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Review

A Review on Composite Materials for Energy Harvesting in Electric Vehicles

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Abstract: The field of energy harvesting is expanding to power various devices, including electric vehicles, with energy derived from their surrounding environments. The unique mechanical and electrical qualities of composite materials make them ideal for energy harvesting applications, and they have shown tremendous promise in this area. Yet additional studies are needed to fully grasp the promise of composite materials for energy harvesting in electric vehicles. This article reviews composite materials used for energy harvesting in electric vehicles, discussing mechanical characteristics, electrical conductivity, thermal stability, and cost-effectiveness. As a bonus, it delves into using composites in piezoelectric, electromagnetic, and thermoelectric energy harvesters. The high strength-to-weight ratio provided by composite materials is a major benefit for energy harvesting. Especially important in electric vehicles, where saving weight means saving money at the pump and driving farther between charges, this quality is a boon to the field. Many composite materials and their possible uses in energy harvesting systems are discussed in the article. These composites include polymer-based composites, metal-based composites, bio-waste-based hybrid composites and cement-based composites. In addition to describing the promising applications of composite materials for energy harvesting in electric vehicles, the article delves into the obstacles that must be overcome before the technology can reach its full potential. Energy harvesting devices could be more effective and reliable if composite materials were cheaper and less prone to damage. Further study is also required to determine the durability and dependability of composite materials for use in energy harvesting. However, composite materials show promise for energy harvesting in E.V.s. Further study and development are required before their full potential can be realized. This article discusses the significant challenges and potential for future research and development in composite materials for energy harvesting in electric vehicles. It thoroughly evaluates the latest advances and trends in this field.

Keywords: composite materials; energy harvesting; energy efficiency; electric vehicles

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1. Introduction

The use of composite materials in electric vehicles for energy harvesting is rising [1,2]. Energy harvesting involves transforming ambient energy into electric power, reducing reliance on the vehicle's battery and enhancing overall energy efficiency [3,4]. Composite materials have distinctive mechanical and electrical characteristics that make them suitable for energy conversion, and their usage in energy harvesting systems is increasing [5–7]. This review article aims to present a comprehensive survey of composite materials for energy harvesting in electric vehicles. The article will commence with an overview of composite materials for energy harvesting in electric vehicles, including the types of composite materials used, a summary of the existing research, and a state-of-the-art review.

The article will then discuss the characteristics of composite materials for energy harvesting, including mechanical properties, electrical conductivity, thermal stability, and cost-effectiveness. The article will also explore the various applications of composite materials in energy harvesting systems, including piezoelectric, electromagnetic, and thermoelectric energy harvesting. Finally, the article will discuss the challenges and opportunities for future research and development in this field.

This review article's key findings and contributions include a comprehensive overview of composite materials for energy harvesting in electric vehicles. This review will provide a valuable resource for researchers, engineers, and practitioners working in the field of energy harvesting and electric vehicles.

The article will comprehensively discuss the various types of composite materials used for energy harvesting, the characteristics that make them well-suited for this application, and the various applications of composite materials in energy harvesting systems. The article will also critically evaluate the challenges and opportunities for future research and development in this field.

In conclusion, using composite materials in energy harvesting systems is becoming increasingly prevalent due to their unique combination of mechanical and electrical properties. This review article will provide a comprehensive overview of the current state of composite materials for energy harvesting in electric vehicles and will provide valuable insights for researchers, engineers, and practitioners working in this field.

2. Background and State of the Art

2.1. Overview of Energy Harvesting in Electric Vehicles

Energy harvesting in electric vehicles is a growing field that aims to optimize the energy efficiency of these vehicles by converting ambient energy into usable electrical energy. This technique plays a crucial role in reducing the dependence on the vehicle's battery and improving its overall energy efficiency. The demand for energy-efficient vehicles has been increasing in recent years, driving the interest in energy-harvesting systems for electric vehicles [2,8–11].

Various energy conversion principles can be used for energy harvesting in electric vehicles, including piezoelectric, electromagnetic, and thermoelectric energy conversion [2,12]. Piezoelectric energy harvesting involves the conversion of mechanical energy into electrical energy through the use of piezoelectric materials [13]. Electromagnetic energy harvesting involves the conversion of magnetic energy into electrical energy through the use of electromagnetic induction [14]. Thermoelectric energy harvesting involves the conversion of thermal energy into electrical energy through the use of thermoelectric materials [15]. Each energy conversion principle has its advantages and limitations [16]. For example, piezoelectric energy harvesting is highly efficient. It can be used in a wide range of applications. However, it is limited because it requires significant mechanical energy to generate a small amount of electrical energy [17]. Electromagnetic energy harvesting is highly efficient and can be used to generate electrical energy from a variety of sources, but it requires a strong magnetic field to work effectively [17].

Thermoelectric energy harvesting is highly efficient and can generate electrical energy from various sources, but it requires a temperature gradient to work effectively [18]. Using energy harvesting systems in electric vehicles offers many benefits, including increased energy efficiency, reduced dependence on the vehicle's battery, and reduced carbon emissions. However, several challenges must be addressed to make energy harvesting systems more effective and practical for their use in electric vehicles. These challenges include improving energy conversion efficiency, reducing energy harvesting systems' costs, and ensuring their reliability and durability over time [2,19,20].

2.2. Types of Composite Materials Used in Energy Harvesting

Using composite materials in energy harvesting systems in electric vehicles offers several advantages over traditional materials [2]. For instance, composites can provide higher mechanical strength and stiffness, improved thermal stability, and better electrical conductivity than traditional materials [21–24]. Additionally, composite materials can be designed to have specific electrical and mechanical properties to meet the specific needs of energy harvesting systems in electric vehicles.

Polymer-based composites are often favored for energy harvesting applications due to their low cost, ease of processing, and high flexibility. The polymer matrix in these composites can be designed to have specific electrical and mechanical properties and can be optimized to improve the overall energy harvesting performance [25–27]. For instance, carbon fiber-reinforced polymer composites are often used for energy harvesting applications due to their high electrical conductivity, mechanical strength, and low weight [28,29]. Piezoelectric composites made from polymers are a popular choice for energy-harvesting applications. This field of research has gained significant attention due to the advantages of piezoelectric materials in converting mechanical energy into electrical energy. Compared to ceramic-based composites, polymeric piezoelectric composites offer the convenience of mechanical flexibility, a suitable voltage with sufficient power output, lower manufacturing cost, and rapid processing [26]. Figure 1 represents a simple structure of a battery comprising carbon fibers and multifunctional polymer matrix.

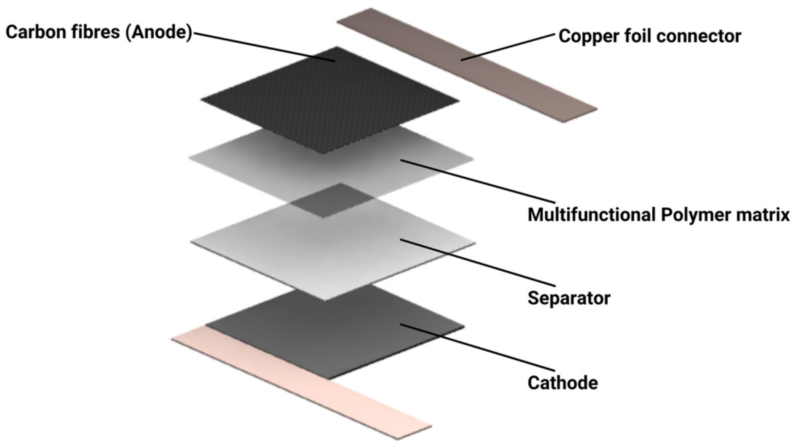

Figure 1. Structural composite battery.

One of the most commonly used piezoelectric polymers is polyvinylidene fluoride (PVDF) due to its high flexibility and piezoelectric performance. Studies have investigated incorporating PVDF-based piezoelectric polymers into engineered cementitious composites (E.C.C.) to create an innovative energy harvesting system that can scavenge energy from mechanical deflection of E.C.C. Results have shown that the voltage/power generated by the system is more efficient for longer PVDF samples, indicating the potential for the development of multi-functional building materials [30].

Electrostrictive polymers, a type of high-strain actuator, are also being investigated for energy harvesting. These polymers offer potential advantages over classical piezoelectric ceramic materials. A model has been developed that can predict the energy harvesting capabilities of an electrostrictive polymer composite (E.P.C.).

An equivalent electrical scheme has been developed using a model of current, which was validated on a macroscopic level. An empirical relationship has been established to predict the power value from the electrostriction coefficient, the dielectric permittivity, and the material's compliance. Results have indicated that dielectric permittivity is the crucial parameter for energy harvesting in E.P.C.s [31].

Yet another promising technology for energy harvesting is the triboelectric nanogenerator (T.E.N.G.). It converts different mechanical energies into electrical energy by utilizing the triboelectric effect. Over the years, significant progress has been made in developing numerous new classes of polymeric and composite polymeric materials for T.E.N.G.s. It has been observed that composite polymeric materials have yielded better output performance compared to using only polymeric materials in most cases [27,32]. Thus, it can be said that polymer-based composites hold immense potential for energy harvesting applications owing to their flexible nature, suitable voltage providing sufficient power output, lower manufacturing costs, and quick processing.

The field of energy harvesting continues to witness active research in the development of new classes of polymeric materials and composite polymeric materials, which is expected to open up significant avenues for their application in various domains. On the other hand, metal-based composites offer higher electrical conductivity, thermal stability, and mechanical strength than polymer-based composites. Metal-based composites, such as electromagnetic energy harvesting, are often used in energy harvesting applications that require a high power output. The metal matrix in these composites can be designed to have specific electrical and mechanical properties and can be optimized to improve the overall energy harvesting performance [33–35]. Using lightweight metal matrix composites for energy harvesting has garnered significant interest recently, with potential applications in the aerospace, automotive, and sporting goods industries [36]. One promising example is the FeCo/AlSi composite, which exhibits excellent energy conversion properties under compression. Studies have investigated the effects of specific structural designs and reverse magnetic fields on energy conversion in these composites. The findings indicate that incorporating twisted FeCo wire in the design improves the output performance of the magnetostrictive FeCo/AlSi composite compared to using straight FeCo wire. Additionally, it was discovered that energy conversion efficiency is notably enhanced by reverse magnetization (N-N mode) [37].

Research has also examined the energy-harvesting properties of FeCo/AlSi composites under impact loading. Studies have fabricated these composites using a casting process and measured their inverse magnetostrictive characteristics under compressive loading. Additionally, researchers have conducted cyclic loading tests on energy-harvesting devices made from FeCo/AlSi composite specimens, two magnets, and a coil. These tests have shown that the devices have excellent durability for impact loading and yield good impact energy-harvesting properties. The FeCo/AlSi-based energy-harvesting devices benefit from the zigzag interface and chemical bonding between the Fe-Co fiber and the Al-Si matrix, which effectively transfer stress and strain, enhancing their energy-harvesting capabilities [38]. These studies suggest that metal-based composites hold promise as a material for energy-harvesting applications in electric vehicles and beyond. Several studies have explored the use of bio-waste-based hybrid composite materials, comprising biowastes such as orange peel, fish scales, and pomegranate peel, as fillers in polymer matrices to induce piezoelectricity. These hybrid materials exhibit significant piezoelectric properties, with power densities ranging from 28.5 $\mu W/cm^2$ to 135 W/cm^2, making them suitable for energy harvesting applications [39–43].

For instance, research on orange peel-poly(vinylidene fluoride) hybrids revealed that adding smaller orange peel powder as filler induced the piezoelectric effect in the polymer matrix, resulting in a 70% electroactive phase in the hybrid. Using the hybrid material, an integrated device was created for energy harvesting, which produced an impressive open circuit voltage of 90 V and power of 135 W/cm^2 by finger tapping.

The hybrid nanogenerator could light up L.E.D.s using various human movements such as bending, twisting, sliding doors, and walking. The mechanism behind the enhanced piezoelectricity in the hybrid was elucidated through structural, morphological, and thermal analyses [43]. Likewise, a study on fish scale-polymer hybrids reported the development of a new bio-waste hybrid for self-powered nanogenerators using self-aligned collagen fibrous fish scales. The fish scales induced the electroactive phase over their surface through synergistic effects, resulting in uniform distribution of scale particles in the polymer matrix and γ-phase formation in the presence of the filler. The energy harvesting performance of the bio-waste-based hybrid device exhibited a high open circuit voltage of 22 V and a high energy density of 28.5 $\mu W/cm^2$, which was considerably superior to that of existing waste-based devices [39]. Another study focused on pomegranate peel-poly(vinylidene fluoride) hybrids, which induced piezoelectricity in the polymer matrix, as revealed through X-ray diffraction, spectroscopic, and calorimetric studies. A model was developed to focus on the synergism between two piezoelectric phases (matrix and filler), which was appropriate for energy harvesting.

The developed device exhibited a high open circuit voltage of 65 V and a power density of 84 $\mu W/cm^2$ and could generate power under human movements such as walking, twisting, and bending, among others [42]. Thus, using bio-waste materials for energy harvesting through the development of piezoelectric hybrids is a promising approach. The hybrids exhibit significant piezoelectric properties and can generate power from various human movements, making them suitable for energy harvesting applications. The underlying mechanisms of enhanced piezoelectricity in the hybrids have been revealed through structural, morphological, and thermal studies. Using bio-waste for energy harvesting can help reduce landfills and environmental pollution and can be one of the solutions to utilize bio-waste.

Recent research also indicates that cement-based composites show promising potential for use in energy harvesting in various applications. One specific application is the conversion of temperature differences between indoor and outdoor surfaces of cement structures in buildings into electrical energy using thermoelectric-based cement composites. This review analyzed multiple papers that investigated the use of thermoelectric-based cement composites for energy harvesting and thermal sensing. These materials can be utilized in various structures, including dams, bridges, housing, roads, and buildings. Construction materials that absorb solar energy can be stored thermally and harvested using thermoelectric-based cement materials. The addition of carbon fibers to cement significantly improved hole conduction, resulting in a Seebeck coefficient of -17 $\mu V/^{\circ}C$, which is significantly higher than the pristine carbon fiber reinforced cement (-0.8 $\mu V/^{\circ}C$). Conversely, steel fiber cement pastes exhibited higher volume electrical resistivity than carbon fiber cement pastes, even with a 1% by mass of cement steel fiber content [44,45]. One reviewed paper discussed using graphene nanoplatelets in cement-based composites for energy harvesting. The researchers found that the maximum electrical conductivity of these composites was 16.2 Scm^{-1}, and the Seebeck coefficient was 34.0 μVK^{-1}. The specimens were characterized for the first time using Hall coefficient measurement, and all demonstrated p-type semiconductor behavior. Thermal diffusivity measurements were also carried out, and the highest figure of merit (0.44×10^{-3}) was achieved at approximately 70 °C [46].

The thermoelectric characteristics of expanded graphite/cement-based composites (E.G.C.C.) were analyzed in a different study. These composites were manufactured through a special dry-pressing and curing process. The researchers discovered that E.G.C.C. exhibited distinctive semiconducting electrical behavior and a relatively high Seebeck coefficient in the temperature range between 30 and 100 °C. Furthermore, the electrical conductivity of E.G.C.C. was exceptionally high at 24.8 S/cm for cement-based materials. They achieved a higher power factor and thermoelectric figure of merit (6.82×10^{-4}) while maintaining the thermal conductivity at 3.213 $Wm^{-1}K^{-1}$. Moreover, E.G.C.C. retained a high compressive strength of 106.51 MPa [47].

One of the reviewed papers discussed the use of piezocatalysis for environmental remediation. Piezocatalysis is the term used to describe the catalytic activity demonstrated by piezoelectric materials when subjected to adequate mechanical stimulation. Cement composites have been investigated for this application, showing promising results in achieving water treatment under dark conditions [48]. The research findings suggest that cement-based composites have substantial potential for energy harvesting across multiple applications. However, significant challenges must be addressed to improve the cost-effectiveness, durability, and optimization of the manufacturing process for efficient and large-scale operation. Further research in these areas is necessary to realize the full potential of cement-based composites for energy harvesting. Table 1 provides a comparison of different types of composites used for energy harvesting, highlighting their advantages and potential applications.

Table 1. Comparison of Composite Materials for Energy Harvesting.

Composite Material	Advantages	Applications
Polymer-based composites	• Inexpensive • Easy to work with • Flexible • Can be designed and optimized for specific properties	• Used in electric vehicles • Piezoelectric composites • Triboelectric nanogenerators
Metal-based composites	• High electrical conductivity • Strong and durable • Can be designed and optimized for specific properties	• Used in electromagnetic energy harvesting • Aerospace • Automotive • Sporting goods
Bio-waste-based hybrid composites	• Significant piezoelectric properties • Can generate power from various human movements	• Energy harvesting through development of piezoelectric hybrids
Cement-based composites	• Can convert temperature differences into electrical energy. • Can be used in various structures	• Thermoelectric-based cement composites • Piezo catalysis for environmental remediation

2.3. Review of Existing Studies on Composite Materials for Energy Harvesting in Electric Vehicles

Several studies have explored using composite materials for energy harvesting in electric vehicles. Piezoelectric energy harvesting systems are one of the composite materials' most promising applications.

Piezoelectric materials generate an electrical charge when subjected to mechanical stress, and composite materials have been shown to have high piezoelectric output. Several studies have investigated using composite materials for piezoelectric energy harvesting in electric vehicles, including composite materials for vibration energy harvesting and road-induced energy harvesting [13,26,49–56]. Composite materials have also been shown to be useful in electromagnetic energy harvesting systems. Electromagnetic energy harvesting involves converting ambient electromagnetic energy into usable electrical energy.

Composite materials have been shown to have high electrical conductivity, which makes them well-suited for electromagnetic energy harvesting systems. Several studies have investigated the use of composite materials for electromagnetic energy harvesting in electric vehicles, including the use of composite materials for wireless power transfer and for ambient electromagnetic energy harvesting [56–61].

Thermoelectric energy harvesting involves converting heat energy into usable electrical energy. Composite materials have been shown to have good thermal stability, making them well-suited for thermoelectric energy harvesting systems. Several studies have investigated using composite materials for thermoelectric energy harvesting in electric vehicles, including composite materials for exhaust gas energy harvesting and ambient heat energy harvesting [2,62–68]. Composite materials, have thus shown immense potential for energy harvesting in electric vehicles. They offer a unique combination of mechanical and electrical properties, including high piezoelectric output, high electrical conductivity, and good thermal stability, which make them well-suited for energy harvesting systems. The use of composite materials for energy harvesting in electric vehicles is an area of ongoing research, and there is still much to be learned about the most effective ways to harness the potential of composite materials for energy harvesting.

Nevertheless, the existing studies suggest that composite materials have enormous potential for energy harvesting in electric vehicles and offer exciting opportunities for future research and development. Low-dimensional structures have emerged as a promising avenue for energy storage devices. Figure 2 illustrates the different types of low-dimensional structures and their applications in energy storage. While much of the research in this area is still in its early stages, several studies have explored the use of low-dimensional structures such as carbon nanotubes, graphene, and metal-organic frameworks for energy storage in electric vehicles. These studies have shown that low-dimensional structures offer high surface area, high electrical conductivity, and excellent mechanical strength, which make them ideal for energy storage applications in electric vehicles.

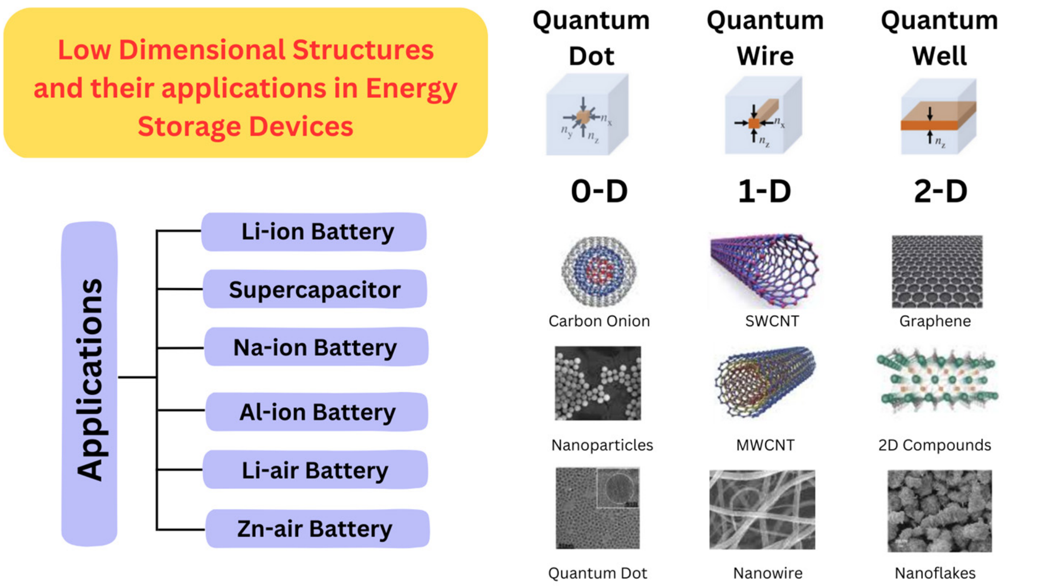

Figure 2. Low dimensional structures and their applications in energy storage devices.

3. Characteristics of Composite Materials for Energy Harvesting

3.1. Mechanical Properties

Mechanical properties are crucial in selecting composite materials for energy harvesting in electric vehicles. The success of energy harvesting systems depends on the ability of the materials to withstand the mechanical stress and strain generated during energy conversion [69,70]. The mechanical properties of composite materials vary depending on the reinforcing material and matrix material used.

Polymer-based composites, consisting of a polymer matrix and reinforcing material such as carbon, glass, or ceramic fibers, are known for their good toughness and ductility. On the other hand, metal-based composites, which consist of a metal matrix and reinforcing material such as ceramic or polymer fibers, exhibit high strength and stiffness [61,71–73]. When choosing composite materials for energy harvesting, it is crucial to consider their mechanical properties, such as tensile strength, compressive strength, modulus of elasticity, and impact resistance, as well as their durability, fatigue resistance, and stability under repeated loading. The mechanical properties of the composite material must be optimized to ensure its durability, reliability, and efficiency in energy harvesting systems.

Therefore, the development and characterization of composite materials for energy harvesting in electric vehicles must consider their mechanical properties and energy conversion properties, such as electrical conductivity and thermal stability, to achieve optimal performance.

3.2. Electrical Conductivity

Electrical conductivity is a crucial aspect of composite materials regarding energy harvesting in electric vehicles [74]. The ability of these materials to conduct electricity effectively makes energy harvesting possible. The electrical conductivity of composite materials varies depending on the combination of reinforcing material and matrix material used [74,75]. Metal-based composites tend to have higher electrical conductivity, whereas polymer-based composites tend to have lower electrical conductivity. However, the electrical conductivity of polymer-based composites can be improved by using conductive fillers or conductive fibers in the composite structure. It is important to note that electrical conductivity alone may not be enough to determine the suitability of a composite material for energy harvesting. Other factors, such as mechanical properties and thermal stability, must also be considered. Overall, the electrical conductivity of composite materials is a crucial factor in the effectiveness and efficiency of energy harvesting in electric vehicles [76–80].

3.3. Thermal Stability

Thermal stability is a crucial characteristic of composite materials for energy harvesting in electric vehicles. Energy harvesting systems in E.V.s can generate heat, and composite materials must withstand the thermal stress associated with energy harvesting operations. The thermal stability of composite materials is also determined by the reinforcing material and matrix material used. For instance, metal-based composites possess good thermal stability, while polymer-based composites tend to have lower thermal stability [81–88]. Thermal stability is an essential factor in ensuring the longevity and reliability of the energy harvesting system [85,89,90]. Suppose the composite material is not able to withstand high temperatures. In that case, it can deteriorate or even fail [83], reducing the efficiency of the energy harvesting system. In severe cases, it can even result in safety hazards. Hence, when selecting composite materials for energy harvesting in E.V.s, it is critical to consider the material's thermal stability.

In addition to the thermal stability of the composite material itself, it is also important to consider the thermal stability of the energy harvesting system as a whole. For instance, the energy harvesting system must be designed to effectively dissipate heat to prevent excessive thermal stress from affecting the performance and lifespan of the energy harvesting system [89]. Hence, a combination of a thermally stable composite material and an effective thermal management system is necessary for ensuring the optimal performance and reliability of the energy harvesting system in electric vehicles.

3.4. Cost-Effectiveness

Cost-effectiveness is a critical consideration when selecting composite materials for energy harvesting in electric vehicles [62,91,92]. The affordability of energy harvesting systems is essential for their widespread adoption and implementation in the automotive industry [93,94]. The cost of composite materials is determined by several factors, including the reinforcing material and matrix material used and the manufacturing process.

Metal-based composites are often more costly than polymer-based composites due to the cost of the metal matrix. However, metal-based composites typically perform better in energy harvesting systems, making them a more attractive option despite the higher cost. On the other hand, polymer-based composites are often more cost-effective due to the lower cost of the polymer matrix. While these composites may perform less in energy harvesting systems, they can still be viable for applications where cost is a primary concern [95,96].

Ultimately, the cost-effectiveness of composite materials for energy harvesting in electric vehicles depends on a careful balance between performance and cost. Manufacturers must consider the trade-offs between performance and cost when selecting composite materials for energy harvesting systems in electric vehicles. In the future, researchers and manufacturers should focus on developing cost-effective composite materials with improved performance for energy harvesting in electric vehicles.

In conclusion, composite materials have several key characteristics that make them suitable for energy harvesting in electric vehicles.

These include mechanical properties such as toughness, ductility, strength, stiffness, electrical conductivity, thermal stability, and cost-effectiveness. The specific characteristics of composite materials for energy harvesting in electric vehicles will depend on the reinforcing material and matrix material used, and the manufacturing process used to produce the composite material. By carefully selecting the appropriate composite material, it is possible to optimize electric vehicles' energy harvesting performance while ensuring that the energy harvesting system is cost-effective and economically viable.

4. Applications of Composite Materials for Energy Harvesting in Electric Vehicles

4.1. Piezoelectric Energy Harvesting

Piezoelectric energy harvesting is a technique that converts mechanical energy into electrical energy through piezoelectric materials [97]. When subjected to mechanical stress, these materials generate an electrical potential, making them ideal for energy harvesting in electric vehicles [98–100]. Composite materials made from piezoelectric ceramics and polymers have proven effective in piezoelectric energy harvesting systems for electric vehicles. The polymers used in these composite materials provide improved mechanical properties, such as flexibility and resistance to mechanical stress. Additionally, the piezoelectric ceramics used in these composites enhance the electrical conductivity of the composite, making it more efficient at generating electrical energy [101–103]. However, piezoelectric energy harvesting has its limitations. The energy generated is relatively small compared to other energy harvesting systems, making it more suitable for low-power applications, such as powering sensors or other low-power electronics in electric vehicles [13,62,104]. Despite this limitation, piezoelectric energy harvesting remains a promising technique for improving the energy efficiency of electric vehicles.

4.2. Electromagnetic Energy Harvesting

Electromagnetic energy harvesting involves converting electromagnetic energy into electrical energy using electromagnetic generators [105,106]. Composite materials, such as metal matrix composites, have been utilized in electromagnetic energy harvesting systems for electric vehicles and can be utilized to create electromagnetic generators. Composite materials made from metal matrix composites offer several advantages for electromagnetic energy harvesting. Metal matrix composites have high electrical conductivity, which makes them well-suited for generating electrical energy from electromagnetic fields.

Additionally, metal matrix composites have high thermal stability, making them well-suited for energy harvesting systems in electric vehicles, where elevated temperatures are generated [86,107,108]. One limitation of electromagnetic energy harvesting is that it requires a strong electromagnetic field to generate electrical energy. This makes electromagnetic energy harvesting better suited for applications with strong electromagnetic fields, such as in high-speed electric vehicles [109].

4.3. Thermoelectric Energy Harvesting

Thermoelectric energy harvesting involves converting thermal energy into electrical energy using thermoelectric materials [5,110,111]. Thermoelectric materials generate an electrical potential when subjected to a temperature gradient, making them well-suited for energy harvesting in electric vehicles [112,113]. Composite materials made from thermoelectric ceramics and polymers have been used in thermoelectric energy harvesting systems for electric vehicles. Composite materials made from thermoelectric ceramics and polymers offer several advantages for thermoelectric energy harvesting. The polymers used in these composites can improve the mechanical properties of the composite, making it more flexible and resistant to mechanical stress. Additionally, the thermoelectric ceramics used in these composites can improve the electrical conductivity of the composite, making it more effective at generating electrical energy [114–117].

One limitation of thermoelectric energy harvesting is that the amount of energy generated is relatively insignificant compared to other energy harvesting systems [66,118,119]. This makes thermoelectric energy harvesting better suited for low-power applications, such as powering sensors or other low-power electronics in electric vehicles.

4.4. Discussion of the Advantages and Limitations of Each Application

Each of the three energy harvesting systems discussed has its own advantages and limitations. Piezoelectric energy harvesting is well suited for low-power applications, such as powering sensors or other low-power electronics in electric vehicles [3,120].

Using composite materials made from piezoelectric ceramics and polymers can improve the mechanical and electrical properties of the energy harvesting system, making it more durable and effective at generating electrical energy [121–125]. Electromagnetic energy harvesting is well suited for applications with strong electromagnetic fields, such as high-speed electric vehicles [126–130]. Using composite materials made from metal matrix composites can improve the energy harvesting system's electrical conductivity and thermal stability, making it more effective at generating electrical energy [131–134]. However, electromagnetic energy harvesting requires a strong electromagnetic field, which may not be present in all-electric vehicles [2,135,136].

Thermoelectric energy harvesting is well suited for low-power applications, such as powering sensors or other electronics in electric vehicles [2,15,137–139]. Using composite materials made from thermoelectric ceramics and polymers can improve the mechanical and electrical properties [112,115,140,141] of the energy harvesting system, making it more durable and effective at generating electrical energy.

However, the amount of energy generated by thermoelectric energy harvesting is relatively small compared to other energy harvesting systems [66,142,143]. In conclusion, each energy harvesting system discussed has its advantages and limitations. Using composite materials can improve the properties of each energy harvesting system, making it more effective at generating electrical energy in electric vehicles. However, the choice of energy harvesting system will depend on the specific needs and requirements of each electric vehicle application. Table 2 provides a comparison of different types of methods/techniques used for energy harvesting, highlighting their advantages, disadvantages and potential applications.

Table 2. Comparison of Energy Harvesting Techniques.

Technique	Principle	Advantages	Disadvantages	Applications
Piezoelectric	Converts mechanical energy into electrical energy using piezoelectric materials	Improved mechanical properties (flexibility, resistance to mechanical stress) provided by polymers in composites, enhanced electrical conductivity provided by piezoelectric ceramics	Relatively small energy generated compared to other techniques	Low-power applications, such as powering sensors
Electromagnetic	Converts electromagnetic energy into electrical energy using electromagnetic generators	High electrical conductivity provided by metal matrix composites, high thermal stability	Requires a strong electromagnetic field to generate electrical energy	Applications with strong electromagnetic fields, energy harvesting systems in electric vehicles
Thermoelectric	Converts thermal energy into electrical energy using thermoelectric materials	Generates electrical potential when subjected to temperature gradient, improved mechanical properties and electrical conductivity provided by polymers in composites	Amount of energy generated is relatively insignificant compared to other techniques	Energy harvesting in electric vehicles

5. Challenges and Opportunities

5.1. Challenges in the Development and Implementation of Composite Materials for Energy Harvesting

Developing and implementing composite materials for energy harvesting in electric vehicles involves several challenges. One of the biggest challenges is finding the right combination of materials that provide the desired electrical conductivity, thermal stability, and mechanical properties [144,145]. These properties are often trade-offs, and finding the right balance between them can be difficult [146]. For example, increasing the electrical conductivity of a composite material often decreases its thermal stability, making it more difficult to use in high-temperature applications [147–150]. Another challenge is the inflated cost of the composite materials used in energy harvesting systems.

The excessive cost of these materials can make implementing energy harvesting systems in large-scale electric vehicles difficult, especially compared to traditional energy sources such as batteries [26,151–153]. Another challenge is the lack of standardization in composite materials for energy harvesting. There is a need for standardization in terms of materials, processing methods, and testing procedures to ensure that energy harvesting systems are reliable, consistent, and cost-effective [154,155].

Finally, there is a lack of understanding about composite materials' long-term performance and durability for energy harvesting in electric vehicles. More research is needed to understand the behavior of these materials over time and how they will perform in real-world applications [156–158].

In conclusion, the development and implementation of composite materials for energy harvesting in electric vehicles involves several challenges, including the need for the right combination of materials, the excessive cost of these materials, the lack of standardization in the field, and the lack of understanding about the long-term performance and durability of these materials. Addressing these challenges will be crucial to fully realize the potential of composite materials for energy harvesting in electric vehicles.

5.2. Opportunities for Future Research and Development

The field of composite materials for energy harvesting in electric vehicles holds great promise for the future, and there are numerous opportunities for further research and development. One of the key areas for future research is the development of new composite materials that can improve the performance and efficiency of energy harvesting systems. This could include developing new piezoelectric, electromagnetic, and thermoelectric materials with enhanced properties, such as increased electrical conductivity, thermal stability, and mechanical strength [74,159]. The use of biowaste-based hybrid composites and cement-based composites can be emphasized as it shall provide a solution for energy harvesting and facilitate the reusability of the wastes, which otherwise would have added to landfills [42,44].

Another key area for future research is optimizing the manufacturing processes for composite materials. Developing cost-effective and scalable manufacturing processes is critical for widely adopting composite materials in energy harvesting systems. One potential approach for developing cost-effective and scalable manufacturing process systems could be to use novel processing techniques, such as 3D printing and nanotechnology, to create complex and functional composite structures [38,160,161].

Moreover, forthcoming research should prioritize integrating current composite materials into energy harvesting systems designed for electric vehicles. This might involve formulating more effective and scalable energy harvesting systems, along with integrating these systems into existing electric vehicle frameworks [2,92]. The goal of this research should be to create energy harvesting systems that are cost-effective, reliable, and scalable and can provide a significant energy source for electric vehicles. Another critical area for future research is composite materials' long-term performance and durability for energy harvesting in electric vehicles. More research is needed to understand how these materials will perform over time and to determine their reliability and durability in real-world applications. This research should focus on materials and energy harvesting systems and include laboratory and field testing.

Finally, future research should focus on developing new applications for composite materials in energy harvesting systems. This could include developing new energy harvesting systems, such as systems that harness energy from waste heat or systems that can be used in remote or off-grid applications. Additionally, research should be conducted to determine the potential for energy harvesting systems to be used in new applications, such as energy storage, renewable energy systems, and sustainable transportation systems. In conclusion, the field of composite materials for energy harvesting in electric vehicles holds great promise for the future, and there are numerous opportunities for further research and development.

The development of new composite materials, the optimization of manufacturing processes, the integration of composite materials into energy harvesting systems, the long-term performance and durability of these materials, and the development of new applications are all important areas for future research. By addressing these challenges and opportunities, the potential of composite materials for energy harvesting in electric vehicles can be fully realized, and this technology can significantly contribute to the sustainable energy and transportation systems of the future.

6. Conclusions

Composite materials hold great potential for energy harvesting in electric vehicles, offering a range of benefits over traditional materials, such as improved mechanical properties, electrical conductivity, thermal stability, and cost-effectiveness. The development and use of composite materials for energy harvesting in electric vehicles is a growing field of research, and numerous studies in recent years have explored the different types of composite materials and their applications.

A key finding from this review is that composite materials offer a range of potential applications for energy harvesting in electric vehicles, including piezoelectric, electromagnetic, and thermoelectric energy harvesting. Each application has unique advantages and limitations, and further research is needed to optimize its performance and efficiency.

Another important finding is that developing and implementing composite materials for energy harvesting in electric vehicles are not without challenges. These challenges encompass the requirement for cost-effective and scalable manufacturing procedures, the creation of energy harvesting systems that are more dependable and long-lasting, as well as conducting of further research to comprehend the long-term durability and performance of such materials.

Despite these challenges, the future of composite materials for energy harvesting in electric vehicles is bright, and there are numerous opportunities for future research and development. The opportunities include the development of new composite materials with enhanced properties, the optimization of manufacturing processes, the integration of composite materials into energy harvesting systems, and the development of new applications for these materials. In conclusion, composite materials offer a promising solution for energy harvesting in electric vehicles, and there is significant potential for future research and development in this field.

By addressing the challenges and opportunities presented by these materials, it is possible to create more efficient, reliable, and cost-effective energy harvesting systems for electric vehicles and to make a significant contribution to the sustainable energy and transportation systems of the future.

Following are the recommendations for future studies.

- Based on the findings of this review, it is recommended that future studies in the field of composite materials for energy harvesting in electric vehicles focus on the following areas:
- Development of new composite materials with enhanced properties, such as increased electrical conductivity, thermal stability, and mechanical strength.

- Optimize manufacturing processes for composite materials, including using novel processing techniques, such as 3D printing and nanotechnology.
- Integrating composite materials into energy harvesting systems in electric vehicles, focusing on creating more efficient, reliable, and cost-effective systems.
- Long-term performance and durability of composite materials and energy harvesting systems, including laboratory and field testing.
- Development of new applications for composite materials in energy harvesting systems, including energy storage, renewable energy systems, and sustainable transportation systems.

By addressing these recommendations, it is possible to further advance the field of composite materials for energy harvesting in electric vehicles and create a more sustainable and efficient energy and transportation system.

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