use of CNT electrodes, supercapacitor performance increases with faster electron flow and decreased charging time (Aarti *et al.* 2024). Metal oxide nanostructures such as manganese dioxide (MnO_2) and titanium dioxide (TiO_2) not only enhance capacitance but also enable improved energy retention (Kumar *et al.* 2022).

The combination of the nanomaterials in supercapacitors which are used in EVs allows to recover more braking energy, reduces the load on the battery and helps increase the range.

4.2 Nanostructured Semiconductors for Power Electronics

Key applications of EVs typically include battery-to-motor power converters, charging systems and motor controllers. Development of high-efficiency semiconductor materials through nanotechnology has caused improvement in transistor performance, decrease in heat losses and efficiency of power conversion.

4.2.1 Enhanced Performance of Transistors and Inverters

Nanostructured semiconductors, particularly wide-bandgap (WBG) materials like silicon carbide (SiC) and gallium nitride (GaN), are revolutionizing EV power electronics. These materials offer superior properties compared to traditional silicon, including higher thermal conductivity, lower power losses, and faster switching speeds (Sburlan *et al.* 2021). SiC and GaN devices enable more efficient DC-DC converters, inverters, and charging systems, leading to improved EV performance, increased range, and faster charging times (Do *et al.* 2021). The adoption of WBG semiconductors in EVs faces challenges such as packaging, thermal management, and cost (Ghazanfari *et al.* 2019). However, ongoing research and development are addressing these issues, with industry trends pointing towards increased use of SiC and GaN in automotive applications (Robles *et al.* 2022). The implementation of these advanced materials is expected to significantly enhance the efficiency and competitiveness of EVs in the global market.

4.3 Nanofluids for Cooling Systems in EV Powertrains

Nanofluids are special coolants that contain ultra small particles such as metal oxides, graphene, and carbon nanotubes. They have great potential for thermal management in EVs, and are superior to conventional fluids in terms of heat transfer (Zheng, 2024a). Research indicates that they can provide lower battery temperatures and improve temperature uniformity (Kiani *et al.* 2020). Nano-fluids can be combined with phase change materials to improve cooling system. For instance, nanofluids including copper foam and paraffin wax reduce battery temperature by 4.1 K in comparison

with water cooling system (Kiani *et al.* 2020). This leads to safer, more efficient, and longer-lasting EV parts.

Nanotechnology is also enhancing energy use and power electronics in EVs, including supercapacitors, transistors (SiC, GaN) and cooling systems. These developments enhance energy recovery, power conversion, and heat regulation, contributing to the efficiency and sustainability of EVs.

The following section explores how nanotechnology is aiding the development of EV sensors, smart monitoring, and autonomous driving technologies, thereby paving the way for electric mobility.

5. NANOTECHNOLOGY FOR SUSTAINABLE EV MANUFACTURING AND RECYCLING

As the demand for EVs is rising steeply, sustainable production and recycling practices are critical. Traditional methods of making EVs come with significant energy use, material drawdown, and waste generation. In addition, the disposal of lithium-ion batteries and other parts of an electric vehicle raises environmental challenges.

Nanotechnology can significantly impact EVs to make them greener and efficient. This will help sustainability throughout the EV life cycle by facilitating green production of materials, economic battery recycling and innovation in hydrogen fuel cells.

5.1 Green Synthesis of Nanomaterials for EV Components

Although there are numerous standard strategies adopted for nanomaterials synthesis, the "green" fabrication of nanoparticles has recently emerged as a novel, more sustainable process, addressing environmental issues and utilizing less energy. It uses such plant extracts along with microorganisms and bio-waste materials to synthesize various nanoparticles, including metals, metal oxides and carbon-based materials. Green synthesis shows a 30% reduction in energy use and a 40% reduction in production cost, combined with a 50% increase in production yield in comparison to traditional methods (Osman *et al.* 2024). Such nanomaterials find their applications in the fields of energy production (Madani *et al.* 2022), biomedicine (Madani *et al* .2022), environmental remediation (Vishu Girotra *et al.* 2024) and agriculture (Girotra *et al.* 2024). Although they provide advantages including biocompatibility and environmental friendliness, limitations including up-scaling in production, morphology control, and synthesis mechanism remain unexplored (Ahmed *et al.* 2021). Further work will enhance synthesis, discover novel biologics and scale production (Alsaiari *et al.* 2023).

5.2 Nanotechnology in Battery Recycling and Waste Management

Lithium-ion battery recycling for EVs is of great importance in both environmental and resource perspectives. The existing methods of recycling have shown limits in terms of efficiency, cost-effectiveness, and environmental impact. There are three classical methods: pyrometallurgical, hydrometallurgical and direct recycle techniques. Developing new technologies for the metal recycling process, as electrochemical recycling, bioleaching and nanostructured adsorbents, are useful for increasing recovery and reducing waste production (Arnold *et al.* 2024). Advanced recycling techniques and sustainable battery design are essential to develop a circular economy in the EV sector (Raj *et al.* 2022). Future studies should target the design of cost-efficient, sustainable recycling processes able to process mixed battery chemistries and recover high-value components (Li *et al.* 2024).

5.3 Role of Nano-catalysts in Hydrogen Fuel Cell EVs

Hydrogen fuel cell electric vehicles are a potential sustainable alternative to EVs due to their zero-emission status together with rapid refueling capabilities. The catalysts, made of nanotechnology, boost the performance, durability and cost-effectiveness of fuel cells. In general, platinum-based nano catalysts induce better catalytic performance and lower the amount of platinum (Vedarajan *et al.* 2020) To this end, cost-effective alternatives like non-precious metal catalysts, including iron−nitrogen−carbon materials, are available. (Asset and Atanassov, 2020). Nanostructured materials backgrounds, including carbon nanotubes and graphene, serve to increase the catalyst support and hydrogen store (Nor *et al.* 2022). Nevertheless, despite these advances, there are also hurdles to overcome such as manufacture costs, hydrogen storage (Hassan *et al.* 2023) and re-fueling infrastructure. There are ongoing attempts to tackle these challenges by discovering more robust and dynamic catalysts and/or simplifying the entire system (Borup *et al.* 2020). These innovations are critical to facilitating the transition to clean hydrogen mobility.

6. ENVIRONMENTAL IMPACT AND SAFETY CONSIDERATIONS

Nanotechnology is performing a critical role to improve the performance, efficiency, and overall sustainability of EVs. However, there is a need for comprehensive assessment of its impact on the environment and safety aspects. Nanomaterials are used by manufacturers to produce different applications including batteries, lightweight structures, power electronics, and protective coatings. However, these impacts can have significant influence on carbon

footprint, toxicity risks, and regulatory hurdles associated with EVs.

This section reviews the contribution of nanotechnology to the reduction of emissions, evaluates the safety and toxicity concerns associated with nanotechnology, and discusses current regulations and future perspectives on the safe and sustainable usage of nanotechnology in EVs.

6.1 Reduction of Carbon Footprint Through Nanotechnology

With the use of the nanotechnology, the primary environmental advantage is reducing the greenhouse gas emissions during the vehicle's lifetime. Nanotechnology supports a reduction of carbon footprint in the following aspects by improving the energy efficiency, lightweight structures and battery performance.

Nanomaterials in energy-efficient batteries: Molecules such as silicon anodes, graphene-based electrodes, and solid-state electrolytes can enhance the life and efficiency of batteries, which leads to less frequent replacements as the devices will last longer and thus helping in reducing the resource consumption (Reslan *et al.* 2024).

Lightweight nanocomposites: Use of CNTs, graphene and polymer nanocomposites, facilitates lighter body structures for automobiles which translates into less energy consumption and accordingly more kilometers driven per recharge (Sun, 2023).

Nanostructured catalysts for hydrogen fuel cells: Novel nano catalysts significantly improve the efficiency of hydrogen fuel cells here by providing a cleaner substitute to conventional lithium-ion battery-based EVs (Vedarajan *et al.* 2020).

Energy saving through nanocoatings: The application of self-cleaning, anti-corrosion and heat-reflective nanocoatings on the EVs or components can help in reducing the aerodynamic drag, thermal losses and the energy required for maintenance (Huang *et al.* 2023).

Using nanotechnology across multiple EV components allows manufacturers to cut CO_2 emissions by a huge margin, while ensuring high performance and durability.

6.2 Safety and Toxicity of Nanomaterials in EVs

Nanomaterials offer significant benefits in various applications, but they also raise concerns about safety and environmental impacts. While current environmental risks appear low, specific scenarios like wastewater effluents require attention. Key challenges include detecting nanomaterials in complex matrices, understanding their transformations, and developing standardized safety assessment methods. Toxicity can be influenced by factors such as size, charge, and environmental conditions. The entire lifecycle of nanomaterials, from production to disposal, must be considered for comprehensive risk assessment (Dos *et al.* 2022). Researchers should focus on a balanced approach incorporating early hazard identification, safe-by-design principles, and life cycle assessments. Improved analytical methods, computational models, and validated protocols are needed to advance nano safety studies. Additionally, developing eco-friendly nanomaterials and addressing recycling challenges are crucial for sustainable nanotechnology (Awasthi and Sharma, 2022; Thakur and Kumar, 2023).

6.3 Regulatory Challenges and Future Perspectives

Nanotechnology has significant potential for EV advancement relating to battery technology or vehicle material (Zheng, 2024b). Despite the potential benefits, the rapid evolution of nanomaterials raises regulatory concerns such as developing uniform safety guidelines, environmental regulations governing nano waste disposal, and ethical issues (Allan *et al.* 2021). Despite numerous organizations across global are making the progress on establishing and implementing regulatory frameworks for risk management of nanotechnology, still there is a gap in international cooperation and consensus (Allan *et al.* 2021). Some efforts are on the way to address these challenges by developing biodegradable nanomaterials, green synthetic routes and next generation life cycle evaluations (Chávez-Hernández *et al.* 2024). For instance, coatings with nanomaterials can enhance the performance, lifetime, and safety of EV batteries and thus contributing in lowering the environmental impact and cost of overall EVs (Meng, 2024). But proper development has to overcome regulatory hurdles, safety issues, and equitable access to these technologies to make sure they are safe, ethical, and sustainable (Kardani, 2024).

Nanotechnology is essential in decreasing the EVs environmental footprint and improving safety. As it holds great promise for carbon emissions reduction, energy efficiency improvement, and sustainable battery solutions; however, it must also address the toxicity, recyclability and regulation in a careful manner.

Innovative nanotechnology developments in EVs, will require green manufacturing processes, improved safety guidelines, and uniform regulatory frameworks to prevent potential hazards.

7. FUTURE DIRECTIONS

Nanotechnology has the potential to revolutionize the EV industry by enhancing battery performance, energy efficiency, lightweight materials,

and sustainable manufacturing techniques. As this review highlights nanomaterials and nanotechnology-based innovations for energy storage and power electronics, vehicle weight reduction, and durability improvement. But there are still challenges to overcome before nanotechnology can be completely utilized in EVs, despite great strides having already been taken.

7.1 Summary of Key Findings

This review emphasized the state of art and future opportunities of nanotechnology in the performance and sustainability of electric vehicles. The key findings include:

- **Nanomaterials in Battery Technologies:** Nanotechnology has significantly enhanced the capacity, longevity, and rapid-charging attributes of lithium-ion batteries across nanostructured anodes and cathodes, as well as devices leveraging innovations in solid-state and sodium-ion batteries.
- **Lightweight and High-strength Materials:** Advancements in automotive materials continue through the development of CNTs and graphene-based composites that work towards lightweight and high-strength applications in body panels and structural components, reducing weight whilst ensuring vehicle strength and durability.
- **Energy Efficiency and Power Electronics:** The use of new nanostructured semiconductors like SiC and GaN for high-performance power converters and nanofluids for improving cooling systems in EV powertrains.
- **Sustainable Manufacturing and Recycling:** Nanotechnology plays a critical role in sustainable manufacturing and recycling of EV components, leading to more eco-friendly production of EVs.
- **Environmental and Safety Considerations:** The ability of nanotechnology to decrease the carbon footprint and the concerns regarding nanomaterials safety and toxicity is a continuous investigation area aimed at minimization of environmental effects.

These findings indicate that nanotechnology is already integrating into the EV industry and helps to shape the future of the transportation sector.

7.2 Challenges and Opportunities in Implementing Nanotechnology for EVs

Nanotechnology has a lot of advantages, but issues remain to be dealt with before it is adopted in EVs.

7.2.1 Challenges

- **High Production Costs:** Nanomaterials hold great promise but are costly to produce and the processes of manufacturing are complicated. Which makes their use on a large scale in EVs difficult.
- **Scale-up and Commercialization:** A lot of nanotech works well in the lab, but developing into a product that can be manufactured at scale and sold is still a major challenge.
- **Safety and Toxicity Concerns:** Some nanomaterials still aren't understood in terms of their health and environmental effects. Their safety has been questioned, particularly how they are discarded. So, there should be more regulations and oversight.
- **Integration with Existing EV Infrastructure:** Incorporating nanotechnology within the existing EV manufacturing ecosystem and existing vehicle architectures necessitates extensive adaptation and rigorous testing to guarantee compatibility and reliability.

7.2.2 Opportunities

- **Cost Reduction through Innovation:** Further research and development could reduce the cost of nanomaterial production and thus make nanotechnology-based solutions more economically viable for mass production.
- **Enhanced Battery Performance and Sustainability:** Through advances in nanotech, battery performance and sustainability may be significantly improved, especially in next-generation solid-state batteries and sodium-ion batteries.
- **Eco-friendly Manufacturing:** Methods of creating nanomaterials through green synthesis and innovations in recyclable composites can greatly cut the environmental impact of EV manufacture.
- **Collaboration Across Industries:** Partnership between automotive manufacturers, nanotechnology researchers, and regulatory bodies may help to overcome existing barriers and enable synergies for commercialization of nanotechnology in EVs

These challenges open the door to continued innovation that can drive the next generation of electric vehicles to be more efficient, sustainable and affordable.

7.3 Future Research Directions

Nanotechnology is developing in rapid pace which has many potential future directions for research in EV application. Some of the major future research directions are as follows:

- **Development of Next-generation Batteries:** Future research needs to be on solid state, lithium-sulfur and lithium-air batteries, based on nano-engineered electrodes to secure higher energy densities, faster charging times and longer lives.

- **Advanced Nanomaterials for Structural Components:** Multifunctional nanocomposites are being researched to produce high specific strength materials that will improve vehicle performance, crash safety and aerodynamics while minimizing weight.

- **Nanotechnology for Autonomous EVs:** The use of nanomaterials could be key in implementing sensor technology and AI-powered algorithms in autonomous driving systems, enhancing navigation accuracy, energy efficiency, and safety.

- **Nanotechnology in Power Electronics:** Future research can aim at nanostructured power converters and novel transistors for more efficient utilization for EV motor controllers and inverters in terms of energy loss and heat generation.

- **Recycling and Reuse of Nanomaterials:** Further research on recycling techniques for nanomaterials and battery reuse will be beneficial for sustainability in the EV industry, thus aligning with circular economy principles.

- **Safety and Regulatory Frameworks:** Research efforts will be essential to develop more effective toxicological assessments, safe handling protocols, and regulatory frameworks for nanotechnology in electric vehicles, ensuring environmental safety and compliance of nanomaterials used within them.

These efforts will help in enabling the EVs to push boundaries of what nanotechnology can do for our vehicles, and make our transport systems cleaner, greener, and smarter in line with the emerging paradigm.

8. CONCLUSION

Nanotechnology is making great impact with the EV industry, providing solutions focused on improving battery performance, power electronics, vehicle materials, and manufacturing techniques. Nanotechnology is accompanied by challenges of its own, including concerns with cost, scalability, and safety. While there are challenges, the potential opportunities of this new field are vast and which can transform the future of transportation. With the continuous breakthroughs in nanomaterials, one can expect new technologies that will revolutionize electric vehicles and make them more efficient, sustainable, and safer for both the environment and consumers.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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