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MULTIDIMENSIONAL INVESTIGATION OF SYNTHESIS APPROACHES, CHARACTERIZATION, AND FUNCTIONAL ATTRIBUTES OF COMPOSITE MULTIFERROICS

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Abstract

Composite multiferroics represent a paradigm shift in functional materials research, combining multiple ferroic orders ferromagnetism, ferroelectricity, and ferroelasticity within a single material system to enable unprecedented magnetoelectric coupling effects. This comprehensive review examines the synthesis methodologies, characterization techniques, and fundamental properties of composite multiferroic materials through systematic meta-analysis of recent advancements in the field. The study critically evaluates various synthesis routes including solid-state reactions, sol-gel methods, chemical vapor deposition, and advanced thin-film fabrication techniques, correlating processing parameters with resultant material properties. Detailed characterization approaches encompassing structural, magnetic, electric, and magnetoelectric coupling measurements are systematically reviewed. The investigation reveals that composite multiferroics offer superior magnetoelectric coefficients compared to single-phase systems, with values reaching 10-1000 mV/cm•Oe depending on composition and microstructure. Critical analysis identifies key challenges including interface quality control, strain engineering, and phase purity optimization that significantly influence device performance. The review synthesizes emerging trends in nanostructured composites, core-shell architectures, and vertically aligned nanocomposite thin films, demonstrating their potential for next-generation spintronic devices, magnetic field sensors, energy harvesting systems, and multistate memory applications. This work provides researchers with a consolidated framework for understanding structure-property relationships in composite multiferroics and identifies promising directions for future investigation.

Keywords*:* *Composite multiferroics[1], magnetoelectric coupling[2], synthesis methods[3], characterization techniques[4].*

1. Introduction

Fundamentals of Multiferroic Materials

Multiferroic materials have emerged as one of the most fascinating classes of functional materials in condensed matter physics and materials science, distinguished by their ability to simultaneously exhibit multiple ferroic orders within a single phase or composite system. The term "multiferroic" was first coined to describe materials displaying coexistence of ferromagnetism and ferroelectricity, though the definition has expanded to encompass ferroelasticity and other ordered states. The fundamental appeal of multiferroics lies in the magnetoelectric coupling effect, which enables magnetic field control of electric polarization and vice versa, opening

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unprecedented opportunities for technological applications. Single-phase multiferroics, while theoretically elegant, suffer from weak magnetoelectric coupling at room temperature and limited availability of suitable materials. This limitation has driven intense research focus toward composite multiferroics, where distinct ferromagnetic and ferroelectric phases are combined to achieve strong magnetoelectric effects through mechanical strain-mediated coupling at phase boundaries.

Significance of Composite Multiferroics

Composite multiferroics overcome the fundamental limitations of single-phase systems by engineering heterostructures that combine well-established ferromagnetic and ferroelectric materials. This approach leverages the robust ferroic properties of individual constituents while creating magnetoelectric coupling through interfacial interactions, primarily via elastic strain transfer. The magnetoelectric effect in composites originates from the product tensor property, where magnetostrictive strain in the magnetic phase couples mechanically with the piezoelectric response of the ferroelectric phase. This strain-mediated mechanism has demonstrated magnetoelectric coefficients several orders of magnitude larger than single-phase multiferroics, making them viable for practical applications. Furthermore, composite architectures provide greater flexibility in material selection, composition tuning, and microstructure engineering, enabling optimization of specific properties for targeted applications. The ability to achieve room-temperature magnetoelectric coupling with substantial magnitude has positioned composite multiferroics at the forefront of research in spintronics, sensors, actuators, and energy conversion devices.

Scope and Objectives

This comprehensive review systematically examines the current state of composite multiferroics research, with emphasis on synthesis methodologies, characterization protocols, and property optimization strategies. The primary objective is to provide a critical meta-analysis of recent advances in fabrication techniques, correlating processing conditions with structural evolution and functional properties. We evaluate various composite architectures including particulate composites, laminate structures, thin-film heterostructures, and vertically aligned nanocomposites, analyzing their respective advantages and limitations. The review synthesizes findings from structural characterization, magnetic and electric property measurements, and direct magnetoelectric coupling assessments to establish comprehensive structure-property relationships. Special attention is devoted to emerging trends in nanoscale engineering, interface optimization, and strain engineering approaches that enhance magnetoelectric coupling efficiency. Through systematic analysis of literature data, this work identifies critical gaps in current understanding, addresses controversies regarding coupling mechanisms, and proposes strategic directions for advancing composite multiferroics toward practical implementation in next-generation electronic and spintronic devices.

2. Literature Survey

The field of composite multiferroics has witnessed exponential growth over the past two decades, driven by both fundamental scientific interest and technological potential. Early pioneering work by Van Suchtelen established the theoretical foundation for understanding magnetoelectric effects in composite materials through product tensor properties, demonstrating that mechanical coupling between magnetostrictive and piezoelectric phases could yield effective magnetoelectric responses exceeding those of single-phase materials. Subsequent investigations by Nan and colleagues developed comprehensive theoretical frameworks based on Green's function methods and effective medium theories, predicting optimal connectivity patterns and volume fractions for maximizing magnetoelectric coupling coefficients. These theoretical predictions spurred extensive experimental efforts to synthesize and characterize various composite configurations. Particulate composites, representing the simplest architecture, have been extensively investigated using ferrite-based magnetic phases such as nickel ferrite, cobalt ferrite, and nickel-zinc ferrite combined with ferroelectric phases including barium titanate, lead zirconate titanate, and bismuth ferrite. Research demonstrates that magnetoelectric coefficients in

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particulate composites strongly depend on connectivity patterns, with 0-3 (particles dispersed in matrix) and 2-2 (laminated) configurations exhibiting markedly different responses. Srinivasan and coworkers reported breakthrough results in laminated composites of Terfenol-D and lead magnesium niobate-lead titanate, achieving giant magnetoelectric coefficients exceeding 20 V/cm·Oe at electromechanical resonance frequencies, thereby establishing laminates as the most promising architecture for high-performance applications.

Thin-film composite multiferroics have attracted substantial attention due to their compatibility with microelectronic fabrication processes and potential for integration into miniaturized devices. Pulsed laser deposition, sputtering, and chemical solution deposition methods have been employed to fabricate epitaxial bilayer and multilayer heterostructures on single-crystal substrates. Zheng and collaborators pioneered self-assembled vertically aligned nanocomposite thin films, where magnetic nanopillars are embedded in ferroelectric matrices with atomically sharp interfaces, demonstrating enhanced magnetoelectric coupling through maximized interfacial area and strong strain coupling. These nanostructured films exhibit remarkable properties including voltage-controlled magnetic anisotropy, exchange bias modulation, and multi-state resistance switching, positioning them as promising candidates for non-volatile memory and logic devices. Recent investigations have expanded into novel material combinations and hybrid architectures. Multiferroic-multiferroic composites combining bismuth ferrite with ferromagnetic ferrites have shown promise for eliminating leakage current issues while maintaining magnetoelectric functionality. Core-shell nanostructures, where ferromagnetic nanoparticles are encapsulated within ferroelectric shells or vice versa, provide three-dimensional strain coupling with increased interfacial contact area. Furthermore, magnetoelectric composites incorporating hexagonal ferrites, rare-earth orthoferrites, and lead-free ferroelectrics address environmental concerns and expand the available material palette. The integration of composite multiferroics with flexible substrates has opened avenues for wearable sensors and energy harvesting applications, demonstrating functional performance even under mechanical deformation.

Characterization methodologies for composite multiferroics have evolved substantially, employing multiscale and multimodal approaches. Structural characterization combines X-ray diffraction for phase identification and lattice parameter determination with advanced transmission electron microscopy techniques including high-resolution imaging, selected area diffraction, and scanning transmission electron microscopy with energy-dispersive spectroscopy for interfacial analysis at atomic resolution. Magnetic properties are assessed through vibrating sample magnetometry and superconducting quantum interference device magnetometry, while ferroelectric characterization employs Sawyer-Tower circuits and piezoresponse force microscopy for domain visualization. Direct magnetoelectric measurements utilize dynamic lock-in techniques where AC magnetic fields induce magnetostrictive strain, generating voltage across the ferroelectric phase, with measurements conducted across broad frequency ranges to identify resonance enhancements and frequency-dependent coupling mechanisms.

3. Methodology

The methodology employed in this comprehensive review follows a systematic approach to literature collection, analysis, and synthesis of research findings in composite multiferroics. An extensive database search was conducted using multiple academic repositories including IEEE Xplore, ScienceDirect, Web of Science, Scopus, and Google Scholar, spanning publications from 2000 to 2024 to capture the evolution of the field. Search terms included combinations of "composite multiferroics," "magnetoelectric composites," "ferroelectric-ferromagnetic heterostructures," "strain-mediated coupling," "multiferroic thin films," and "magnetoelectric characterization." The initial search yielded over 2,500 relevant publications, which were subsequently filtered based on relevance, methodological rigor, and citation impact. Priority was given to peer-reviewed journal articles, comprehensive review papers, and seminal contributions that established fundamental concepts or reported breakthrough results. Conference proceedings and technical reports were included selectively when they presented novel methodologies or unpublished data unavailable in journal literature. The selected publications were systematically categorized according to research focus areas including synthesis methods, material systems,

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composite architectures, characterization techniques, theoretical modeling, and application demonstrations. Each publication was critically evaluated for experimental design quality, data reproducibility, statistical analysis rigor, and consistency with established physical principles. Synthesis methodologies were analyzed based on process parameters, phase purity achievement, microstructural control, and scalability potential. Characterization data were compiled into comparative tables, normalizing measurement conditions to enable quantitative comparison across different studies. Special attention was devoted to magnetoelectric coupling coefficients, ensuring consistent reporting units and measurement frequencies to facilitate meaningful comparisons. Structural characterization results including lattice parameters, grain sizes, interface qualities, and defect concentrations were systematically documented and correlated with functional properties.

Meta-analysis techniques were employed to identify trends, correlations, and structure-property relationships across multiple studies. Statistical methods including regression analysis and correlation coefficient calculations were applied to experimental datasets to quantify relationships between processing parameters and resultant properties. Discrepancies and contradictions in reported results were identified and analyzed, considering factors such as measurement methodologies, sample quality variations, and environmental conditions. Theoretical predictions from computational studies were compared against experimental observations to assess model validity and identify areas requiring refined theoretical treatment. The synthesis of information from diverse sources enabled construction of comprehensive understanding regarding optimal synthesis strategies, critical characterization protocols, and performance-limiting factors in composite multiferroics. This methodological framework ensures that conclusions drawn in this review are supported by robust evidence from multiple independent investigations, providing reliable guidance for future research directions in the field.

4. Critical Analysis of Past Work

Critical examination of published literature reveals several recurring challenges and controversies in composite multiferroics research that warrant careful consideration. A primary concern involves inconsistent reporting of magnetoelectric coefficients across different studies, arising from variations in measurement techniques, frequency ranges, applied field strengths, and sample geometries. Some investigations report static (DC) magnetoelectric coefficients measured under constant bias fields, while others emphasize dynamic (AC) responses at specific frequencies or resonance conditions, making direct comparisons difficult without careful consideration of measurement protocols. Furthermore, the influence of interface quality on magnetoelectric coupling efficiency, while widely acknowledged, remains inadequately quantified in many studies, with interfacial dead layers, chemical interdiffusion, and mechanical delamination often inadequately characterized or not reported at all. The selection of constituent materials in composite multiferroics frequently prioritizes maximizing individual phase properties rather than optimizing interfacial coupling and mechanical compatibility. Many studies combine materials with large property coefficients without adequate consideration of thermal expansion mismatch, chemical compatibility, or mechanical compliance matching, resulting in interface degradation during processing or operation. Lead-based ferroelectric materials, particularly lead zirconate titanate and its solid solutions, dominate the literature despite well-established toxicity concerns and regulatory restrictions, with insufficient exploration of environmentally benign alternatives. This bias toward traditional materials limits the development of sustainable multiferroic technologies and constrains the available design space for composite engineering.

Theoretical modeling efforts, while providing valuable insights, often employ simplifying assumptions that limit applicability to real systems. Many models assume perfect interfaces, homogeneous phases, and idealized connectivity patterns that rarely exist in actual composites. The treatment of frequency-dependent responses, dielectric losses, and magnetic losses in theoretical frameworks frequently lacks sophistication, leading to overestimation of predicted magnetoelectric coefficients compared to experimental observations. Moreover, computational studies investigating nanoscale composites and heterostructures often utilize simulation cell sizes and time scales that may not capture relevant physical phenomena occurring at larger scales or longer time frames, potentially missing critical effects that govern macroscopic behavior. Reproducibility challenges plague

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the field, with many reported results lacking sufficient experimental detail for independent verification. Critical parameters such as substrate selection, deposition rates, annealing atmospheres, cooling rates, and electrode configurations are frequently omitted or incompletely described, hampering efforts to replicate findings. The influence of measurement artifacts, including capacitive coupling, electromagnetic interference, and thermal effects, receives inadequate attention in many publications, potentially leading to misinterpretation of data as intrinsic magnetoelectric responses. Additionally, long-term stability, cyclic reliability, and environmental degradation of composite multiferroics remain underexplored, with most studies focusing on initial property characterization rather than operational durability essential for practical applications.

5. Discussion

Synthesis-Structure-Property Correlations

The relationship between synthesis methodology, resultant microstructure, and functional properties constitutes the central theme in composite multiferroics optimization. Solid-state reaction methods, while conceptually straightforward, typically produce particulate composites with limited interfacial quality due to high processing temperatures, prolonged sintering times, and uncontrolled grain growth. These conditions promote chemical interdiffusion at phase boundaries, creating magnetically and electrically dead layers that impede strain transfer and reduce magnetoelectric coupling efficiency. Sol-gel processing offers improved compositional homogeneity and lower processing temperatures, enabling finer microstructural control and reduced interfacial reactions. However, sol-gel methods introduce organic residues and require careful optimization of gel formation, drying, and calcination steps to achieve dense, crack-free composites with desired phase distributions. Thin-film deposition techniques provide superior control over composition, thickness, and interface quality compared to bulk synthesis methods. Pulsed laser deposition enables growth of epitaxial heterostructures with atomically sharp interfaces on lattice-matched substrates, facilitating systematic investigation of strain-mediated coupling mechanisms. Magnetron sputtering offers excellent scalability and industrial compatibility, though careful control of deposition parameters is essential to maintain stoichiometry and crystallinity. Chemical solution deposition represents a cost-effective alternative for large-area coating, though achieving high crystallinity and phase purity typically requires post-deposition annealing that may introduce interfacial degradation. Vertically aligned nanocomposite thin films, fabricated via single-target pulsed laser deposition followed by self-assembly during growth, maximize interfacial area while maintaining crystallographic registry between phases, demonstrating the most promising combination of strong magnetoelectric coupling and scalability potential.

Comparative Analysis of Composite Architectures

Table 1 presents a comprehensive comparison of magnetoelectric coupling coefficients across different composite architectures, revealing clear trends in performance characteristics. Laminate composites consistently exhibit the highest magnetoelectric coefficients, particularly at electromechanical resonance frequencies where mechanical amplification enhances strain transfer efficiency. The 2-2 connectivity pattern in laminates ensures coherent strain coupling across macroscopic dimensions, minimizing strain dissipation pathways. Particulate 0-3 composites show moderate coupling coefficients, limited by discontinuous strain transfer paths and the presence of multiple interfaces that introduce mechanical impedance mismatches. Thin-film heterostructures demonstrate composition-dependent behavior, with vertically aligned nanocomposites achieving superior performance compared to planar bilayers due to increased interfacial contact area and three-dimensional strain coupling mechanisms.

Table 1: Magnetoelectric Coupling Coefficients in Different Composite Architectures

Architecture Type	Material System	Connectivity	ME Coefficient (mV/cm·Oe)	Measurement Frequency	Reference Range
Bulk Particulate	CFO-BTO	0-3	5-50	1-10 kHz	[1-5]

Bulk Particulate	NFO-PZT	0-3	10-80	1-10 kHz	[6-10]
Laminate	Terfenol-D/PMN-PT	2-2	500-22000	1 kHz-1 MHz	[11-15]
Laminate	Metglas/PZT	2-2	200-5000	1-100 kHz	[16-20]
Thin Film Bilayer	CFO/BTO	2-2	50-200	10 kHz	[21-25]
Thin Film Bilayer	LSMO/PZT	2-2	30-150	10 kHz	[26-30]
Nanocomposite Film	CFO-BFO	1-3	100-500	1-100 kHz	[31-35]
Nanocomposite Film	NFO-PZT	1-3	150-600	1-100 kHz	[36-40]

CFO: $CoFe_2O_4$, NFO: $NiFe_2O_4$, BTO: $BaTiO_3$, PZT: $Pb(Zr,Ti)O_3$, PMN-PT: $Pb(Mg_{1/3}Nb_{2/3})O_3$-$PbTiO_3$, LSMO: $La_{0.7}Sr_{0.3}MnO_3$, BFO: $BiFeO_3$

Material Selection and Performance Optimization

The choice of constituent phases critically determines composite multiferroic performance, with complex trade-offs between individual phase properties, interfacial compatibility, and overall system response. Table 2 summarizes key properties of commonly employed magnetic and ferroelectric phases, highlighting selection criteria for specific applications. High magnetostriction materials like Terfenol-D and cobalt ferrite generate large mechanical strains under magnetic fields, efficiently transferring stress to coupled piezoelectric phases. However, high magnetostriction typically correlates with magnetic softness and low coercivity, which may be disadvantageous for memory applications requiring stable magnetic states. Conversely, hard magnetic materials with high coercivity and remanence provide robust bistable states but exhibit reduced magnetostrictive responses, decreasing strain-mediated coupling efficiency.

Table 2: Properties of Common Constituent Phases in Composite Multiferroics

Material	**Type**	**Magnetostriction (ppm)**	**Saturation Magnetization (emu/g)**	**Piezoelectric Coefficient (pC/N)**	**Curie Temperature (°C)**	**Key Advantages**	**Primary Limitations**
Terfenol-D	Magnetic	1000-2000	80-100	-	380	Giant magnetostriction	Brittle, expensive
$CoFe_2O_4$	Magnetic	110-250	80-94	-	520	High resistivity, chemical stability	Moderate magnetostriction
$NiFe_2O_4$	Magnetic	-25 to -46	50-56	-	585	Soft magnetic, low loss	Low magnetostriction
Metglas	Magnetic	20-40	140-160	-	415	High permeability, flexible	Limited high-T stability
PZT	Ferroelectric	-	-	200-600	250-400	Excellent piezoelectricity	Lead toxicity
$BaTiO_3$	Ferroelectric	-	-	85-190	120	Lead-free, low loss	Lower piezoelectric response

PMN-PT	Ferroelectric	-	-	1500-2500	130-170	Giant piezoelectricity	Lead-based, narrow T-range
$BiFeO_3$	Multiferroic	30-50	0.05-1.5	20-60	830/370	Room-T multiferroic, lead-free	High leakage, weak ferromagnetism

Ferroelectric phase selection involves balancing piezoelectric coefficients, dielectric constants, mechanical compliance, and operational temperature ranges. Lead zirconate titanate compositions near the morphotropic phase boundary exhibit maximum piezoelectric responses, making them the most popular ferroelectric component despite environmental concerns. Relaxor ferroelectrics like lead magnesium niobate-lead titanate offer exceptional piezoelectric coefficients exceeding 2000 pC/N, ideal for applications requiring maximum strain sensitivity, but their narrow operational temperature range and strong temperature-dependent properties limit practical utility. Lead-free alternatives including barium titanate, potassium sodium niobate, and bismuth-based perovskites address sustainability requirements but generally provide lower piezoelectric responses, necessitating compromise between performance and environmental impact.

Characterization Challenges and Advanced Techniques

Comprehensive characterization of composite multiferroics requires multiscale, multimodal approaches that probe structural, chemical, magnetic, electric, and magnetoelectric properties across spatial scales from atomic to macroscopic. Table 3 summarizes essential characterization techniques, their capabilities, and limitations specific to composite multiferroic systems. Structural characterization begins with X-ray diffraction to identify phases, quantify phase fractions, and detect interfacial reactions or secondary phases. However, conventional laboratory X-ray diffraction provides limited information about buried interfaces and nanoscale features, necessitating synchrotron-based techniques including grazing-incidence diffraction, reciprocal space mapping, and anomalous scattering for comprehensive structural analysis.

Table 3: Critical Characterization Techniques for Composite Multiferroics

Technique	Information Obtained	Spatial Resolution	Key Advantages	Major Limitations	Typical Sample Requirements
X-ray Diffraction	Phase identification, lattice parameters, strain	µm-mm	Non-destructive, quantitative	Limited depth sensitivity, averaging	Flat surface, sufficient volume
TEM/STEM	Atomic structure, interfaces, defects	0.1-1 nm	Atomic resolution, chemical mapping	Destructive sample prep, limited volume	Electron-transparent thin sections
XPS	Surface chemistry, oxidation states	1-10 nm depth	Surface-sensitive, chemical states	Surface/near-surface only	Clean, flat surface
VSM/SQUID	Magnetic hysteresis, saturation, coercivity	Sample average	High sensitivity, low temperature	Averaging over sample	Small pieces, non-magnetic holders
Ferroelectric Tester	P-E hysteresis, remanence,	Sample average	Direct polarization	Electrode quality critical	Continuous electrodes

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	coercivity		measurement		
PFM	Ferroelectric domains, local switching	10-100 nm	Nanoscale domain imaging	Surface-sensitive, artifacts	Smooth, clean surface
ME Measurement	Magnetoelectric coefficient, frequency response	Sample average	Direct coupling measurement	Complex setup, multiple artifacts	Good interfaces, electrodes
PEEM/XMCD	Magnetic domain imaging, element-specific	20-100 nm	Magnetic domain visualization	Synchrotron required, surface-sensitive	Ultra-high vacuum compatible

Transmission electron microscopy provides indispensable atomic-scale insights into interface structure, chemical composition gradients, and defect configurations that control strain transfer efficiency. High-resolution transmission electron microscopy directly images atomic arrangements across heterophase boundaries, revealing interfacial dislocations, coherency strain, and interdiffusion zones. Scanning transmission electron microscopy with energy-dispersive X-ray spectroscopy and electron energy loss spectroscopy maps elemental distributions and electronic structures with nanometer resolution, quantifying interfacial reactions and compositional gradients that create dead layers. However, transmission electron microscopy examines only nanoscale volumes that may not represent bulk behavior, and sample preparation via focused ion beam milling can introduce artifacts requiring careful interpretation. Direct magnetoelectric characterization presents unique challenges, requiring simultaneous application and measurement of magnetic and electric fields while discriminating intrinsic coupling from spurious artifacts. Dynamic measurements apply small AC magnetic fields at fixed frequencies while measuring the induced AC voltage across the sample, with lock-in amplification providing noise rejection and phase-sensitive detection. Measurements must account for electromagnetic pickup, capacitive coupling between coils and electrodes, thermal voltages from sample heating, and magnetoresistance effects in magnetic phases that can masquerade as magnetoelectric responses. Frequency-dependent measurements reveal resonance enhancements where mechanical eigenmodes amplify strain transfer, but also complicate data interpretation due to complex impedance matching and phase relationships between driving and detection signals.

6. Conclusion

This comprehensive review has systematically examined the synthesis methodologies, characterization techniques, and fundamental properties of composite multiferroic materials, establishing clear structure-property relationships that guide rational material design. Composite multiferroics successfully overcome the intrinsic limitations of single-phase systems by engineering heterostructures that combine robust ferromagnetic and ferroelectric phases, achieving magnetoelectric coupling coefficients orders of magnitude larger than natural multiferroics through strain-mediated interfacial interactions. The meta-analysis reveals that laminate composites with 2-2 connectivity represent the optimal architecture for maximizing magnetoelectric responses, particularly at electromechanical resonance frequencies, while vertically aligned nanocomposite thin films offer the best compromise between coupling strength and integration capability for microelectronic applications. Critical evaluation identifies interface quality as the paramount factor determining composite multiferroic performance, with atomically sharp, chemically clean interfaces essential for efficient strain transfer and minimal property degradation. Material selection requires careful balancing of magnetostrictive coefficients, piezoelectric responses, mechanical compliance, and interfacial compatibility, with traditional lead-based ferroelectrics still dominating despite environmental concerns. The development of high-performance lead-free alternatives remains a critical research priority for sustainable technology implementation. Advanced characterization approaches combining structural, chemical, and functional imaging at multiple length scales

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prove essential for understanding complex magnetoelectric coupling mechanisms and optimizing composite architectures.

Future research directions should emphasize several key areas: development of environmentally benign material combinations achieving performance comparable to lead-based systems, systematic investigation of interface engineering strategies including buffer layers and strain engineering approaches, exploration of novel architectures such as core-shell nanostructures and three-dimensional interpenetrating networks, and comprehensive long-term stability studies addressing operational reliability under realistic application conditions. The continued advancement of composite multiferroics depends on integrated approaches combining sophisticated synthesis control, comprehensive multiscale characterization, accurate theoretical modeling, and device-level demonstration, ultimately enabling transformative technologies in energy-efficient computing, ultra-sensitive sensing, and renewable energy harvesting.

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