Journal of
Environmental
Nanotechnology

Review Article

Nanotechnology Applications in Electric Vehicles: Boosting Energy Efficiency and Minimizing Environmental Impact

A. Soundararajan[1], K. Balachander[1*], A. Nagamani Prabu[2], S. Vijayabaskar[3], K. S. Neelu Kumari[4] and M. Venkatesan[5]

[1]Department of Electrical and Electronics Engineering, Sri Ramakrishna Engineering College, Coimbatore, TN, India
[2]Department of Physics, Karpagam Academy of Higher Education, Coimbatore, TN, India
[3]Department of Electrical and Electronics Engineering. P. A. College of Engineering and Technology, Coimbatore, TN, India
[4]Department of Electronics and Communication Engineering, P. A. College of Engineering and Technology, Coimbatore, TN, India
[5]Department of Electronics and Communication Engineering, Dhanalakshmi Srinivasan College of Engineering, Coimbatore, TN, India
Received: 22.07.2025 Accepted: 11.09.2025 Published: 30.09.2025
*kaybe.ind@gmail.com

ABSTRACT

Electric Vehicles (EVs) have become a critical component in global strategies to combat climate change and reduce dependence on fossil fuels. Despite significant advances, EVs still face challenges related to energy storage, limited range, long charging times, and environmental sustainability. Nanotechnology, the science of manipulating materials at the atomic or molecular scale, presents innovative solutions to these challenges. This paper explores how nanotechnology enhances energy efficiency and reduces the environmental impact of EVs. It focuses on advances in battery technologies, lightweight nanomaterials, thermal management, and nanostructured power electronics. Furthermore, it critically assesses the environmental implications of using nanomaterials and provides a roadmap for future research.

Keywords: Nanotechnology; Electric vehicle; Environmental impact; Energy efficiency.

1. INTRODUCTION

The transportation sector is one of the primary contributors to global greenhouse gas emissions, accounting for nearly 24% of direct CO_2 emissions from fuel combustion worldwide (Alsaiari *et al*. 2023). The growing environmental concerns, combined with rapid urbanization and increasing energy demands, have created an urgent need for cleaner and more sustainable mobility solutions. EVs, which operate on electricity rather than internal combustion engines, represent a transformative step toward reducing reliance on fossil fuels and curbing carbon emissions. Their adoption aligns with the global goals set under the Paris Agreement and the United Nations Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action) (Balaji *et al*. 2024).

Despite their potential, several technical and economic challenges hinder the large-scale integration of EVs. These include high initial vehicle costs, limited energy density of batteries, long charging durations, thermal management issues, and the environmental impact associated with battery production and end-of-life disposal (Dresselhaus and Thomas, 2001; Tarascon and Armand, 2001). Conventional materials and technologies have reached their physical limits in addressing these issues, creating a pressing need for innovative solutions (Esiri *et al*. 2023).

Nanotechnology, defined as the design, characterization, and application of materials and devices with structures at the nanometer scale (typically 1–100 nm) has emerged as a key enabler for next-generation EV advancements (Roco, 2003). At this scale, materials often exhibit novel optical, mechanical, electrical, and chemical properties that are distinctly different from their bulk counterparts. These characteristics enable significant enhancements in battery energy density, charge/discharge rates, structural integrity, and environmental sustainability (Fengbo *et al*. 2023; Goti *et al*. 2023).

Nanomaterials such as carbon nanotubes (CNTs), graphene, silicon nanowires, lithium iron phosphate nanoparticles, and solid-state nanocomposites are revolutionizing the design of high-performance lithium-ion batteries (LIBs) and super capacitors (Manthiram, 2020). They also offer innovative solutions for lightweight vehicle structures, thermal management systems, self-healing materials, and smart sensors. In doing so, nanotechnology contributes to reducing the total vehicle weight, extending driving range, optimizing powertrain efficiency, and lowering overall energy consumption (Dresselhaus and Thomas, 2001).

This paper explores the diverse and rapidly evolving applications of nanotechnology in EVs focusing on how nanostructures can enhance energy storage, reduce environmental impact, and promote long-term sustainability in the transportation sector (Mehdi *et al.* 2022).

2. LITERATURE REVIEW

Nanotechnology has emerged as a transformative field in EV technology, particularly in addressing energy density, charging time, lifecycle sustainability, and environmental impact. Several researchers have explored the role of nanomaterials in enhancing various EV subsystems, primarily batteries, capacitors, thermal systems, and structural components.

2.1 Nanomaterials in Battery Technology

The performance of EVs is heavily reliant on the efficiency and durability of their energy storage systems, particularly LIBs. Traditional LIBs face limitations such as low energy density, poor thermal stability, and aging-related capacity fading. Nanotechnology has shown the potential to resolve these constraints through the integration of nanostructured electrodes and electrolytes.

Zhang *et al.* (2019) demonstrated that the use of silicon nanowires as anode materials significantly enhances the charge storage capacity of LIBs due to silicon's high theoretical capacity of ~4200 mAh/g (Janek and Zeier, 2016). However, silicon's large volume expansion during lithiation can cause structural degradation. Researchers have proposed encapsulating silicon nanostructures with CNTs or graphene layers to improve conductivity and mechanical stability (Kan, 2024).

Similarly, cathode materials such as lithium iron phosphate ($LiFePO_4$) have been synthesized with nano scale coatings to improve electron transport and cycle life. Sburlan *et al.* (2021) noted that nanostructured cathode materials not only provide a larger surface area for electrochemical reactions but also reduce ion diffusion paths, improve electron transport, and enhance overall electrochemical performance.

2.2 Supercapacitors and Hybrid Storage Systems

Beyond conventional batteries, nanomaterials have advanced the development of supercapacitors for EVs. These devices store energy through electrostatic charge separation, offering faster charge-discharge cycles. Activated carbon, graphene, and transition metal oxides like MnO_2 and RuO_2 have been widely investigated as electrode materials in supercapacitors. Nel *et al.* (2006) revealed that graphene-based electrodes provide high specific surface areas (~2630 m^2/g) and excellent electrical conductivity, which are ideal for EV applications requiring rapid power delivery (Khan and Halder, 2020).

Hybrid energy storage systems combining LIBs with supercapacitors are also gaining traction. Nanotechnology enables seamless integration by matching the electrochemical properties of both systems and improving charge balancing through nanostructured control layers (Goti *et al*. 2023).

2.3 Nanotechnology in Thermal Management

Effective thermal management is essential for battery safety and performance in EVs. Overheating can result in thermal runaway, battery degradation, and potential safety hazards. Nanofluids, such as Al_2O_3, CuO, or graphene have been introduced into cooling systems to enhance heat transfer properties.

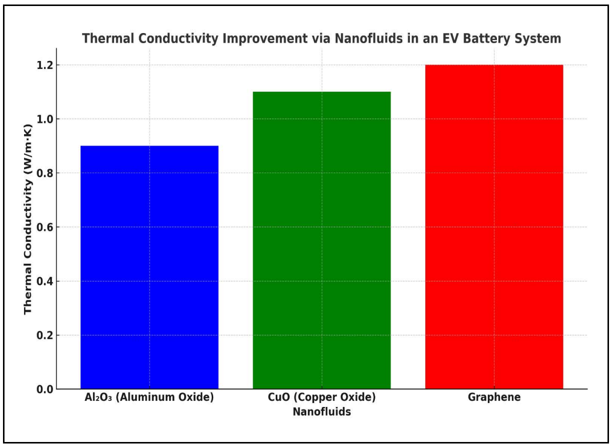

Fig. 1: Thermal conductivity improvement via nanofluids in EV battery system

Jalali *et al*. (2021) reported that graphene-based nanofluids demonstrated up to 35% improvement in thermal conductivity over conventional coolants, significantly enhancing heat dissipation from battery modules under high-load conditions (Kardani *et al.* 2024; Li *et al*. 2024). Phase change materials (PCMs) embedded with nanoparticles also help regulate temperature during charging and discharging cycles (Manthiram 2020). Fig. 1 shows the thermal conductivity improvement via nanofluids in EV battery system.

2.4 Structural Components

Vehicle weight directly affects energy consumption and driving range. Nanocomposites and lightweight materials such as carbon fiber reinforced with nanoclays or CNTs are being used to manufacture

EV frames, panels, and structural components. These materials offer improved strength-to-weight ratios and corrosion resistance. According to Khan and Halder, (2020), polymer nanocomposites embedded with CNTs not only reduce weight but also offer electromagnetic interference shielding, an essential feature for electric drive systems (Maynard *et al*. 2011). Such advancements contribute to lower energy consumption and enhanced vehicle safety.

2.5 Environmental Impact and Lifecycle Sustainability

Although EVs are environmentally cleaner in operation, battery production and disposal pose significant environmental challenges. Nanotechnology enables the development of recyclable and eco-friendly battery materials. Biodegradable nano-polymers and green synthesis methods using plant extracts or bio-based reducing agents are under active research to minimize toxic byproducts (Malhotra *et al.* 2020).

Moreover, life cycle assessment (LCA) studies indicate that nanostructured batteries, owing to their extended lifespan and recyclability, result in a lower cumulative environmental footprint compared to conventional systems (Mohanty *et al.* 2018).

3. NANOTECHNOLOGY IN ENERGY STORAGE SYSTEMS

3.1 Lithium-ion Batteries

The performance of LIBs in EVs depends heavily on electrode materials, electrolytes, separators, and the cell architecture. Nanotechnology enhances these components as follows:

Nanostructured Anodes and Cathodes: Silicon nanoparticles offer a much higher theoretical capacity than conventional graphite anodes. However, they suffer from large volume changes during cycling. Incorporating silicon into nanocomposites with graphene or CNTs mitigates this issue, improving both capacity and cycle life.

Cathode Improvement: Nanoscale lithium iron phosphate ($LiFePO_4$) and lithium nickel manganese cobalt oxide particles reduce the diffusion distance for lithium ions, enhancing charge/discharge rates.

Electrolyte Optimization: Solid-state nano-electrolytes like $Li_7La_3Zr_2O_{12}$ provide high ionic conductivity and thermal stability while reducing the risk of leakage and fire associated with liquid electrolytes.

Separator Coatings: Nanoparticles such as alumina or silica improve the thermal resistance and mechanical integrity of polymer separators, enhancing overall battery safety. Table 1 describes the applications of nanotechnology in energy storage systems for EVs.

Table 1. Applications of nanotechnology in energy storage systems for EVs

Nano Material	Storage System	Function/Role	Key Properties	Benefits
CNTs	LiBs	Battery anode material	High electrical conduc-tivity, mechanical strength	Faster charge/ discharge rates, increased lifespan
Graphene	Super-capacitors, LIBs	Elec-trode material conduc-tive coating	Large surface area, high thermal/ electrical conduc-tivity	Improved energy/power density, fast energy storage
Silicon Nano- wires	LIBs	Anode material	High energy storage capacity, nanoscale lithiation	High energy density, better capacity retention
Lithium Iron Phos-phate nano particles ($LiFePO_4$)	LIBs	Cathode material	Stable structure, non-toxic	Enhanced cycle life, thermal stability
MnO_2 Nano- structures	Super-capacitors	Pseudo-capaci-tive material	High surface reactivity	High capacitance, quick charge storage
TiO_2 nano particles	LIBs, Super-capacitors	Anode/ coating material	Photo-catalytic UV resistance	Self-cleaning, safety, stable charging/ discharging
Al_2O_3 nano coatings	LIB separators and electrolytes	Protec-tive barrier layer	Thermal stability, ionic conduc-tivity	Reduces degradation, enhances battery safety
Nano structured polymers	Solid-state batteries	Solid electro-lyte	Ion-conduc-tive, flexible	Improves safety, allows thinner and flexible cells
Metal-organic Frame works	Hybrid capacitors, fuel cells	Electro-lyte storage or ion trans-port	High porosity, tunable structure	Increases energy density, customizable performance
Cellulose nanofibers	Eco-batteries flexible devices	Binder or struc-tural support	Biode-gradable, renewable	Sustainable design, lightweight, environ-mental safety

3.2 Supercapacitors

Supercapacitors store energy through electrostatic processes and offer extremely fast charging and discharging capabilities. Nanomaterials such as activated carbon, CNTs and graphene significantly increase surface area and capacitance, making supercapacitors more viable for energy recovery systems like regenerative braking.

4. NANOMATERIALS FOR LIGHTWEIGHT AND HIGH-STRENGTH COMPONENTS

Reducing vehicle weight directly correlates with increased energy efficiency and extended driving range. Nanotechnology contributes by enabling the design of stronger and lighter materials:

Carbon Nanotube Reinforced Polymers (CNRPs): CNTs possess high tensile strength and low density. When embedded into polymers, they produce composite materials that can replace heavier steel or aluminum parts without compromising safety.

Nano-Metal Alloys: Aluminum and magnesium alloys with nanoscale grain sizes offer enhanced strength-to-weight ratios. Their incorporation into vehicle frames and engine components reduces mass and improves fuel efficiency.

Nanostructured Steel: Nanophase steel exhibits superior fatigue and fracture resistance. Advanced forging techniques create ultrafine-grained steel for use in crash structures and protective frameworks.

These materials help lower the overall energy consumption of EVs and improve performance without increasing environmental costs.

5. THERMAL MANAGEMENT AND COOLING SYSTEMS

Thermal management is critical in EVs, particularly in battery packs and power electronics. Nanotechnology enhances thermal conductivity and heat dissipation via:

Nanofluids: Base fluids like water or ethylene glycol, when mixed with nanoparticles such as aluminum oxide, copper oxide, or graphene, create nano fluids with superior thermal properties. These are used in cooling systems to maintain optimal temperatures during battery operation.

Phase Change Materials: Nano-enhanced PCMs absorb and release thermal energy during phase transitions. When used in battery casings, they prevent overheating during rapid charging or high-current discharge.

Heat Dissipation Coatings: Thermally conductive nanocoatings are applied to battery surfaces and electronic components to facilitate more efficient heat flow and prevent localized hot spots.

6. NANOTECHNOLOGY IN POWER ELECTRONICS

Power electronics manage energy flow within EVs, and their efficiency impacts overall vehicle performance. Nanotechnology improves these systems through:

Wide Bandgap Semiconductors: Silicon carbide and gallium nitride are key materials in advanced power electronics. Their nanoscale fabrication allows higher efficiency and operation at higher voltages and temperatures compared to conventional silicon.

Nanostructured Dielectrics: High dielectric strength and thermal stability in capacitors are achieved through the use of barium titanate or polymer nanocomposites. These components reduce energy losses and increase longevity.

Miniaturization: Nanoscale transistors and integrated circuits enable compact and lightweight control systems, reducing space and energy requirements.

7. ENVIRONMENTAL IMPACT OF NANOTECHNOLOGY IN EVs

Nanotechnology has transformed EV technology by enhancing battery efficiency, energy storage, and thermal management. However, as with any emerging technology, it is essential to critically evaluate its environmental impact across the product lifecycle, from raw material extraction and synthesis to operational use and end-of-life disposal.

7.1 Life Cycle Assessment

LCA is a comprehensive tool for evaluating the environmental burdens associated with the entire lifespan of a product. In the context of nano technology in EVs, LCA provides insight into the environmental balance between energy-intensive nanoparticle synthesis and the long-term operational gains of using nanomaterials.

Although synthesizing nanomaterials like CNTs, graphene, and metal oxides requires high energy inputs and sometimes hazardous precursors, studies indicate that these impacts can be offset by significant reductions in energy use during the operation phase of EVs. For instance, lightweight nanocomposites reduce vehicle weight and improve energy efficiency, while nanostructured batteries offer longer life cycles and faster charging, minimizing energy losses (Vahidi and Sciarretta, 2018; Dresselhaus and Thomas, 2001).

A comparative LCA conducted by Shafique and Luo (2019) showed that LIBs incorporating nanostructured electrodes had a 15–20% lower carbon footprint over their entire lifespan compared to conventional LIBs, largely due to improved energy density and lifecycle (Naskar *et al.* 2016). Similarly, a study by Fthenakis and Kim (2020) confirmed that EVs with nanotechnology-enhanced components exhibit a lower environmental impact per kilometer driven than standard EVs, when assessed over a typical 150,000 km usage period (Roco, 2003).

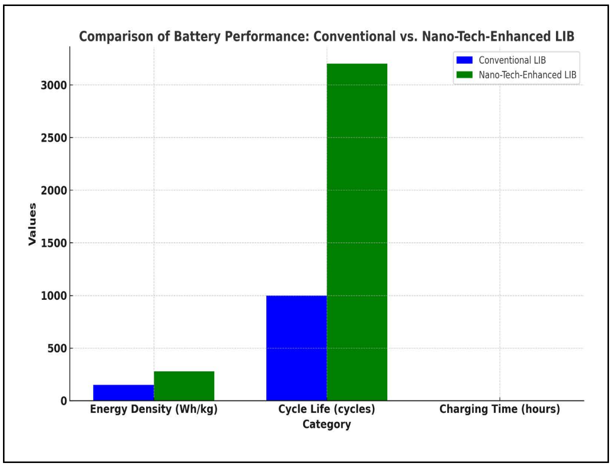

Fig. 2: Comparison of battery performance metrics between conventional and nanotechnology-enhanced lithium-ion batteries

Fig. 2 illustrates a performance comparison between conventional LIBs and nanotechnology-enhanced LIBs based on three key metrics: energy density, lifecycle, and charging time. However, these benefits are highly dependent on the energy source used during the manufacturing process. If nanomaterial synthesis relies heavily on fossil-based electricity, the environmental advantage diminishes. Therefore, green energy integration in nanomanufacturing is crucial for realizing the full ecological benefits of nanotechnology-enabled EVs.

7.2 Toxicity and Disposal Concerns

Despite their utility, engineered nanomaterials pose potential environmental and human health risks. Due to their small size and high surface reactivity, nano particles can easily enter biological systems via inhalation, ingestion, or skin contact. Once released into air, water, or soil, nanoparticles can accumulate in ecosystems and potentially cause toxicity to aquatic organisms, soil microbes, and even humans (Sburlan *et al.* 2021). Fig. 3 shows energy efficiency *vs* environmental impact in EVs.

Table 2. Summary of environmental impacts

Factor	Positive Impact	Negative Concern
Energy Efficiency	Reduced operational carbon footprint	High energy demand during synthesis
Material Use	Lower quantity due to high performance	Rare/critical raw material demand
Emissions	Less during vehicle operation	Potential nanoparticle emissions during production
Waste Management	Longer battery life = less waste	Difficult recycling of hybrid nanocomposites
Human Health	Reduced fuel-related diseases	Inhalation risk of nanoparticles

Bioaccumulation: Nanoparticles such as silver, zinc oxide, and titanium dioxide can accumulate in biological tissues and disrupt cellular processes (Keller *et al.* 2013).

Unknown long-term impacts: The chronic toxicity, mutagenic potential, and ecological persistence of many nanoparticles remain poorly understood due to limited long-term studies (Maynard *et al.* 2011).

To mitigate these risks, current research has shifted toward the development of green synthesis methods and eco-friendly nanomaterials. Green synthesis involves producing nanoparticles using biological agents such as plant extracts, bacteria, or algae. This approach eliminates the use of toxic solvents and harsh chemical reducers traditionally used in nanoparticle synthesis (Iravani, 2011).

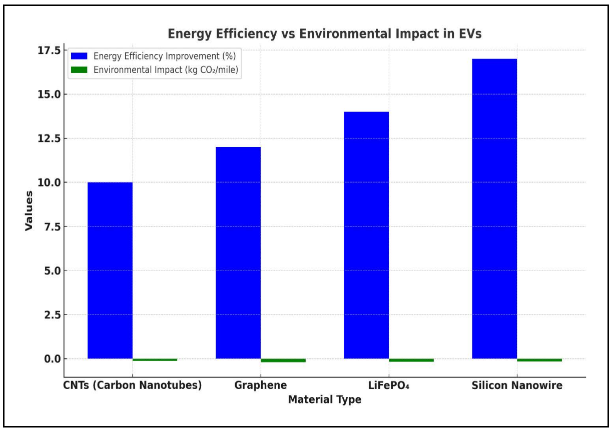

Fig. 3: Energy efficiency Vs environmental impact in EVs

Khan and Helder, (2020) demonstrated the successful use of *Azadirachta indica* (neem) leaf extract to synthesize silver nanoparticles with significant antimicrobial properties and minimal environmental toxicity. Such methods not only reduce chemical hazards but also lower energy consumption, making nanotechnology more sustainable.

Additionally, biodegradable nanomaterials, such as cellulose nanofibers and polylactic acid-based nanocomposites, are being explored for their low toxicity and end-of-life recyclability. These materials degrade naturally in the environment, posing little risk of long-term accumulation (Mohanty *et al.* 2018). Furthermore, innovative recycling methods for nanomaterials, including solvent-based separation and electrochemical recovery, are under development to recover valuable components and minimize landfill waste (Wang *et al.* 2023).

While these advancements offer promising solutions, regulatory frameworks are yet to develop. There is a need for standardized testing protocols, transparent labeling, and international regulations to ensure the safe production, usage, and disposal of nanomaterials in the EV industry. Table 2 describes the summary of environmental impacts of EVs.

8. FUTURE PERSPECTIVES AND RESEARCH DIRECTIONS

As the demand for high-efficiency, environmentally sustainable, and technologically advanced EVs continues to grow, the role of nanotechnology will become increasingly central. The next generation of nanotechnology applications in EVs is expected to show improvements, offering disruptive innovations in energy storage, structural materials, and smart vehicle systems. These advancements depend not only on technological breakthroughs but also on interdisciplinary collaboration, sustainable practices, and scalable manufacturing.

8.1 Solid-state Batteries with Nanoscale Interfaces

Solid-state batteries are widely considered the future of EV energy storage due to their potential to offer higher energy density, faster charging, improved safety, and longer cycle life compared to traditional liquid-electrolyte LIBs. The integration of nanostructured solid electrolytes and nanoscale electrode–electrolyte interfaces plays a critical role in overcoming challenges such as interfacial instability, dendrite formation, and low ionic conductivity.

Recent research highlights the use of garnet-type nanoceramics (e.g.,$Li_7La_3Zr_2O_{12}$) and sulfide-based nanocomposites, which provide high ionic conductivity (~10^{-3} S/cm) and excellent chemical compatibility with lithium metal anodes (Xu *et al.* 2024). Optimizing these interfaces at the nanometer scale ensures more uniform ion transport and reduces internal resistance, thereby enhancing battery safety and performance.

8.2 Self-healing Nanomaterials

The incorporation of self-healing nanomaterials in EV components and battery systems is a promising frontier. These materials are engineered to autonomously repair micro-cracks, delamination, and fatigue damage caused by mechanical stress, vibration, or thermal cycling. For instance, polymers embedded with microcapsules containing healing agents or nanofillers (e.g., graphene oxide) can respond to mechanical damage by releasing the healing substance at the damaged site (White *et al.* 2001).

Such materials have significant implications for extending the lifespan of EV batteries, lightweight structural parts, and insulation materials. They also reduce the need for frequent maintenance and replacement, thereby contributing to lifecycle sustainability and cost reduction (Zheng *et al.* 2024).

8.3 Smart Nanocoatings for Vehicle Protection

Nanotechnology is facilitating the development of intelligent surface coatings that provide multi-functional protection. Smart nanocoatings with anti-corrosion, self-cleaning, anti-fouling, UV-resistance, and thermal insulation capabilities are gaining traction in the automotive sector. These coatings often utilize nanomaterials like TiO_2, SiO_2, or ZnO, which possess photocatalytic, hydrophobic, and antimicrobial properties.

Moreover, UV-curable nanocoatings and sol-gel-derived hybrid films are being fabricated to offer high hardness and optical clarity, while minimizing environmental impact during application. Such coatings enhance the durability and aesthetic value of EVs while reducing the use of harsh cleaning chemicals or surface treatments.

8.4 AI-driven Nanomanufacturing

The future of nanomaterial production lies in integrating artificial intelligence and machine learning with nanomanufacturing techniques. Artificial intelligence algorithms can optimize synthesis parameters, predict material behavior, detect structural defects, and ensure consistency in large-scale production. This is especially important for maintaining quality control in commercial EV battery production and advanced coatings.

Deep learning models can analyze real-time spectroscopic or microscopic data to detect anomalies in nanomaterial batches. Reinforcement learning can further be employed to adjust process parameters dynamically for desired outcomes. This level of precision reduces waste, improves throughput, and lowers costs, making nanotechnology more accessible to EV manufacturers.

8.5 Need for Cross-disciplinary Research

To fully realize the potential of nanotechnology in EVs, strong collaboration across disciplines is vital. Material scientists, chemists, electrical engineers, mechanical designers, and environmental analysts must converge to address the multifaceted challenges of integrating nanomaterials into real-world EV platforms. Focus areas should include:

- Developing scalable and environmentally benign nanofabrication techniques
- Enhancing recyclability and lifecycle traceability of nano-enhanced components
- Integrating nanotechnology into vehicle-to-grid (V2G) and smart charging systems
- Ensuring regulatory compliance and public health safety regarding nanoparticle exposure

Moreover, partnerships between academia, automotive industries, and governmental policy-makers are essential to support innovation through funding, infrastructure, and regulatory frameworks.

9. CONCLUSION

Nanotechnology is redefining the future of EVs by introducing ground breaking solutions that address critical limitations in energy storage, power management, thermal regulation, and structural design. Its application has led to the development of high-capacity batteries with faster charge cycles, lightweight yet durable materials, advanced cooling systems, and intelligent surface coatings, all of which collectively enhance energy efficiency, safety, and vehicle performance.

Moreover, the integration of nanotechnology enables EVs to achieve greater driving range and reduced charging times without compromising environmental integrity. From CNTs nanotubes and graphene-enhanced electrodes to self-healing polymers and AI-assisted nanomanufacturing, the scope of innovation is vast and still expanding.

However, these technological advancements must be matched by a strong commitment to environmental responsibility. The synthesis, usage, and end-of-life management of nanomaterials raise valid concerns regarding toxicity, bioaccumulation, and lifecycle emissions. Green synthesis techniques, biodegradable materials, and improved recycling strategies are crucial for ensuring that the environmental footprint of nanotechnology remains within sustainable limits.

As the automotive industry moves toward full electrification, the convergence of nanotechnology with artificial intelligence, circular economy principles, and interdisciplinary research will be pivotal. Policymakers, researchers, and manufacturers must work collaboratively to establish safe, scalable, and ethical frameworks for nanotechnology deployment in EVs.

In summary, nanotechnology holds the potential to not only accelerate the adoption of EVs but also to redefine the standards of sustainability, energy efficiency, and innovation in the global transportation sector.

FUNDING

This research received no specific grant from any funding agency in the public, commercial, or not-forprofit sectors.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

REFERENCES

Alsaiari, N. S., Alzahrani, F. M., Amari, A., Osman, H., Harharah, H. N., Noureddine Elboughdiri, & Tahoon, M. A., Plant and Microbial Approaches as Green Methods for the Synthesis of Nanomaterials: Synthesis, Applications, and Future Perspectives, *Mol.*, 28(1), 463–463 (2023). https://doi.org/10.3390/molecules28010463

Balaji, N. K. R., Pratyusha, D., Sravanthi, B., and Jayakiran, R. E., Recent AI Applications in Electrical Vehicles for Sustainability, *Int. J. Mech. Eng.,* 11(3), 50–64 (2024). https://doi.org/10.14445/23488360/ijme-v11i3p106

Dresselhaus, M. S and Thomas, I. L., Alternative energy technologies, *Nat.*, 414, 332–337 (2001). https://doi.org/10.1038/35104599

Esiri, A. E., Mensah, J. K., Darlington, E. E., Ogundipe, B. O. and Heavens, A. I., Assessing the environmental footprint of the electric vehicle supply chain, *Magna Scientia Adv. Res. Rev.*, 8(2), 219–227 (2023). https://doi.org/10.30574/msarr.2023.8.2.0099

Fengbo, W., Jinbao, S. and Tantan, X., Oxide ceramic coatings on orthopaedic implants: A review of TiO2 AND Al2O3, *Ceram. Silik.*, 67(4), 525–542 (2023). https://doi.org/10.13168/cs.2023.005

Goti, E., Mura, A., Confiengo, G. M. G. D. and Casalegno, V., The tribological performance of super-hard Ta:C DLC coatings obtained by low-temperature PVD, *Ceram. Int.,* 49(24), 40193–40210 (2023). https://doi.org/10.1016/j.ceramint.2023.09.355

Iravani, S., Green synthesis of metal nano particles using plants. *Green Chem.,* 13(10), 2638–2650 (2011). https://doi.org/10.1039/c1gc15386b

Mehdi Honarvar Nazari, Yan Zhang, Ali Mahmoodi, Gang Xu, Jiang Yu, Junliang Wu, Xianming Shi, Nanocomposite organic coatings for corrosion protection of metals: A review of recent advances, *Progress in Organic Coatings*, 162, 2022, 106573. https://doi.org/10.1016/j.porgcoat.2021.106573.

Janek, J. and Zeier, W. G., A solid future for battery development: The rise of solid-state electrolytes, *Nat. Energy,* 1, 16141 (2016). https://doi.org/10.1038/nenergy.2016.141

Kan, J., Optimization of Electrode Materials for Lithium-Ion and Sodium-Ion Batteries in Electric Vehicles, *Highlights Sci. Eng. Technol.,* 121, 619–624 (2024). https://doi.org/10.54097/xca1qg21

Keller, A. A., McFerran, S., Lazareva, A. and Suh, S., Global life cycle releases of engineered nanomaterials, *J. Nanopart. Res.,* 15(6), 1692 (2013). https://doi.org/10.1007/s11051-013-1692-4

Khan, N. I. and Halder, S., Self-healing fiber-reinforced polymer composites for their potential structural applications, *Self-Healing Polymer-Based Systems*, 455–472 (2020). https://doi.org/10.1016/b978-0-12-818450-9.00015-5

Kardani, S. L., Nanocarrier-based formulations: Regulatory Challenges, Ethical and Safety Considerations in Pharmaceuticals, *J. Pharm.,* 18(02), (2024). https://doi.org/10.22377/ajp.v18i02.5444

Li, P., Luo, S., Zhang, L., 202, Q., Wang, Y., Lin, Y., Xu, C., Guo, J., Cheali, P. and Xia, X., Progress, challenges, and prospects of spent lithium-ion batteries recycling: A review, *J. Energy Chem.,* 89, 144–171(2024). https://doi.org/10.1016/j.jechem.2023.10.012

Manthiram, A., A reflection on lithium-ion battery cathode chemistry, *Nat. Commun*., 11(1), 1550 (2020). https://doi.org/10.1038/s41467-020-15355-0

Maynard, A. D., Warheit, D. B. and Philbert, M. A., The new toxicology of sophisticated materials: Nano toxicology and beyond, *Toxicol. Sci.,* 120(suppl_1), S109–S129 (2011). https://doi.org/10.1093/toxsci/kfq372

Malhotra, R., Han, Y. M., Morin, J. L. P., E. K., Luong-Van, Chew, R. J. J., Neto, A. H. C., Nijhuis, C.A. and Rosa, V., Inhibiting Corrosion of Biomedical-Grade Ti-6Al-4V Alloys with Graphene Nanocoating, *J. Dent. Res*., 99(3), 285–292 (2020). https://doi.org/10.1177/0022034519897003

Mohanty, A. K., Vivekanandhan, S., Pin, J. M. and Misra, M., Composites from renewable and sustainable resources: Challenges and innovations, *Sci*., 362(6414), 536–542 (2018). https://doi.org/10.1126/science.aat9072

Nel., Toxic potential of materials at the nano-level, *Sci*., 311(5761), 622–627 (2006). https://doi.org/10.1126/science.1114397

Naskar, A. K., Keum, J. K. and Boeman, R. G., Polymer matrix nanocomposites for automotive structural components, *Nat. Nanotechnol*., 11(12), 1026–1030 (2016). https://doi.org/10.1038/nnano.2016.262

Roco, M. C., Nanotechnology: convergence with modern biology and medicine, *Curr. Opin. Biotechnol.,* 14(3), 337–346 (2003). https://doi.org/10.1016/S0958-1669(03)00068-5

Sburlan, I. C., Vasile, I. and Tudor, E., Comparative study between semiconductor power devices based on silicon Si, silicon carbide SiC and gallium nitrate GaN used in the electrical system subassembly of an electric vehicle, 2021 *Int. Semicond. Conf.* (CAS), 107–110 (2021). https://doi.org/10.1109/cas52836.2021.9604127

Shafique, M. and Luo, X., Nanotechnology in Transportation Vehicles: An Overview of Its Applications, Environmental, Health and Safety *Concerns, Mater*., 12(15), 2493–2493 (2019). https://doi.org/10.3390/ma12152493

Tarascon, J. M. and Armand, M., Issues and challenges facing rechargeable lithium batteries, *Nat.,* 414, 359–367 (2001). https://doi.org/10.1038/35104644

United Nations., transforming our world: the 2030 Agenda for Sustainable Development, (2015). https://sdgs.un.org/2030agenda

Vahidi, A. and Sciarretta, A., Energy saving potentials of connected and automated vehicles, *Transp. Res. Part C: Emerging Technol.,* 95, 822–843 (2018). https://doi.org/10.1016/j.trc.2018.09.001

Wang, Y., The application challenge of electric vehicles, *Appl. Comput. Eng*., 26(1), 86–91(2023). https://doi.org/10.54254/2755-2721/26/20230800

White, S. R., Sottos, N. R., Geubelle, P. H., Moore, J. S., Kessler, M. R., Sriram, S. R., Brown, E. N. and Viswanathan, S., Autonomic healing of polymer composites, *Nat.,* 409, 794–797 (2001). https://doi.org/10.1038/35057232

Xu, Y., Innovations in Energy Through Nanomaterials Enhancing Solid-State Battery Safety and Efficacy, *Highlights Sci. Eng. Technol.,* 116, 125–131 (2024). https://doi.org/10.54097/6p096226

Zhang, L., Wu, H. B. & Lou, X. W., Nanostructured materials for energy conversion and storage and Nano-structured silicon anodes for advanced lithium-ion batteries, *Adv. Energy Mater*., 7, 1300958 (2019). https://doi.org/10.1002/aenm.201300958

Zheng, W., Diverse Applications of Frontier Nanotechnology in Electric Vehicles, *Highlights Sci. Eng. Technol.,* 121, 510–521 (2024). https://doi.org/10.54097/7he20n09