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A Comprehensive Review on Piezoelectric Composites for Energy Harvesting and Sensing

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Abstract

The capacity of piezoelectric composites to transform mechanical energy into electrical energy and vice versa has drawn a lot of interest recently. This property makes them very appealing for use in energy harvesting and sensing applications. These materials combine the high piezoelectric performance of ceramics with the mechanical flexibility and processability of polymers or other matrices, enabling a wide range of practical uses in flexible electronics, wearable systems, and embedded sensor networks. Unlike monolithic ceramics, which are often brittle and difficult to process, piezoelectric composites offer enhanced mechanical robustness and design versatility while maintaining functional efficiency. This review presents a comprehensive analysis of the current landscape of piezoelectric composites, focusing on their material constituents, structural classifications, fabrication techniques, and performance characteristics. It explores various connectivity models such as 0-3, 1-3, and 2-2 composites and evaluates their advantages and limitations in specific applications. The role of nanostructured fillers, eco-friendly alternatives, and multifunctional additives is also discussed in the context of enhancing piezoelectric response and durability. The article further highlights cutting-edge advancements in processing technologies, including 3D printing, electrospinning, and additive manufacturing, which are revolutionizing the development of next-generation piezoelectric devices. Applications in energy harvesting include powering wearable electronics, structural health monitoring, and autonomous wireless sensors, while sensing applications range from biomedical diagnostics to smart infrastructure. Despite rapid progress, challenges such as interface compatibility, material degradation, and scalability remain. This review concludes by outlining potential research directions aimed at overcoming these challenges through novel material design, modeling, and integration strategies. Overall, piezoelectric composites continue to evolve as a key class of materials that bridge the gap between rigid ceramics and soft electronics, paving the way for future innovations in self-powered and intelligent systems.

Keywords: Piezoelectric composites, energy harvesting, sensing, smart materials, lead-free ceramics, nanocomposites

INTRODUCTION

The increasing demand for sustainable, portable, and autonomous electronic systems has accelerated research into self-powered technologies capable of operating without conventional batteries. In this context, energy harvesting systems that can capture ambient mechanical energy and convert it into usable electrical energy have attracted considerable attention [1, 2]. Among the various energy conversion mechanisms explored—such as thermoelectric, photovoltaic, and electromagnetic methods—piezoelectric energy harvesting has emerged as a particularly promising strategy due to

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its simplicity, compactness, and ability to operate across a wide frequency range and under low mechanical input conditions [3, 4].

Piezoelectric materials exhibit the unique ability to convert mechanical stress into electrical charge (direct effect) and, conversely, to produce mechanical deformation when subjected to an electric field (converse effect). This bidirectional coupling makes them highly suitable not only for energy harvesting applications but also for sensing, actuation, and signal processing [5]. While traditional piezoelectric ceramics, such as lead zirconate titanate (PZT), offer high piezoelectric coefficients and excellent energy conversion efficiency, they are inherently brittle and lack mechanical flexibility, thus limiting their use in applications that demand mechanical compliance, wearability, or integration into curved or deformable surfaces [6, 7].

To address these limitations, the development of *piezoelectric composites* has emerged as an effective strategy. These hybrid materials typically combine piezoelectric ceramics or nanostructures with polymeric matrices or other flexible hosts, resulting in materials that retain functional electromechanical properties while gaining mechanical durability, ease of processing, and structural adaptability [8]. Depending on the design, such composites can be tailored for enhanced flexibility, higher output performance, better fatigue resistance, and tunable anisotropic behavior, making them ideal candidates for wearable electronics, structural health monitoring, soft robotics, and biomedical devices [9].

Piezoelectric composites are generally classified based on the connectivity patterns between the piezoelectric and matrix phases—commonly referred to as 0-3, 1-3, 2-2, and 3-3 composites [10]. These connectivity patterns significantly influence the overall electromechanical performance, dielectric behavior, and mechanical robustness of the composites. Advances in nanotechnology and materials processing have further enabled the incorporation of nanoscale fillers, such as barium titanate ($BaTiO_3$) nanoparticles, zinc oxide (ZnO) nanowires, and two-dimensional materials like MXenes, which can enhance both the piezoelectric response and the interfacial charge transfer properties of the composite systems [11, 12].

In addition to energy harvesting, piezoelectric composites are widely utilized in sensing applications due to their high sensitivity to mechanical stimuli. They have been successfully implemented in pressure sensors, acoustic transducers, tactile arrays, and strain gauges, often outperforming conventional sensors in terms of sensitivity, flexibility, and responsiveness [13]. With growing interest in the Internet of Things (IoT), smart materials, and next-generation electronics, the role of piezoelectric composites in enabling autonomous sensing and actuation is becoming increasingly critical [14, 15].

FUNDAMENTALS OF PIEZOELECTRICITY

Piezoelectricity is a phenomenon observed in specific crystalline and composite materials that enables them to generate an electric charge when subjected to mechanical stress. This effect is reversible; not only can these materials convert mechanical energy into electrical energy (known as the direct piezoelectric effect), but they can also deform mechanically when an electric field is applied (the converse piezoelectric effect). These dual characteristics make piezoelectric materials especially valuable in sensing, actuation, and energy harvesting applications. The effectiveness of a piezoelectric material is governed by several intrinsic parameters, which are essential for evaluating its performance in practical devices. These parameters include:

- *Piezoelectric coefficient (d_{33}, d_{31}):* Indicates the material's ability to generate electric charge per unit of mechanical stress.
- *Electromechanical coupling factor (k):* Reflects the efficiency of energy conversion between mechanical and electrical domains.
- *Dielectric constant (ε):* Determines the material's ability to store electrical energy.
- *Mechanical quality factor (Qm):* Describes energy losses due to internal friction or damping during mechanical oscillation.

CLASSIFICATION OF PIEZOELECTRIC COMPOSITES

Piezoelectric composites are commonly categorized based on the connectivity pattern between the piezoelectric phase and the matrix material. This classification helps in understanding the electromechanical performance and structural behavior of the composite system. The major types include:

- *0-3 composites:* Comprise discrete piezoelectric particles dispersed within a continuous polymer matrix. These are relatively easy to fabricate and offer good flexibility, though their piezoelectric efficiency may be limited due to poor connectivity.
- *1-3 composites:* Feature piezoelectric rods aligned within a polymer matrix. This configuration enhances anisotropic properties, making them suitable for directional sensing and energy harvesting applications.
- *2-2 composites:* Consist of alternating laminar layers of piezoelectric and polymer materials. This structure is known for its balanced electromechanical response.
- *3-3 composites:* Involve interpenetrating continuous networks of both phases. They offer excellent mechanical-electrical coupling but may pose greater fabrication challenges.

Each configuration involves trade-offs among piezoelectric output, mechanical compliance, and manufacturability.

MATERIAL CONSTITUENTS

The performance and functionality of piezoelectric composites are significantly influenced by the choice of constituent materials, particularly the piezoelectric fillers and the matrix phase. A well-optimized combination of these materials can enhance electromechanical coupling, mechanical durability, and application-specific performance.

Piezoelectric Fillers

Piezoelectric fillers serve as the active phase responsible for converting mechanical energy into electrical energy. Common types include:

- *Lead-based ceramics (PZT, PMN-PT):* These offer high piezoelectric coefficients and electromechanical coupling factors, making them widely used in high-performance applications.
- *Lead-free ceramics ($BaTiO_3$, KNN):* In response to environmental regulations and health concerns, these materials provide a more eco-friendly alternative while maintaining satisfactory piezoelectric behavior.
- *ZnO and AlN nanostructures:* Nanostructured materials, including zinc oxide and aluminum nitride, are favored for their ease of synthesis, scalability, and compatibility with micro/nanoscale devices.

Matrix Materials

The matrix provides mechanical support, flexibility, and protection to the piezoelectric phase.

- Polymers such as PVDF, PDMS, epoxy, and polyurethane are used for flexibility and toughness. These materials facilitate stretchability and lightweight features in wearable and flexible devices.
- Bio-based and eco-friendly matrices are emerging for sustainable solutions. Such matrices support the development of biodegradable and green piezoelectric systems.

FABRICATION TECHNIQUES

The performance, reliability, and functionality of piezoelectric composites are significantly influenced by the microstructural characteristics, particularly the dispersion of the active piezoelectric phase, the orientation of the fillers, and the quality of the interfacial bonding between the piezoelectric elements and the polymer matrix. Achieving uniform distribution and strong interfacial adhesion is critical to maximize the electromechanical coupling and ensure consistent energy conversion under dynamic loading conditions. Proper alignment of the piezoelectric phase, especially in anisotropic systems like 1-3 or 2-2 composites, can greatly enhance directional sensitivity and output performance.

To achieve these structural optimizations, a variety of fabrication techniques are employed, each offering unique advantages in terms of scalability, precision, and material compatibility:

- *Solution casting and spin coating* – ideal for thin films with controlled thickness and homogeneity
- *Hot pressing and melt blending* – commonly used for bulk composites with improved mechanical integrity
- *3D printing and direct ink writing* – enables complex geometries and tailored microstructures
- *Electrospinning for fiber-based composites* – useful for fabricating flexible and high-surface-area membranes
- *Freeze casting and templating techniques* – facilitate the creation of aligned porous structures with enhanced functional properties

APPLICATIONS IN ENERGY HARVESTING

Piezoelectric composites are increasingly being explored as sustainable power sources by harvesting mechanical energy from ambient environments. These materials are capable of converting dynamic mechanical inputs—such as vibrations, pressure, or motion—into usable electrical energy. This makes them ideal for environments where traditional battery-based systems are impractical due to size, maintenance, or limited lifespan. The ability of piezoelectric composites to be engineered with varying flexibility, mechanical durability, and electrical responsiveness enhances their suitability for diverse use-cases. Major applications include:

- *Wearable electronics:* Integration into fabrics and footwear enables energy capture from body motion, providing localized power for health monitoring devices or communication tools.
- *Structural health monitoring:* Embedded piezoelectric sensors in infrastructure such as bridges, buildings, or aircraft can autonomously monitor mechanical strain and integrity while simultaneously harvesting energy for long-term operation.
- *Internet of Things (IoT):* These materials can power distributed sensor nodes in remote or inaccessible areas, supporting maintenance-free, wireless data collection and communication.
- *Biomedical devices:* Miniaturized harvesters, when implanted or placed on the skin, can utilize bodily movements to power sensors, drug delivery systems, or health diagnostics.

APPLICATIONS IN SENSING

Piezoelectric composites are extensively used in a broad range of sensing applications due to their inherent ability to convert mechanical stimuli into electrical signals with high precision and responsiveness. These materials are particularly favoured in the development of modern sensor technologies where mechanical flexibility, structural adaptability, and multifunctionality are required. Their composite nature allows for tailored performance characteristics by adjusting the ratio, dispersion, and alignment of piezoelectric fillers within the host matrix. Common application areas include:

- *Pressure and force sensors:* Utilized in industrial automation, automotive systems, and biomedical devices to detect applied pressure or mechanical load changes with high accuracy.
- *Acoustic and ultrasonic transducers:* Deployed in medical imaging, underwater sonar systems, and non-destructive testing, where the conversion of sound waves into electrical signals is crucial.
- *Vibration and strain monitoring devices:* Applied in structural health monitoring of bridges, aircraft, and machinery to detect dynamic stress and deformation in real-time.
- *Smart skin and tactile sensors:* Integrated into robotics and wearable electronics to emulate the sense of touch and detect surface interactions.

Their high sensitivity, mechanical flexibility, lightweight nature, and resilience to temperature and humidity fluctuations make piezoelectric composites highly versatile for next-generation sensing platforms in both harsh and sensitive environments.

RECENT ADVANCES

Nanostructured Composites

Use of carbon nanotubes, graphene, or MXenes to enhance mechanical and electrical connectivity: Nanomaterials such as carbon nanotubes (CNTs), graphene, and MXenes have been increasingly integrated into piezoelectric matrices to improve charge mobility, mechanical strength, and interfacial bonding. These nanostructures provide superior conductivity and surface area, leading to higher piezoelectric outputs and improved mechanical compliance.

Lead-Free and Eco-Friendly Composites

Development of green alternatives to address environmental concerns: The shift toward lead-free piezoelectric materials such as barium titanate ($BaTiO_3$), potassium sodium niobate (KNN), and other bio-compatible ceramics reflects the growing demand for sustainable and non-toxic solutions. These composites maintain competitive performance while minimizing ecological and health hazards.

Multifunctional Systems

Integration with triboelectric or thermoelectric mechanisms for hybrid energy harvesting: Advanced systems now combine piezoelectricity with triboelectric or thermoelectric effects to capture multiple forms of ambient energy simultaneously, increasing overall energy conversion efficiency.

Self-Healing and Recyclable Systems

Incorporation of smart polymers and dynamic bonds to extend lifespan: Innovative self-healing polymers and reversible chemical bonds have been introduced to create composites that can repair minor damage autonomously, improving operational lifespan and recyclability.

CHALLENGES AND FUTURE DIRECTIONS

Despite considerable advancements in piezoelectric composite technology, several critical challenges continue to hinder widespread implementation across real-world applications. One of the primary obstacles is achieving a high piezoelectric output without sacrificing the mechanical flexibility that is essential for integration into wearable or structural systems. Moreover, maintaining long-term operational stability under repeated mechanical loading, environmental fluctuations such as humidity and temperature, and material fatigue remains a pressing concern.

To address these challenges, future research should concentrate on the following directions:

- AI-assisted materials discovery for predictive optimization of composite formulations
- Multi-physics modeling to enable accurate simulation of electromechanical behavior under diverse operating conditions
- Development of biocompatible and implantable piezoelectric systems for use in medical and biological devices
- Advancement of wireless, flexible, and miniaturized platforms that can seamlessly integrate into next-generation electronics

These initiatives are expected to significantly accelerate the maturity and adoption of piezoelectric composites across energy harvesting and sensing domains.

CONCLUSION

Piezoelectric composites represent a versatile and rapidly evolving class of materials with immense potential in energy harvesting and sensing. By engineering material composition, structure, and interface, it is possible to tailor their performance to meet the growing demands of smart and sustainable systems. Ongoing research into nanostructures, eco-friendly components, and multifunctional integration is expected to propel the next generation of adaptive and autonomous technologies.

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