



Triboelectric And Piezoelectric Nanogenerators Using Binary and Ternary Oxide Nanostructures: Optimization of Energy Conversion Efficiency for Wearable Harvesting

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Abstract

This study investigates the persistent challenge of optimizing energy-conversion efficiency in triboelectric nanogenerators (TENGs) and piezoelectric nanogenerators (PENGs) incorporating binary and ternary oxide nanostructures for wearable energy-harvesting applications. The problem addressed arises from considerable variability in nanogenerator performance caused by differences in material composition, nanoscale morphology, interface quality, device configuration, and mechanical excitation, which makes it difficult to determine the most influential design factors. The purpose of the research was therefore to quantitatively evaluate how oxide material properties, nanostructure morphology and surface characteristics, device architecture and interface design, and mechanical operating conditions influence energy-conversion efficiency and subsequent wearable energy-harvesting performance. A quantitative, cross-sectional, case-study-based design was employed using a structured five-point Likert questionnaire administered to technically knowledgeable researchers, engineers, materials scientists, nanotechnology specialists, and wearable-energy professionals. Of 220 questionnaires distributed, 204 valid responses were retained, producing a 92.7% usable response rate. Data were analyzed using descriptive statistics, Cronbach's alpha reliability analysis, Pearson correlation, comparative testing, and multiple regression at $p < .05$. Findings showed strong positive relationships between energy-conversion efficiency and oxide material properties ($r = .64$), nanostructure morphology ($r = .59$), device architecture ($r = .67$), and mechanical conditions ($r = .53$), all $p < .001$. Energy-conversion efficiency was strongly associated with wearable performance ($r = .72$, $p < .001$). The principal regression model explained 62.4% of the variance in energy-conversion efficiency, with device architecture emerging as the strongest predictor ($\beta = .31$, $p < .001$), followed by material properties ($\beta = .26$), morphology ($\beta = .19$), and mechanical conditions ($\beta = .17$). Ternary oxides achieved higher overall assessed performance than binary oxides, 4.22 versus 3.98, with a significant mean difference of 0.24 ($p < .001$). These findings imply that wearable nanogenerator optimization should prioritize coordinated material selection, nanoscale engineering, interface design, flexible architecture, and realistic mechanical matching rather than relying on material composition alone.

Keywords

Triboelectric Nanogenerators; Piezoelectric Nanogenerators; Oxide Nanostructures; Energy-Conversion Efficiency; Wearable Energy Harvesting.

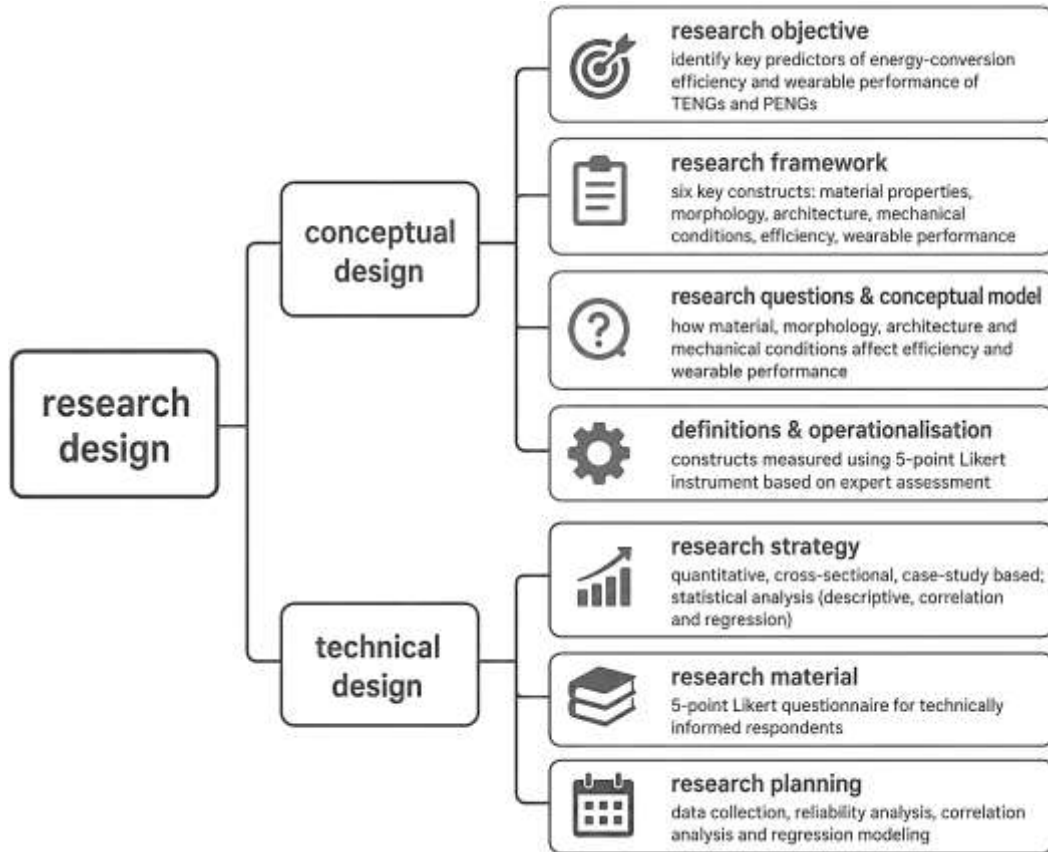
INTRODUCTION

Triboelectric nanogenerators (TENGs) and piezoelectric nanogenerators (PENGs) are solid-state energy-harvesting devices that convert ambient mechanical motion into electrical output through different but complementary physical mechanisms. A PENG operates through the direct piezoelectric effect, in which mechanical stress or strain imposed on a non-centrosymmetric material produces electrical polarization and a potential difference, whereas a TENG primarily relies on contact electrification coupled with electrostatic induction as two materials repeatedly contact, separate, slide, or deform. These mechanisms have become increasingly important because wearable electronics, distributed sensors, health-monitoring systems, smart textiles, and low-power body-integrated devices require energy sources that are lightweight, flexible, and capable of responding to irregular human movement. Early nanoscale piezoelectric theory demonstrated that deformation of one-dimensional ZnO structures can generate spatially distributed piezopotential and that the magnitude and distribution of this potential depend on geometry, boundary conditions, and the electromechanical properties of the material (Gao & Wang, 2007). Flexible fine-wire generators subsequently established that cyclic stretching and releasing of packaged piezoelectric structures can be converted into alternating electrical output on flexible substrates (Yang et al., 2009). TENG theory has similarly formalized the relationships among charge transfer, capacitance, displacement, terminal voltage, and external electrical loading, providing a quantitative foundation for understanding how mechanical contact and separation produce useful electrical energy (Niu et al., 2013; Niu & Wang, 2015). These advances have positioned nanogenerators as a distinct class of mechanical-energy converters in which nanoscale materials, interfaces, mechanical loading, and electrical circuits interact. Their international significance has increased with the expansion of wearable and self-powered sensing applications because human locomotion, arm movement, bending, breathing, foot pressure, garment friction, and other low-frequency activities provide continuously available but spatially distributed mechanical energy. The central engineering challenge is therefore not merely to demonstrate voltage generation, but to optimize the complete pathway from mechanical excitation to charge generation, charge collection, useful output power, and stable operation under repeated wearable deformation. This requirement has placed binary and ternary oxide nanostructures at the center of current design strategies because their piezoelectric, dielectric, ferroelectric, semiconducting, and surface properties can be adjusted through composition and nanoscale architecture.

Binary oxide nanostructures, particularly zinc oxide, have provided an important experimental foundation for wearable nanogenerator research because they combine relatively simple chemistry with controllable nanoscale morphology and direct piezoelectric functionality. ZnO can be produced as nanowires, nanorods, nanoflakes, branched nanotrees, nanoparticles, and hierarchical structures, allowing researchers to change the active surface area, strain distribution, polarization direction, and electrical transport pathways without changing the underlying binary chemical composition. Such morphology control has been shown to influence both the mechanical and electrical behavior of the material. Branched ZnO nanotrees on flexible fiber-paper substrates, for example, have demonstrated how three-dimensional branching can increase mechanically active regions and improve harvesting geometry compared with simple vertical nanowires (Qiu et al., 2015). Hydrothermally grown ZnO nanowires have also shown that free-carrier concentration and defect-related screening can reduce usable piezopotential, while annealing and electronic control can improve nanogenerator response (Opoku et al., 2015). Ultra-thin ZnO nanoflakes have further demonstrated that two-dimensional morphology can support transparent and flexible energy-harvesting devices with strong output characteristics (Ngoc & Kang, 2016). These findings are internationally relevant because scalable, low-temperature, and substrate-compatible oxide growth methods can support integration with textiles, polymers, paper, fibers, and flexible electrodes. At the same time, binary oxides present engineering limitations associated with carrier screening, surface states, interfacial losses, brittleness in dense ceramic form, and the need to maintain controlled strain transfer. Interface passivation has therefore become important; improved ZnO nanogenerator performance after CuSCN passivation has illustrated how surface-state suppression can preserve charge generated within the piezoelectric material (Jalali et al., 2014). Collectively, this literature shows that a binary oxide should not be evaluated solely by its nominal piezoelectric behavior. Energy conversion is determined by how crystal structure, defects,

morphology, interfaces, electrodes, mechanical deformation, and external load interact. These observations have motivated the present study to treat oxide material properties and nanostructure morphology as separate but related explanatory variables rather than assuming that chemical composition alone determines performance.

Figure 1: Conceptual and Technical Structure of the Research



Ternary oxide nanostructures provide a broader compositional and crystallographic design space because two cation species and oxygen can form polar, dielectric, ferroelectric, or multiferroic structures whose electrical response is tunable through composition, phase, grain structure, and processing. Barium titanate, zinc stannate, bismuth ferrite, and related ternary oxides have therefore attracted considerable attention for flexible and wearable nanogenerators. BaTiO₃ is particularly relevant because its ferroelectric polarization and high dielectric permittivity can strengthen piezoelectric conversion and can also enhance triboelectric layers when incorporated into flexible polymer matrices. Flexible BaTiO₃-based fibers have demonstrated that ceramic functionality can be incorporated within compliant architectures compatible with repeated bending (Lu et al., 2017), while microporous BaTiO₃/PDMS nanocomposites have shown that dielectric filler and porous mechanical structure can jointly enhance triboelectric response (Jang & Oh, 2018). Direct fabrication of BiFeO₃ films on polyimide has further demonstrated that functional ternary oxide layers can be integrated with flexible substrates when processing conditions are sufficiently controlled (Tomczyk et al., 2017). Comparative research has also shown that vertically aligned BaTiO₃ nanowire arrays can provide strong harvesting performance relative to ZnO under controlled loading, emphasizing the potential value of stronger ferroelectric and piezoelectric properties (Koka et al., 2014). Ternary oxides nevertheless introduce additional complexity because phase purity, stoichiometry, crystallinity, processing temperature, filler dispersion, polymer compatibility, interfacial adhesion, and mechanical stiffness can strongly affect the usable response. The advantage of a high intrinsic dielectric or piezoelectric coefficient can therefore be lost when an active phase is poorly dispersed or mechanically

isolated. Research on BaTiO₃ nanowire/polymer composites has shown that high-aspect-ratio fillers can strengthen interfacial polarization and dielectric response relative to less optimized filler geometries (Feng et al., 2015). These findings provide a strong basis for comparing binary and ternary oxides within one performance framework while recognizing that chemical complexity does not guarantee superior wearable performance. The present research has consequently approached oxide selection as a multidimensional optimization problem in which intrinsic material properties must be considered together with morphology, interface engineering, architecture, and mechanical compatibility.

Nanostructure morphology and surface engineering have become critical because the conversion mechanisms of TENGs and PENGs are inherently sensitive to the way mechanical force is distributed and the way electrical charge is generated, trapped, screened, or transferred at interfaces. In PENGs, dimensions, orientation, aspect ratio, grain structure, and alignment determine how applied strain produces polarization and how effectively the generated potential reaches electrodes. Atomistic analysis of one-dimensional ZnO has shown that electromechanical properties vary with size scale, surface effects, cross-sectional geometry, and loading configuration, demonstrating that nanoscale form modifies functional response rather than simply miniaturizing bulk behavior (Momeni & Attariani, 2014). In TENGs, effective contact area, surface roughness, chemical functionalization, dielectric properties, and charge affinity influence the amount and stability of surface charge. Electrodeposited gold nanoflower structures have demonstrated that hierarchical roughness can increase effective contact and triboelectric output, while excessive or poorly matched roughness can reduce real contact between surfaces (Park et al., 2015). Molecular surface functionalization has also been used to alter surface potential and increase triboelectric charge density, showing that electrical output can be enhanced by controlled chemistry at the interface (Wang et al., 2016). These mechanisms have direct implications for oxide nanostructures because oxide surfaces can exhibit hydroxyl groups, defects, adsorbates, polar sites, and charge-trapping states that change under humidity, friction, and repeated cycling. Wearable conditions intensify these challenges because the device is subjected to irregular bending, stretching, pressing, sliding, sweating, humidity, and repeated contact rather than a single standardized laboratory load. A surface modification that produces a high initial voltage may have limited practical value if it wears, contaminates, delaminates, or loses charge after repeated use. Therefore, nanoscale morphology must be designed simultaneously for electrical activity, mechanical compliance, surface durability, and interface stability. The present study has incorporated these requirements into a specific morphology and surface-characteristics construct so that the statistical analysis can distinguish the contribution of nanoscale form from the contribution of oxide composition and device architecture.

Device architecture is another central determinant because the electrical potential created within a nanostructure becomes useful only when the generator transfers mechanical stress to the active phase, collects generated charge through appropriate electrodes, and maintains reliable operation during repetitive deformation. Flexible hybrid designs have illustrated how mechanical and electrical architecture can integrate piezoelectric and triboelectric mechanisms in a single platform. A hybrid generator based on P(VDF-TrFE) nanofibers and PDMS/MWCNT structures has shown that active-layer arrangement, conductive filler, surface structure, external loading, and mechanical deformation jointly affect output (Wang et al., 2016). Carbon-fiber/ZnO-nanowire systems have similarly shown that electrical interface barriers and electrode pathways determine whether piezoelectric potential is effectively accumulated and transferred (Du et al., 2017). Low-frequency devices have also been structurally tuned to match the characteristic frequencies of ambient or human motion; tuning-fork-type ZnO nanorod harvesters illustrate how mechanical geometry can amplify or better couple weak vibration to an active nanostructure (Deng et al., 2018). These results are especially important for wearable harvesting because human motion has variable amplitude and frequency and frequently combines bending, compression, contact, sliding, and twisting. A successful wearable generator therefore requires compliant substrates, stable electrodes, low-resistance connections, optimized layer thicknesses, and interfaces that can transfer stress without cracking or delamination. Research on sustainably powering wearable electronics from biomechanical energy has demonstrated that practical

output depends on the integration of the generator with flexible structures and usable load delivery rather than on an isolated materials measurement (Wang et al., 2016). Self-charging systems have further shown that power management and energy storage are necessary to convert irregular generator output into regulated energy suitable for electronics (Niu et al., 2015). Accordingly, this research has treated device architecture and interface design as an independent construct and has tested whether it predicts energy-conversion efficiency after material properties, morphology, and mechanical conditions are considered simultaneously.

Energy-conversion efficiency and wearable performance provide the functional outcomes through which the success of material and device optimization can be evaluated. High open-circuit voltage is not sufficient evidence of efficient energy harvesting because useful power also depends on current, transferred charge, electrical impedance, mechanical input, power density, and the stability of output over repeated cycles. Wearable applications add requirements of flexibility, conformability, durability, low-frequency responsiveness, environmental tolerance, and comfort. Low-frequency human-limb harvesters have demonstrated that structural frequency conversion and mechanical coupling can make piezoelectric devices responsive to joint motion in ranges relevant to daily activity (Li et al., 2018). Woven piezoelectric textiles have shown that fiber-based architectures can provide electrical output while maintaining the flexibility and environmental tolerance expected of wearable fabrics (Lund et al., 2018). Triboelectric textiles have also been developed to harvest skin-touch and garment-related energy while retaining operation under repeated folding, stretching, and washing (Xiong et al., 2018). Self-healing and highly stretchable TENG architectures have extended the durability concept by demonstrating recovery of function after mechanical damage (Parida et al., 2019), while stretchable systems designed for underwater or wet environments have highlighted the need to evaluate environmental robustness as part of practical performance (Zou et al., 2019). These studies indicate that wearable performance is an emergent outcome rather than a single electrical metric. The present study has therefore distinguished energy-conversion efficiency from wearable energy-harvesting performance: efficiency represents the perceived effectiveness of mechanical-to-electrical conversion, whereas wearable performance represents the ability of that conversion capability to remain useful under flexible, low-frequency, repeated, and body-compatible operating conditions. This distinction has enabled the research to test whether efficiency functions as a central pathway through which optimized materials and device design translate into wearable functionality.

Against this background, a quantitative assessment has been required to organize the diverse technical determinants identified in the nanogenerator literature into a coherent and statistically testable framework. Previous studies have often optimized a particular oxide composition, morphology, interface treatment, electrode configuration, or mechanical condition using distinct laboratory protocols, which makes direct comparison difficult. Performance values reported for voltage, current, charge density, power density, or efficiency can differ because of device area, excitation force, frequency, load resistance, surface preparation, humidity, substrate properties, and measurement procedures. Theoretical work on TENGs has emphasized the importance of common figures of merit and standardized relationships among charge, displacement, capacitance, and voltage for meaningful performance comparison (Niu & Wang, 2015), while broader electromagnetic analysis has shown that the field and geometry of a contact-mode device govern measurable output characteristics (Dharmasena et al., 2017). The present study has responded to this integration problem by defining six principal constructs: oxide material properties, nanostructure morphology and surface characteristics, device architecture and interface design, mechanical operating conditions, energy-conversion efficiency, and wearable energy-harvesting performance. These constructs have been operationalized through a five-point Likert instrument administered to technically informed respondents, and their relationships have been evaluated using descriptive statistics, reliability analysis, Pearson correlation, multiple regression, and comparative assessment of binary and ternary oxide systems. The study has been guided by piezoelectric constitutive theory and triboelectric electrostatic-induction theory, which collectively explain why material coefficients, stress, electric field, charge transfer, capacitance, and mechanical displacement should affect electrical output. By connecting these physical foundations to an expert-assessment model, the research has sought to identify the strongest perceived predictors of

performance while maintaining a clear distinction between survey-based constructs and direct laboratory measurement. This integrated structure has provided the basis for the study objectives and hypotheses and has allowed the subsequent findings to be interpreted in relation to both material-level mechanisms and wearable device engineering.

Background of the Study

The growing demand for autonomous, flexible, lightweight, and self-powered electronic systems has increased scientific attention toward energy-harvesting technologies capable of converting naturally available mechanical energy into electrical power. Wearable devices, portable health-monitoring systems, smart textiles, wireless sensors, and body-integrated electronics require continuous or intermittent electrical energy to perform sensing, processing, communication, and monitoring functions. Conventional batteries remain widely used for these purposes, yet they introduce limitations associated with finite operating life, repeated charging or replacement requirements, rigid packaging, added weight, environmental waste, and challenges in maintaining long-term operation in distributed wearable systems. Mechanical energy produced by routine human activities, including walking, running, bending, stretching, arm movement, foot pressure, breathing, and clothing deformation, provides an accessible energy source that can be captured directly at the point of use. Triboelectric nanogenerators and piezoelectric nanogenerators have emerged as promising approaches for utilizing these low-frequency mechanical inputs because both technologies can generate electrical signals from small-scale deformation and contact events without requiring conventional rotary or electromagnetic generation systems. Piezoelectric nanogenerators convert mechanical strain into electrical polarization through piezoelectric materials, whereas triboelectric nanogenerators generate electrical output through contact electrification and electrostatic induction between materials with different charge-transfer characteristics. The performance of both systems is strongly influenced by active material selection, nanostructure morphology, dielectric properties, polarization behavior, surface characteristics, device architecture, electrode configuration, mechanical loading, and interfacial compatibility. Oxide nanostructures have become particularly important because their electrical, dielectric, piezoelectric, structural, and chemical characteristics can be modified through composition and nanoscale engineering. Binary oxides such as zinc oxide provide relatively simple structures with established piezoelectric and semiconducting properties, while ternary oxides such as barium titanate, zinc stannate, and bismuth ferrite offer additional opportunities for stronger polarization, dielectric enhancement, phase engineering, and compositional control. Their incorporation into flexible polymers, fibers, films, nanowires, nanorods, nanosheets, and hybrid composites creates a broad design space for wearable energy harvesting. The central challenge is therefore not limited to generating electrical output, but to optimizing the relationship among material composition, nanostructure characteristics, mechanical deformation, charge production, power delivery, and long-term wearable functionality. This study is positioned within that multidisciplinary context by examining triboelectric and piezoelectric nanogenerators based on binary and ternary oxide nanostructures and by quantitatively assessing the factors that contribute to higher energy-conversion efficiency and improved wearable harvesting performance.

Problem Statement

Although triboelectric and piezoelectric nanogenerators have demonstrated considerable potential for wearable energy harvesting, achieving consistently high energy-conversion efficiency under practical mechanical conditions remains a significant materials and device-engineering problem. Many nanogenerator systems can produce measurable voltage or current under controlled laboratory loading, yet their performance often varies considerably when changes occur in force, pressure, frequency, bending angle, contact area, strain, device geometry, surface morphology, or active-layer composition. This inconsistency is particularly important in wearable applications because human motion is irregular, multidirectional, low-frequency, and continuously changing rather than precisely controlled. Binary and ternary oxide nanostructures provide attractive electrical and electromechanical characteristics, but their contribution to overall nanogenerator performance depends on much more than the chemical composition of the material. Surface roughness, crystallinity, particle or grain size, nanowire alignment, dielectric response, defect structure, interfacial adhesion, charge trapping, electrode design, polymer compatibility, and mechanical stress transfer can either enhance or restrict

the usable electrical output. In piezoelectric devices, weak stress transfer, charge screening, insufficient polarization, and mechanical brittleness may reduce the effective conversion of strain into electrical energy. In triboelectric devices, limited contact electrification, charge leakage, low dielectric response, insufficient effective contact area, and unstable surface interaction may similarly reduce output. A further problem is that binary and ternary oxide nanostructures are frequently evaluated using different fabrication techniques, geometries, loading conditions, performance metrics, and experimental setups, making direct comparison difficult. Reported improvements in voltage, current, power density, charge density, or durability may arise from simultaneous changes in multiple design parameters, which makes it difficult to isolate the relative influence of material properties, nanostructure morphology, device architecture, and mechanical operating conditions. There is therefore a need for a structured quantitative assessment capable of examining these determinants collectively and determining which factors show the strongest relationships with energy-conversion efficiency and wearable harvesting performance. The absence of such an integrated analytical perspective limits the ability to establish clear optimization priorities across oxide-based triboelectric and piezoelectric systems. This study addresses that problem by organizing the main determinants into measurable variables and evaluating their relationships using descriptive statistics, correlation analysis, and regression modeling. By comparing binary and ternary oxide nanostructures within the same analytical framework, the research seeks to provide a clearer understanding of the conditions associated with improved nanogenerator performance in wearable energy-harvesting contexts.

Purpose/Objectives of the Study

The primary purpose of this study is to quantitatively evaluate the factors that influence the energy-conversion efficiency of triboelectric and piezoelectric nanogenerators incorporating binary and ternary oxide nanostructures and to determine how these factors relate to the practical performance of wearable energy-harvesting systems. The study is designed to move beyond isolated consideration of a single material characteristic by examining energy conversion as the combined outcome of material, structural, device, and mechanical variables. Specifically, the research seeks to assess how oxide nanostructure material properties, including dielectric behavior, piezoelectric response, polarization capability, electrical stability, and charge-related characteristics, contribute to the generation and transfer of electrical energy. It also aims to determine the role of nanostructure morphology and surface characteristics, including size, aspect ratio, roughness, porosity, orientation, effective surface area, and structural uniformity, in enhancing triboelectric and piezoelectric output. A further objective is to evaluate how device architecture and interface design, including electrode configuration, active-layer organization, substrate compatibility, oxide-polymer interaction, and layer thickness, influence energy-conversion performance. The study also seeks to assess the effects of mechanical operating conditions such as pressure, strain, frequency, contact area, bending, and repeated deformation on the ability of nanogenerators to produce stable electrical output under wearable conditions. Another important objective is to compare the performance characteristics of binary and ternary oxide nanostructure systems and determine whether differences in material complexity, dielectric properties, polarization behavior, and structural characteristics are associated with measurable differences in energy-conversion efficiency. The research further aims to examine the relationship between energy-conversion efficiency and wearable energy-harvesting performance, particularly in relation to flexibility, durability, mechanical stability, low-frequency operation, and suitability for body-worn applications. Through statistical analysis, the study intends to identify the most influential predictors of energy-conversion efficiency and determine the relative contribution of each independent variable to the dependent outcomes. The overall objective is therefore to establish a coherent quantitative framework that can explain the relationships among oxide composition, nanostructure design, device configuration, mechanical excitation, energy-conversion efficiency, and wearable performance within triboelectric and piezoelectric nanogenerator systems.

Research Hypotheses

The hypotheses of this study have been developed to statistically examine the proposed relationships among oxide material characteristics, nanostructure morphology, device architecture, mechanical operating conditions, energy-conversion efficiency, and wearable energy-harvesting performance. H1 proposes that oxide nanostructure material properties have a statistically significant positive

relationship with energy-conversion efficiency, because stronger dielectric characteristics, piezoelectric response, polarization capability, charge retention, and electrical stability are expected to support improved mechanical-to-electrical conversion. H2 states that nanostructure morphology and surface characteristics have a statistically significant positive effect on energy-conversion efficiency, as optimized surface roughness, effective surface area, porosity, dimensional structure, and orientation may improve charge generation, stress transfer, and electrostatic interaction. H3 proposes that device architecture and interface design significantly influence energy-conversion efficiency, since the arrangement of active layers, electrodes, substrates, interfaces, and structural geometry determines how efficiently mechanical energy is transferred to the active material and how effectively the generated charge is collected. H4 states that mechanical operating conditions have a statistically significant relationship with nanogenerator energy-conversion efficiency, because pressure, strain, deformation frequency, contact area, and repeated mechanical loading directly affect the degree of polarization, contact electrification, and electrostatic induction produced during operation. H5 proposes that binary and ternary oxide nanostructures exhibit statistically significant differences in their contribution to nanogenerator performance due to variations in crystal structure, dielectric behavior, polarization properties, chemical composition, and interfacial characteristics. H6 states that energy-conversion efficiency has a statistically significant positive relationship with wearable energy-harvesting performance, meaning that devices capable of generating and transferring electrical energy more effectively are also expected to demonstrate stronger functional suitability for body-worn applications. H7 proposes that the combined effects of oxide material properties, nanostructure morphology, device architecture, and mechanical operating conditions significantly predict energy-conversion efficiency when evaluated through multiple regression analysis. These hypotheses provide a structured statistical basis for testing the conceptual relationships proposed in the study and allow the research to identify both individual and combined determinants of nanogenerator performance.

Significance of the Research

- i. Significance to nanomaterials research: This study is significant to nanomaterials research because it examines how the intrinsic and engineered properties of binary and ternary oxide nanostructures are associated with energy-conversion efficiency. By considering dielectric behavior, piezoelectric response, charge retention, morphology, orientation, and surface characteristics within one quantitative framework, the study can support a more integrated understanding of how oxide nanostructures contribute to electrical generation under mechanical stimulation.
- ii. Significance to nanogenerator engineering: The research is relevant to the engineering of triboelectric and piezoelectric nanogenerators because it evaluates the relative contribution of material characteristics, device architecture, interfaces, and mechanical operating conditions. This makes it possible to identify which design factors are most strongly associated with improved energy-conversion performance rather than treating output as the result of material selection alone.
- iii. Significance to wearable energy harvesting: The study is important for wearable harvesting because body-worn devices require electrical performance to coexist with flexibility, durability, low-frequency responsiveness, mechanical stability, and repeated deformation tolerance. The research links energy-conversion efficiency with these wearable performance characteristics and therefore provides a basis for evaluating nanogenerator systems from both electrical and practical perspectives.
- iv. Significance to comparative materials assessment: By examining binary and ternary oxide nanostructures in the same research framework, the study supports clearer comparison of two important material categories. This can help distinguish the potential contribution of compositional complexity, polarization characteristics, dielectric properties, and nanoscale morphology to nanogenerator performance.
- v. Significance to quantitative research: The use of descriptive statistics, correlation analysis, and regression modeling adds an empirical dimension to the study by identifying statistical relationships among the major variables. Rather than relying only on qualitative comparison, the research evaluates the strength and direction of relationships and determines the relative predictive contribution of selected material, structural, and device factors.
- vi. Significance to interdisciplinary research: The study connects materials science, nanotechnology, electrical engineering, mechanical energy harvesting, and wearable electronics within a single

analytical framework. This interdisciplinary structure is important because nanogenerator performance is governed by interactions among crystal properties, surface behavior, mechanical deformation, electrical transport, device design, and wearable operating conditions.

LITERATURE REVIEW

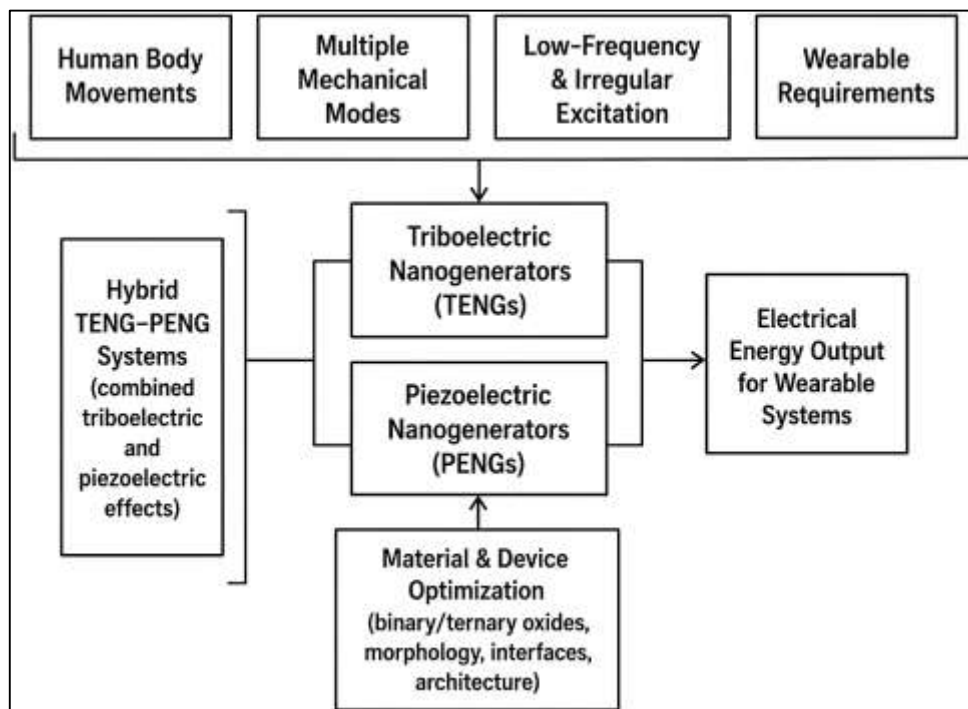
The literature on triboelectric and piezoelectric nanogenerators has developed around the broader objective of converting low-frequency mechanical energy into electrical output through compact, flexible, and material-efficient systems. Within wearable applications, this research area is particularly important because the human body continuously produces mechanical motion through walking, bending, stretching, breathing, joint movement, pressure, and contact between clothing and skin or external surfaces. Piezoelectric nanogenerators rely primarily on mechanically induced polarization within non-centrosymmetric or ferroelectric materials, while triboelectric nanogenerators operate through contact electrification and electrostatic induction generated between interacting surfaces. Both approaches are strongly dependent on material selection, structural configuration, surface engineering, electrode design, mechanical loading, and device geometry. Oxide nanostructures have received substantial attention because they provide tunable electrical, dielectric, piezoelectric, semiconducting, and structural characteristics at the nanoscale. Binary oxide materials, particularly zinc oxide, have provided an important foundation for nanogenerator development because of their relatively simple chemistry, piezoelectric behavior, and compatibility with nanowire and nanorod structures. Ternary oxides such as barium titanate, zinc stannate, bismuth ferrite, and potassium niobate extend this material space through more complex crystal structures, stronger dielectric or ferroelectric characteristics, and broader compositional control. The literature also demonstrates that the same oxide composition can produce substantially different output depending on morphology, alignment, porosity, crystallinity, particle dimensions, surface roughness, filler distribution, polymer interaction, and electrode configuration. For triboelectric systems, surface charge density, dielectric constant, charge trapping, contact area, and interfacial polarization are central determinants of performance, whereas piezoelectric devices additionally depend on polarization orientation, piezoelectric coefficients, strain transfer, mechanical compliance, and charge screening. Hybrid configurations further connect these mechanisms by combining triboelectric and piezoelectric effects within a single energy-harvesting structure. Wearable integration introduces additional requirements because the generator must tolerate repeated bending, compression, stretching, and irregular loading while maintaining stable electrical output and mechanical comfort. Consequently, the literature relevant to this study spans fundamental energy-conversion mechanisms, binary and ternary oxide materials, nanoscale morphology, surface and interface engineering, flexible device architecture, mechanical operating conditions, electrical-performance metrics, and wearable functionality. These interconnected themes provide the foundation for examining how material and structural variables jointly influence energy-conversion efficiency in oxide-based triboelectric and piezoelectric nanogenerators.

Triboelectric and Piezoelectric Nanogenerators for Wearable Energy Harvesting

Triboelectric and piezoelectric nanogenerators represent two major classes of mechanical energy-harvesting technologies developed for converting small, irregular, and low-frequency mechanical inputs into electrical energy suitable for portable and wearable systems. Triboelectric nanogenerators operate through the coupled processes of contact electrification and electrostatic induction, in which repeated contact and separation between dissimilar materials create surface charges and drive electron flow through an external circuit. Their relatively simple architecture, broad material selection, high voltage output, and ability to respond to pressing, sliding, stretching, and impact make them attractive for harvesting biomechanical energy from walking, arm movement, finger tapping, fabric motion, and joint deformation. Piezoelectric nanogenerators, in comparison, rely on the development of electrical polarization when a non-centrosymmetric piezoelectric material is mechanically strained. Their output therefore depends strongly on polarization orientation, piezoelectric coefficients, strain transfer, mechanical compliance, electrode configuration, and the ability of the active material to retain its electromechanical properties during repeated deformation. Wearable implementation requires both technologies to function under mechanical conditions that differ substantially from controlled laboratory excitation, including variable pressure, changing frequency, multidirectional movement, and prolonged cyclic loading. The power source must also remain flexible, lightweight, conformable,

and compatible with body motion. A flexible and biocompatible TENG based on PDMS and PDMS/MWCNT layers demonstrated that tuning internal resistance and dielectric behavior could improve output while retaining characteristics relevant to wearable operation (Debasish, 2021; Zhu et al., 2016). Similarly, a tube-structured TENG designed around stretchable and weavable materials harvested biomechanical energy from walking and jogging and supplied power to wearable electronics, showing how material selection and structural configuration can connect mechanical energy harvesting directly with body-worn applications (Abdur & Iftkhar, 2021; Wang et al., 2016). Accordingly, wearable nanogenerator design must integrate electrical generation with mechanical resilience, because useful performance depends on sustaining charge production during repeated human motions without compromising flexibility, comfort, or structural integrity.

Figure 2: Integrated Framework for Wearable Triboelectric and Piezoelectric Nanogenerator Performance



The distinction between triboelectric and piezoelectric conversion does not require the two mechanisms to remain technologically separate, because wearable nanogenerators can be engineered to exploit both within a single device. Hybrid triboelectric–piezoelectric systems are particularly relevant where mechanical deformation simultaneously produces surface charge transfer and internal polarization, allowing different electrical responses to be obtained from one mechanical event. This approach can increase the fraction of available mechanical energy that is captured while also enabling designers to balance the high-voltage characteristics of triboelectric generation with the strain-responsive behavior of piezoelectric materials. A flexible hybrid device using electrospun P(VDF-TrFE) nanofibers as a piezoelectric functional layer and triboelectric friction layer together with a patterned PDMS/MWCNT membrane demonstrated that structural roughness, conductive filler incorporation, dielectric behavior, and external load matching jointly influenced electrical output (Debasish, 2022; Wang et al., 2016). Such findings are important for oxide-based systems because binary and ternary oxide nanostructures can be introduced into flexible polymer matrices to alter dielectric permittivity, interfacial polarization, surface morphology, charge trapping, local stress concentration, and piezoelectric response. The active role of ceramic nanostructures becomes especially clear when piezoelectric and triboelectric functions are deliberately combined. In a flexible piezo-triboelectric nanogenerator based on BCZT/PVDF-HFP composite nanofibers, incorporation of lead-free ceramic nanoparticles strengthened both mechanisms,

while the fibrous architecture enabled sensitivity to small body motions and maintained flexible operation (Hasan & Adnan, 2022; Wu et al., 2019). For wearable harvesting, this combined design logic is valuable because mechanical inputs from the human body rarely occur as a single idealized loading mode. Pressure, bending, stretching, rubbing, and vibration may occur together, so a hybrid generator capable of responding through multiple electromechanical pathways can utilize a wider range of available biomechanical activity while preserving the thin, compliant form required for integration into clothing, patches, accessories, and other body-worn platforms. Performance must remain stable during wear.

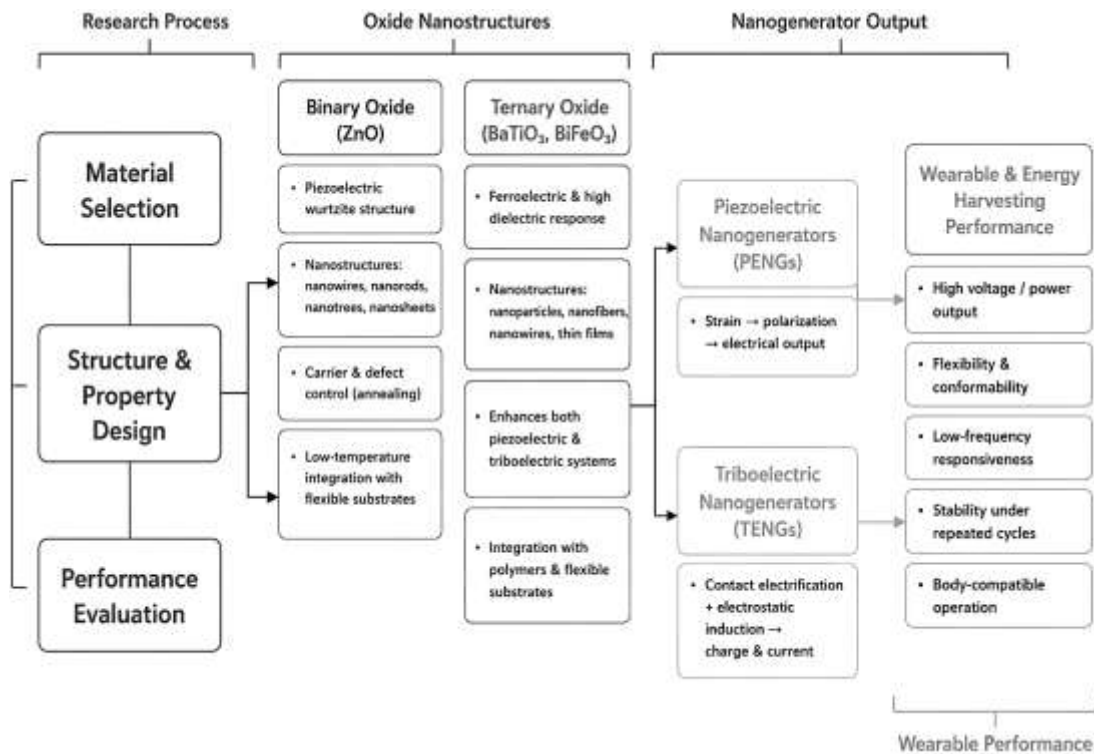
Energy-conversion performance in wearable TENGs and PENGs is determined by an interacting set of material, surface, structural, electrical, and mechanical variables rather than by generator type alone. In triboelectric systems, surface charge density, dielectric constant, effective contact area, charge affinity, internal resistance, electrode arrangement, and contact-separation dynamics govern the amount of charge that can be generated and transferred. In piezoelectric systems, crystal symmetry, polarization, piezoelectric coefficient, active-phase alignment, stress distribution, strain-transfer efficiency, conductivity, and dielectric loss influence the electrical response obtained from deformation. These factors become more complex in nanocomposites because filler concentration, particle dispersion, oxide-polymer adhesion, porosity, surface roughness, and percolation behavior can modify several properties simultaneously. Optimization must therefore consider whether a change that increases dielectric response also affects flexibility, leakage, mechanical stiffness, or interfacial stress transfer. This relationship was demonstrated in a PDMS/ZnSnO₃/MWCNT triboelectric system in which dielectric constant, internal resistance, and surface modification were systematically adjusted, producing strong biomechanical energy-harvesting performance and highlighting the importance of coordinated rather than isolated optimization (Mahbubul et al., 2022; Paria et al., 2019). For the present research, these observations establish a direct connection between the general literature on wearable nanogenerators and the specific examination of binary and ternary oxide nanostructures. Binary oxides can provide comparatively simple piezoelectric, semiconducting, or dielectric functions, while ternary oxides offer additional compositional control over polarization, permittivity, crystal structure, and interfacial behavior. Their effectiveness in TENG and PENG architectures depends on how these intrinsic properties are translated through nanoscale morphology and device design into measurable voltage, current, charge, power density, and conversion efficiency. Wearable performance adds further requirements involving flexibility, durability, low-frequency responsiveness, repeated-cycle stability, and compatibility with irregular human motion, making energy harvesting a multidimensional optimization problem. This integrated perspective is essential when comparing material systems whose electrical advantages may be accompanied by differences in stiffness, processability, or endurance.

Binary and Ternary Oxide Nanostructures for Nanogenerator Applications

Binary and ternary oxide nanostructures have become important functional materials in nanogenerator research because their electrical, dielectric, piezoelectric, semiconducting, and surface properties can be tailored through composition, morphology, defect control, and nanoscale architecture. Binary oxides contain oxygen and one additional element, and zinc oxide is among the most extensively investigated examples for mechanical energy harvesting because its wurtzite crystal structure lacks centrosymmetry and therefore develops piezoelectric polarization when mechanically deformed. ZnO can be synthesized as nanowires, nanorods, nanotrees, nanoparticles, nanosheets, and other high-aspect-ratio structures using accessible growth techniques, allowing its electromechanical properties to be incorporated into flexible substrates. The morphology of ZnO is important because the magnitude and spatial distribution of piezopotential depend on the orientation, aspect ratio, density, crystallinity, and deformation mode of the nanostructures. Branched ZnO nanotrees grown on flexible fiber-paper substrates demonstrated that increasing mechanically active branches and improving the three-dimensional harvesting geometry could increase output voltage and power density compared with conventional vertically aligned nanowires, emphasizing the contribution of architecture to applied-stress utilization (Ashfaq & Mohammad, 2022; Qiu et al., 2015). Similar evidence from hydrothermally grown ZnO nanowires showed that electrical carrier concentration is another critical variable because excessive free carriers can screen the piezoelectric potential produced during deformation. Thermal

annealing was used to reduce free-carrier concentration and improve the electrical output of ZnO nanowire nanogenerators, demonstrating that defect and carrier management can be as important as geometric optimization (Sheak & Risha, 2022; Opoku et al., 2015). For wearable systems, these characteristics make binary oxide nanostructures attractive because low-temperature growth and nanoscale dimensions can facilitate integration with polymers, paper, fibers, and flexible electrodes. Their performance remains dependent on effective mechanical stress transfer, stable electrical contacts, controlled conductivity, and resistance to repeated deformation. Binary oxides therefore provide a comparatively simple platform through which relationships among composition, morphology, electrical behavior, and nanogenerator output can be examined.

Figure 3: Comparative Framework of Binary and Ternary Oxide Nanostructures for Wearable Nanogenerators



Ternary oxide nanostructures expand the functional possibilities of nanogenerators because the presence of two cation species and oxygen permits more complex crystal structures, stronger ferroelectric polarization, adjustable dielectric properties, and broader control of phase stability than is generally available in simple binary oxides. Perovskite oxides such as barium titanate and bismuth ferrite are particularly relevant because their non-centrosymmetric or ferroelectric structures support electromechanical coupling while remaining free from lead content. BaTiO₃ combines high dielectric permittivity with spontaneous polarization and can be fabricated as nanoparticles, nanofibers, nanotubes, nanowires, and thin films, supporting incorporation into flexible polymer matrices. Piezoelectric microstructured fibers based on BaTiO₃-containing polymer layers demonstrated that a ternary oxide could be integrated within a multimaterial fibrous architecture while maintaining mechanical durability under repeated bending, important for textile-compatible energy harvesting (Lu et al., 2017; Rashedul & Kaium, 2022). The value of ternary oxides is not limited to direct piezoelectric conversion because their dielectric properties can also strengthen triboelectric systems. Microporous BaTiO₃/PDMS nanocomposites fabricated for triboelectric nanogenerators showed that introducing BaTiO₃ nanoparticles into a porous elastomer could modify dielectric behavior and contribute to enhanced triboelectric output, while the porous architecture increased deformation during contact (Jang & Oh, 2018; Chowdhury & Tonay, 2022). BiFeO₃ represents another important ternary oxide

because it combines ferroelectric, piezoelectric, and multiferroic characteristics, although its processing temperature and integration with flexible substrates can create engineering challenges. Direct fabrication of BiFeO₃ thin films on polyimide at reduced temperature demonstrated that functional ferroelectric and piezoelectric oxide layers could be formed on flexible polymer supports without relying exclusively on rigid substrates (Hossan, 2022; Tomczyk et al., 2017). These findings show that ternary oxides offer routes for increasing nanogenerator performance through polarization, dielectric enhancement, interface engineering, and structural design. Their complex compositions also introduce sensitivity to phase purity, stoichiometry, grain structure, defects, processing temperature, and oxide-polymer compatibility, all of which can influence response.

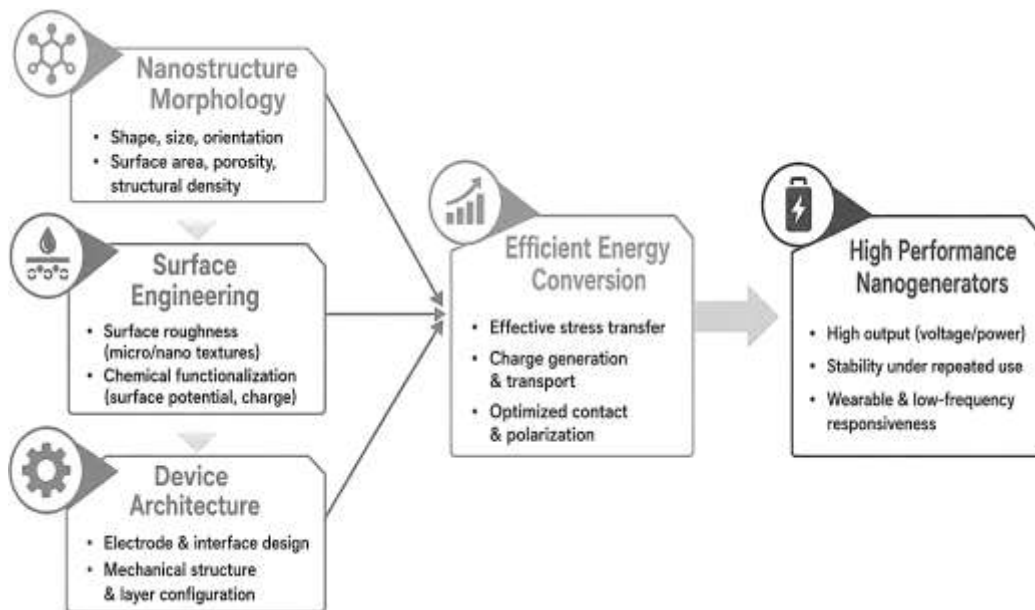
A comparison of binary and ternary oxide nanostructures indicates that energy-harvesting performance is controlled by the interaction between intrinsic material characteristics and the architecture through which those characteristics are converted into electrical output. Binary oxides such as ZnO offer advantages associated with simple chemical composition, established synthesis routes, semiconducting behavior, morphology control, and direct piezoelectric response, making them useful for studying nanowire alignment, carrier concentration, surface states, and mechanical deformation. Ternary oxides such as BaTiO₃ and BiFeO₃ introduce additional compositional and crystallographic freedom that can increase dielectric polarization and electromechanical coupling, yet their fabrication may require greater control over phase formation, interfaces, and processing conditions. For piezoelectric nanogenerators, the relevant material must develop sufficient polarization under applied strain while allowing generated charges to reach electrodes without excessive screening or leakage. For triboelectric nanogenerators, oxide nanostructures can increase surface roughness, effective dielectric constant, interfacial polarization, charge trapping, or mechanical deformability when incorporated into a polymeric triboelectric layer. The distinction between binary and ternary oxides is therefore not simply a comparison of chemical formulas; it reflects different opportunities for controlling charge generation and transmission at structural levels. Nanoparticles can improve dielectric response and interfacial area, nanowires and nanorods can direct stress and polarization along preferred orientations, porous structures can increase deformability and contact area, and fibrous architectures can distribute active material through wearable substrates. Material loading must be controlled because excessive ceramic content can increase stiffness, promote agglomeration, introduce electrical loss, or reduce mechanical conformity required for body-worn devices. Consequently, oxide selection for wearable nanogenerators should be evaluated together with morphology, interface quality, substrate properties, electrode arrangement, mechanical excitation, and electrical loading. This integrated perspective provides the basis for comparing binary and ternary oxide nanostructures and examining how material properties and device-level factors relate quantitatively to energy-conversion efficiency and wearable harvesting performance.

Nanostructure Morphology and Device Architecture

Nanostructure morphology is a decisive factor in the performance of triboelectric and piezoelectric nanogenerators because the geometry of an active material governs how mechanical stress, interfacial contact, polarization, and charge transport are distributed throughout the device. At the nanoscale, variations in thickness, aspect ratio, orientation, surface area, porosity, and structural density can change the extent to which an applied force is transferred into useful electrical response. For piezoelectric systems, one-dimensional structures such as nanowires and nanorods provide directional pathways for strain-induced polarization, while two-dimensional structures such as nanosheets and nanoflakes can create large active surfaces and short transport distances. Three-dimensional hierarchical structures may further increase mechanical interaction by combining multiple length scales within the same active region. A ZnO nanoflake nanogenerator developed by Ngoc and Kang (2016) illustrates the importance of morphology, as ultrathin ZnO nanoflakes below approximately ten nanometers in thickness were integrated into a flexible and transparent device that produced high electrical output under mechanical stimulation. The work showed that morphology was not merely a visual or structural characteristic but a functional variable connected to deformation behavior, polarization development, and electrical collection. In wearable energy harvesting, this relationship becomes especially important because body motion produces nonuniform stress rather than perfectly controlled compression. Nanostructures must therefore be capable of responding to bending, pressing,

stretching, and vibration while remaining attached to compliant substrates. Dense structures may increase the quantity of active material, but excessive packing can restrict deformation or increase screening, whereas sparse structures may deform readily but provide insufficient active volume. Morphological optimization consequently requires balance among active surface area, mechanical compliance, structural integrity, and electrical connectivity. For binary and ternary oxides, the ability to synthesize nanowires, nanorods, nanoflakes, nanoparticles, porous networks, and hierarchical architectures provides pathways for tuning these relationships without changing the chemical composition of the material.

Figure 4: Integrated Influence of Nanostructure Morphology, Surface Engineering, and Device Architecture on Nanogenerator Performance



Surface engineering provides a second route for improving nanogenerator performance because the electrical output of a TENG is dependent on the amount, distribution, and stability of charge produced at contacting interfaces, while PENG performance can also be affected by surface states, electrode contact, and interface quality. Physical surface engineering modifies topography through microcones, pyramids, nanowires, nanoflowers, pores, grooves, or other textured features that alter contact area and mechanical pressure. (Kaniz, 2022); Park et al. (2015) demonstrated this principle using electrodeposited gold nanoflowers, where hierarchical micro-to-nanoscale roughness increased the effective contact area and produced higher triboelectric output than a flat gold surface. Their results also showed that roughness must be optimized rather than maximized, because excessively tall or irregular structures can create incomplete tip-to-tip contact and reduce effective interfacial interaction. Chemical surface engineering provides another method by altering surface potential and charge-transfer tendency without necessarily changing bulk geometry. (Nishat & Kaniz, 2022); S. Wang et al. (2016) used self-assembled monolayers with different molecular head groups to modify triboelectric surfaces and established a relationship between surface potential and triboelectric charge density, with functionalization substantially increasing power output. These findings are relevant to oxide-based TENGs because binary and ternary oxide nanostructures possess surfaces whose defect states, hydroxyl groups, adsorbed species, chemical termination, and polarity can influence charge transfer and retention. Surface treatment can also affect oxide-polymer adhesion, dispersion, moisture sensitivity, and dielectric interfaces. In wearable devices, engineered surfaces must retain their morphology during repeated contact, bending, friction, and exposure to humidity or skin-associated conditions. A surface structure that initially increases charge density may lose effectiveness if it fractures, wears, contaminates, or collapses under cyclic loading. Accordingly, surface engineering involves

simultaneous control of nanoscale roughness, chemical functionality, mechanical durability, environmental stability, and interfacial compatibility so that electrical enhancement persists under the repetitive and irregular mechanical conditions characteristic of wearable energy harvesting.

Device architecture determines how nanostructured materials are mechanically excited, electrically connected, protected, and integrated into a usable energy-harvesting platform. Even when an oxide possesses piezoelectric or dielectric characteristics, poor electrode contact, inefficient stress transfer, inappropriate layer thickness, or unsuitable structural geometry can prevent those properties from producing usable output. In ZnO-based PENGs, architecture has been modified through fiber substrates, nanowire arrays, cantilevers, layered composites, and interfacial barriers. [Du et al. \(2017\)](#); [\(Shaiful et al., 2022\)](#) developed a carbon-fiber/ZnO-nanowire hybrid nanogenerator in which ZnO nanowires were grown on carbon fibers and an insulating interface barrier was used to support charge accumulation while avoiding dependence on noble-metal contacts. The study highlighted the importance of electrical interfaces because the barrier, fiber conductivity, nanowire contact, and relative sliding motion determined whether piezoelectric potential could be converted into measurable current. Mechanical architecture is equally important for matching a generator to low-frequency excitation. [Deng et al. \(2018\)](#); [\(Nishat & Kaniz, 2022\)](#) designed a tuning-fork-shaped cantilever incorporating ZnO nanorods and showed that modifying the elastic beam geometry enabled the PENG to respond to weak, low-frequency vibration. This type of structural matching is relevant to wearable applications, where motion frequencies are lower and less regular than those produced by laboratory vibration equipment. Device architecture for oxide-based TENGs and PENGs must therefore coordinate active-layer placement, electrode configuration, substrate flexibility, interface resistance, encapsulation, mechanical neutral planes, contact gaps, and force-transfer pathways. Polymer matrices can improve flexibility and protect brittle oxide structures, but excessive thickness may reduce stress delivery to the active phase. Thin structures may improve deformation sensitivity while becoming vulnerable to fatigue or mechanical damage. Similarly, larger contact areas can increase available charge while creating challenges in maintaining uniform pressure. Architectural optimization therefore links nanoscale morphology and surface engineering with macroscale mechanical behavior, determining how efficiently binary or ternary oxide nanostructures operate under realistic wearable loading conditions.

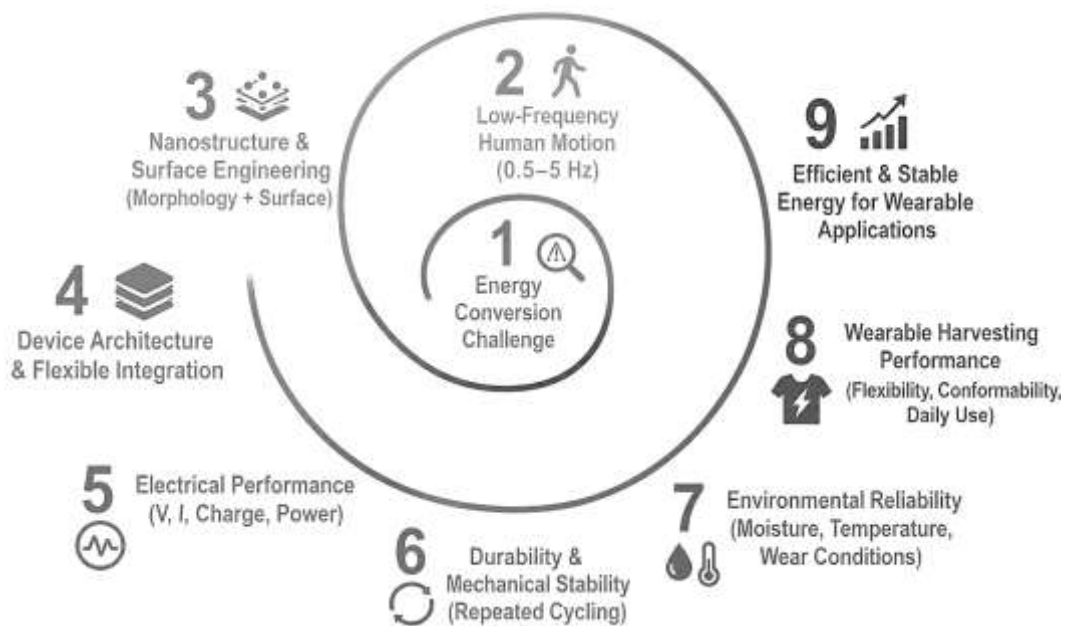
Energy-Conversion Efficiency and Wearable Harvesting Performance

Energy-conversion efficiency is a central criterion for evaluating triboelectric and piezoelectric nanogenerators because wearable devices must transform weak and irregular mechanical inputs into electrical outputs that are sufficiently stable for sensing, storage, or low-power operation. In practical assessment, efficiency cannot be represented by peak voltage alone; it must be interpreted together with current, charge transfer, power density, energy generated per mechanical cycle, load matching, operating frequency, and the stability of output under repeated deformation. Human motion is particularly demanding because walking, joint rotation, bending, stretching, and garment movement occur mainly at low and variable frequencies. A useful wearable generator must therefore respond to these motions without requiring high-frequency resonance or carefully controlled laboratory excitation. [Li et al. \(2018\)](#) demonstrated this problem directly through a flexible piezoelectric harvester designed for low-frequency limb movement, where a frequency-up-conversion structure enabled energy generation from joint motion across approximately 0.5–5 Hz and maintained relatively stable energy per movement cycle. This finding shows that mechanical architecture can determine whether intrinsic piezoelectric properties are effectively converted into usable energy under wearable conditions. Textile integration introduces another performance dimension because a generator must retain electrical functionality while being bent, worn, and exposed to moisture. [Lund et al. \(2018\)](#) developed woven piezoelectric textiles using conducting-core PVDF microfibres and demonstrated that the textile could generate several volts at low strain and continue functioning under wet conditions. These studies indicate that wearable energy-conversion performance depends on the interaction between active material response and system-level characteristics, including flexibility, mechanical coupling, environmental stability, and electrical extraction. For oxide-based nanogenerators, the same principle requires binary and ternary oxide nanostructures to be evaluated not only for polarization or dielectric properties but also for how efficiently their properties are translated through flexible substrates and interfaces into stable electrical output during realistic body

motion consistently overall.

Wearable harvesting performance in triboelectric nanogenerators is similarly determined by the combined effectiveness of charge generation, charge retention, contact mechanics, material deformability, and structural durability. Triboelectric output originates at contacting surfaces, so surface chemistry and physical contact strongly affect electrical response, while practical wearability additionally requires resistance to stretching, folding, washing, abrasion, humidity, and repetitive body movement. [Xiong et al. \(2018\)](#) demonstrated a skin-touch-actuated textile TENG incorporating black phosphorus with a hydrophobic cellulose-derived coating, producing substantial electrical output from low-force and low-frequency human contact while maintaining operation after repeated folding, twisting, stretching, and washing. Their work illustrates that high output and wearability must be optimized together because an electrically active surface has limited value if its charge-trapping behavior deteriorates under routine use. Mechanical recoverability is another important dimension of wearable performance. [Parida et al. \(2019\)](#) reported a three-dimensionally printed triboelectric nanogenerator using an extremely stretchable and self-healing thermoplastic elastomer conductor, with the device sustaining very large deformation and recovering its energy-harvesting functionality after mechanical damage. This evidence broadens the definition of performance from instantaneous electrical generation to functional resilience, indicating that wearable nanogenerators should be assessed through durability, recoverability, conformability, and long-term electrical stability. These considerations are highly relevant to binary and ternary oxide nanostructures because ceramic or semiconducting oxide phases are often integrated into elastomeric or polymer matrices whose mechanical properties control stress transfer and surface contact. Increasing oxide concentration may improve dielectric response, polarization, or charge trapping, yet excessive loading can increase stiffness, agglomeration, or interfacial defects. Consequently, the energy-conversion efficiency of an oxide-containing wearable TENG or PENG must be interpreted as an outcome of balanced electrical and mechanical design, where material enhancement is maintained without sacrificing the flexibility required for body-conformal operation. This balance is fundamental when nanogenerator structures are intended for comfortable, mechanically unobtrusive daily wear.

Figure 5: Key Determinants of Energy-Conversion Efficiency and Wearable Nanogenerator Performance



The relationship between energy-conversion efficiency and wearable harvesting performance becomes more complex when environmental exposure and diverse deformation modes are considered, because a wearable generator may operate on skin, clothing, joints, footwear, or equipment under changing

temperature, moisture, pressure, and motion. A strong device should maintain useful output across these conditions while remaining lightweight, soft, mechanically stable, and capable of repeated cycling. [Zou et al. \(2019\)](#) demonstrated this broader performance requirement through a bionic stretchable nanogenerator designed for underwater energy harvesting and sensing; the system combined triboelectrification with electrostatic induction, generated electrical output from underwater human motion, and retained functionality through extensive tensile cycling. The study is important for evaluating wearable nanogenerators because it shows that conversion performance should be judged in relation to the operating environment rather than only under dry, stationary laboratory conditions. For the present research, this perspective supports a multidimensional treatment of energy-conversion efficiency in which material properties, nanostructure morphology, device architecture, and mechanical operating conditions are considered jointly. Binary oxides such as ZnO can contribute piezoelectric response, semiconducting behavior, and controllable nanoscale morphology, while ternary oxides such as BaTiO₃, ZnSnO₃, BiFeO₃, and related compositions can provide strong polarization, dielectric enhancement, and additional compositional control. Their wearable effectiveness depends on successful integration with flexible matrices, efficient stress transfer, stable interfaces, low leakage, reliable electrodes, and resistance to repeated deformation. Therefore, electrical measures such as voltage, current, charge density, and power density should be interpreted alongside flexibility, durability, low-frequency responsiveness, cycling stability, and environmental tolerance. This combined view aligns with the quantitative structure of the study because perceived energy-conversion efficiency can be analyzed in relation to material and structural predictors, while wearable harvesting performance can be treated as a functional outcome reflecting whether electrical improvements remain useful under realistic mechanical and environmental conditions over prolonged wearable operation.

Theoretical Framework

The theoretical framework of this study is grounded first in piezoelectric energy-conversion theory, which explains how mechanical stress applied to a non-centrosymmetric material produces electrical polarization and a measurable potential difference. In a piezoelectric nanogenerator, external pressure, bending, stretching, compression, or vibration produces strain within the active crystal lattice, causing relative displacement of positive and negative charge centers and generating an internal electric field. At the nanoscale, this process is strongly influenced by crystal orientation, aspect ratio, carrier concentration, boundary conditions, and the geometry through which force is transferred to the active material. [Gao and Wang \(2007\)](#) developed a fundamental theoretical description of the electrostatic potential produced in a bent piezoelectric nanowire and demonstrated that surface piezopotential is associated with mechanical deformation and nanowire geometry, providing an important mathematical foundation for interpreting ZnO-based nanogenerator operation. Their framework is particularly relevant to the present study because binary oxide nanostructures such as ZnO translate externally applied mechanical deformation into electrical potential through coupled mechanical and electrical fields. Experimental work further demonstrated that laterally packaged piezoelectric fine wires subjected to cyclic stretching and releasing can generate alternating electrical output on flexible substrates, connecting the theoretical piezopotential mechanism with practical mechanical-energy harvesting ([Yang et al., 2009](#)). The direct piezoelectric effect can be represented through constitutive relationships that connect electrical displacement, stress, dielectric response, electric field, strain, and elastic compliance. These relationships indicate that electrical response is jointly dependent on mechanical loading, dielectric properties, electromechanical coupling, and material structure. Within this study, piezoelectric theory therefore provides a basis for explaining why oxide material properties, nanostructure morphology, mechanical operating conditions, and device configuration are expected to influence energy-conversion efficiency. It also supports comparison between binary and ternary oxides whose crystal structures, polarization characteristics, dielectric behavior, and mechanical responses differ.

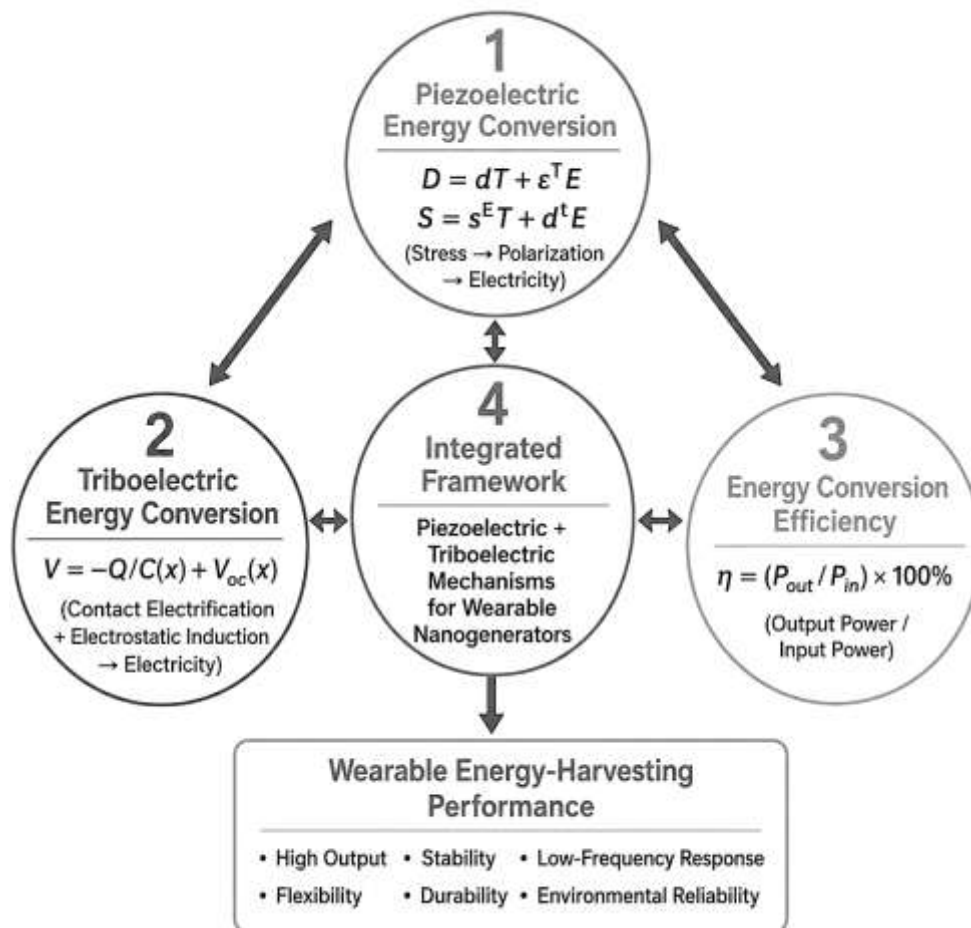
$$D = dT + \varepsilon^T E$$

$$S = s^E T + d^E E$$

where D represents electric displacement, d represents the piezoelectric coefficient, T represents

applied mechanical stress, ϵ^T represents dielectric permittivity measured at constant stress, E represents electric field, S denotes strain, and s^E represents elastic compliance at constant electric field. The second component of the theoretical framework is triboelectric energy-conversion theory, which explains electrical generation through the combined processes of contact electrification and electrostatic induction. When two materials with different surface charge-transfer characteristics repeatedly contact each other, opposite charges can develop at their interfaces, while subsequent separation or relative displacement creates an electrostatic potential difference that causes compensating charge to flow between electrodes through an external circuit. The resulting electrical response is influenced by surface charge density, dielectric thickness, material permittivity, effective contact area, separation distance, relative displacement, movement velocity, electrode configuration, and external electrical resistance. Niu et al. (2013) established a comprehensive theoretical model for contact-mode triboelectric nanogenerators and derived relationships among structural parameters, mechanical movement, voltage, current, optimum resistance, and electrical power. Their analysis provides an important theoretical foundation for understanding why changing material or architectural parameters can substantially modify nanogenerator output even when the fundamental triboelectric mechanism remains unchanged.

Figure 6: Integrated Theoretical Framework for Piezoelectric and Triboelectric Energy Conversion in Wearable Nanogenerators



Wang (2015) subsequently consolidated the theoretical system of TENG operation and described the fundamental relationship among transferred electrical charge, output voltage, device capacitance, and mechanical displacement across different TENG configurations. A generalized voltage-charge-displacement relationship for TENG operation can therefore express terminal voltage as a function of transferred charge, displacement-dependent capacitance, and open-circuit voltage. The theoretical

relationship is highly relevant to oxide-based TENGs because material composition, dielectric permittivity, nanostructure morphology, surface roughness, charge trapping, layer thickness, and electrode spacing can modify charge generation or the capacitance of the system. Binary and ternary oxide nanostructures incorporated into triboelectric polymer layers can consequently modify energy harvesting through dielectric polarization, interfacial charge storage, surface engineering, and deformation behavior. Triboelectric theory therefore supports the study's treatment of material properties, morphology, architecture, and operating conditions as interconnected determinants of electrical output rather than isolated technical attributes.

$$V = -Q/C(x) + V_o c(x)$$

where V is the terminal voltage, Q represents transferred charge between the electrodes, $C(x)$ is capacitance as a function of mechanical displacement x , and $V_o c(x)$ represents open-circuit voltage at a specified displacement.

Integration of piezoelectric and triboelectric energy-conversion theories provides an appropriate overarching theoretical framework because wearable nanogenerators may employ strain-induced polarization, contact electrification, electrostatic induction, or combined conversion mechanisms depending on their material composition and architecture. Dharmasena et al. (2017) developed a broader electromagnetic framework for contact-mode triboelectric nanogenerators based on Maxwell's equations and demonstrated that distance-dependent electric fields can be used to predict important output characteristics including voltage, current, transferred charge, and power for devices with different surface geometries. This theoretical approach is particularly applicable to nanostructured oxide devices because variations in dielectric permittivity, polarization, surface topology, electrode distance, interface configuration, and mechanical displacement modify the electrical field responsible for charge transport. Piezoelectric systems similarly depend on interactions among stress, strain, electric displacement, polarization, and electric fields, allowing both PENG and TENG mechanisms to be incorporated within a common mechanical-to-electrical conversion perspective. For the complete quantitative study, the energy-conversion-efficiency equation is selected as the principal integrative expression because it can be applied to both technologies regardless of their different microscopic mechanisms. This equation provides the most suitable theoretical bridge to the study because energy-conversion efficiency constitutes its principal performance variable. The theoretical framework therefore proposes that stronger dielectric or piezoelectric material properties, optimized nanoscale morphology, efficient interface and device architecture, and appropriately matched mechanical conditions should correspond with greater conversion performance. These theoretical dimensions are operationalized quantitatively as oxide material properties, nanostructure morphology and surface characteristics, device architecture and interface design, and mechanical operating conditions, while energy-conversion efficiency is treated as the main performance construct and wearable energy-harvesting performance as the functional outcome. Correlation analysis will evaluate associations among these constructs, while regression modeling will estimate their relative predictive contributions without equating Likert-scale expert evaluations with direct laboratory measurements.

$$\eta = (P_{out} / P_{in}) \times 100\%$$

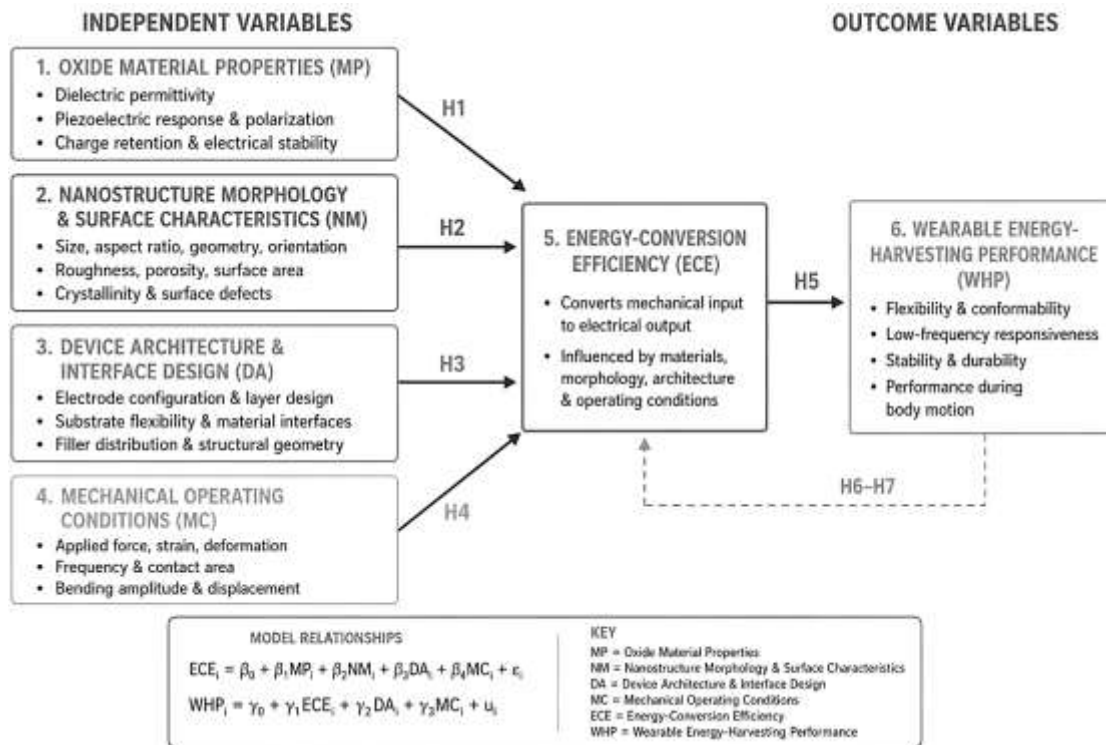
where η represents energy-conversion efficiency, P_{out} represents usable electrical output power, and P_{in} represents mechanical input power delivered to the nanogenerator.

Conceptual Framework and Hypothesized Relationships

The conceptual framework of this study organizes the determinants of triboelectric and piezoelectric nanogenerator performance into a set of measurable relationships connecting oxide material properties, nanostructure morphology, device architecture, mechanical operating conditions, energy-conversion efficiency, and wearable harvesting performance. The first explanatory construct, oxide material properties, represents dielectric permittivity, piezoelectric response, polarization capability, charge retention, electrical stability, conductivity, and characteristics that determine how effectively a binary or ternary oxide responds to mechanical excitation. The second construct, nanostructure morphology and surface characteristics, includes size, aspect ratio, geometry, orientation, roughness, porosity, effective surface area, crystallinity, and defect-related surface behavior. These variables are conceptually separated because identical chemical compositions can exhibit different

electromechanical responses when nanoscale dimensions or loading configurations change. Atomistic analysis of one-dimensional ZnO structures showed that piezoelectric and mechanical properties vary with size, cross-sectional geometry, surface reconstruction, and loading configuration, providing direct support for treating morphology as an independent determinant rather than as a simple extension of composition (Momeni & Attariani, 2014). The framework further recognizes that favorable material properties do not automatically produce high generator output when charges are screened or lost at interfaces. Surface passivation of ZnO nanorods with CuSCN was reported to reduce parasitic losses related to surface states and substantially improve the power density of a ZnO energy harvester, illustrating how interface modification can influence the conversion of intrinsic piezoelectric potential into externally measurable electrical performance (Jalali et al., 2014). Accordingly, the model proposes that oxide material properties and nanostructure morphology exert positive effects on energy-conversion efficiency, while surface and interface quality determine how completely these advantages are preserved at device level. This conceptual separation allows the quantitative analysis to identify whether respondents associate performance more strongly with the composition of the oxide itself or with the nanoscale form and interface through which the oxide is utilized.

Figure 7: Conceptual Framework and Hypothesized Relationships



The third construct in the conceptual framework is device architecture and interface design, which translates material-scale properties into a nanogenerator capable of delivering electrical charge. It encompasses active-layer thickness, electrode configuration, substrate flexibility, oxide-polymer compatibility, filler distribution, interfacial adhesion, structural geometry, electrical pathways, and the arrangement of the active nanostructures within the device. This is important for ternary oxides because their strong dielectric or piezoelectric behavior can be limited by brittle ceramic characteristics unless integrated into a compliant matrix. Charoonsuk et al. (2019) demonstrated that tetragonal BaTiO₃ nanowires incorporated with CNTs and PDMS produced a flexible piezoelectric nanocomposite whose output depended on nanowire structure, poling, conductive filler, and composite architecture; the poled device exhibited substantially stronger piezoelectric response than the non-poled configuration. This evidence supports the proposition that device architecture positively influences energy-conversion efficiency by determining stress transfer, polarization utilization, and

charge collection. The framework also considers interactions among materials rather than assuming that increasing the concentration of a high-permittivity oxide always improves performance. Ponnammam and Al-Maadeed (2019) showed that combining BaTiO₃ nanoparticles with hexagonal boron nitride nanolayers in PVDF-HFP produced a filler-synergy effect in which dielectric and piezoelectric performance depended on hybrid nanocomposite composition. Such behavior supports the conceptual assumption that optimized interfaces and material distributions can strengthen conversion performance while excessive or poorly dispersed fillers can introduce dielectric loss, stiffness, agglomeration, or inefficient mechanical coupling. Within the present study, device architecture therefore functions as an independent predictor that captures how effectively material and morphological advantages are incorporated into a functional TENG or PENG. Its proposed positive relationship with energy-conversion efficiency reflects the expectation that optimized electrodes, interfaces, flexible substrates, layer dimensions, and active-material distributions enable a greater proportion of mechanically generated polarization or triboelectric charge to become usable electrical output under comparable operating conditions during repeated wearable deformation.

Mechanical operating conditions constitute the fourth explanatory construct and connect the material-device system to wearable motion. Applied force, pressure, strain, deformation frequency, contact area, bending amplitude, displacement, and repeated loading determine the mechanical energy available for conversion and nanogenerator activation. These conditions are expected to influence energy-conversion efficiency directly because piezoelectric polarization depends on deformation of the active phase, while triboelectric output depends on contact, separation, sliding, and the associated electrostatic field. Wearable energy-harvesting performance is positioned as the functional outcome of the framework and includes flexibility, durability, low-frequency responsiveness, output stability, conformability, and operation during repeated body movement. Evidence from ultra-flexible piezoelectric devices integrated with the heart showed that output varied with mounting position, orientation, deformation amplitude, and physiological motion, indicating that the same active piezoelectric system can generate different electrical responses when its mechanical coupling to the energy source changes (Lu et al., 2015). This observation supports the proposed pathway in which mechanical operating conditions influence conversion efficiency and higher efficiency is associated with stronger wearable harvesting performance. For quantitative testing, the framework specifies energy-conversion efficiency as the primary dependent performance construct predicted by material properties, nanostructure morphology, device architecture, and mechanical conditions. Wearable harvesting performance is treated as a secondary outcome associated with conversion efficiency and relevant device and mechanical characteristics. The relationships will be tested using correlation analysis to evaluate direction and strength of association and multiple regression to estimate the unique contribution of each predictor while other variables are controlled. The conceptual specification does not treat Likert-scale responses as direct laboratory measurements of voltage, current, or physical efficiency; rather, they represent expert assessments of performance determinants. This distinction allows the statistical model to remain aligned with the cross-sectional survey design while preserving engineering logic from nanogenerator research and the theoretical relationships established in the preceding section.

$$\{MP, NM, DA, MC\} \rightarrow ECE \rightarrow WHP$$

$$ECE_i = \beta_0 + \beta_1 MP_i + \beta_2 NM_i + \beta_3 DA_i + \beta_4 MC_i + \varepsilon_i$$

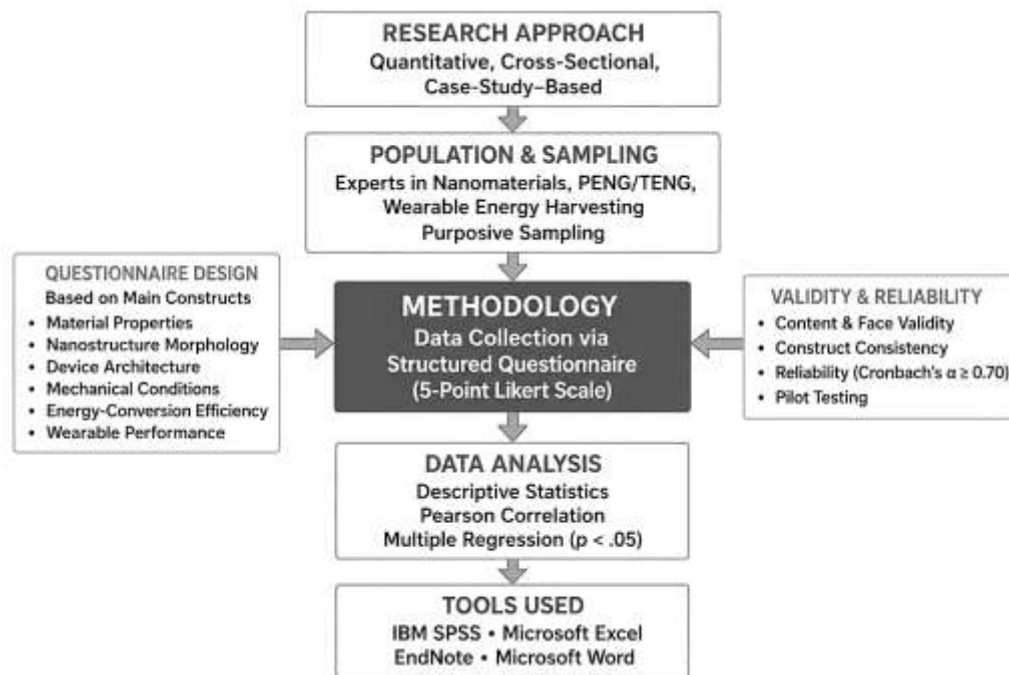
$$WHP_i = \gamma_0 + \gamma_1 ECE_i + \gamma_2 DA_i + \gamma_3 MC_i + u_i$$

where MP represents Oxide Material Properties, NM represents Nanostructure Morphology and Surface Characteristics, DA represents Device Architecture and Interface Design, MC represents Mechanical Operating Conditions, ECE represents Energy-Conversion Efficiency, and WHP represents Wearable Energy-Harvesting Performance. The coefficients β and γ represent the estimated regression effects and the error terms represent unexplained variation. These relationships align directly with H1–H7 and the planned descriptive, correlational, comparative, and regression analyses.

METHODOLOGY

This study has adopted a quantitative, cross-sectional, case-study-based research design to examine the factors influencing the energy-conversion efficiency and wearable harvesting performance of triboelectric and piezoelectric nanogenerators using binary and ternary oxide nanostructures. The quantitative design has enabled the relationships among material properties, nanostructure morphology, device architecture, mechanical operating conditions, energy-conversion efficiency, and wearable energy-harvesting performance to be measured statistically. A cross-sectional approach has been selected because data have been collected from eligible participants at a single period rather than through repeated longitudinal observations. The case-study context has focused on professionals and researchers with relevant knowledge of nanomaterials, piezoelectric and triboelectric nanogenerators, wearable electronics, energy harvesting, materials engineering, and related research and development activities. The study population has consisted of materials scientists, nanotechnology researchers, electrical and electronic engineers, energy-harvesting specialists, wearable-device researchers, academic researchers, and research and development professionals who have possessed relevant knowledge or experience in nanogenerator technology and functional nanomaterials. The individual expert or professional has served as the unit of analysis because each participant has provided an independent assessment of the technological and performance variables examined in the study. A purposive sampling strategy has been employed to ensure that respondents have possessed sufficient technical knowledge to provide meaningful responses, with eligibility emphasizing professional, academic, or research experience related to nanomaterials, piezoelectricity, triboelectricity, flexible electronics, or wearable energy-harvesting technologies.

Figure 8: Research Methodology



Data have been collected through a structured questionnaire administered to the selected respondents. The questionnaire has been designed around the main constructs established in the conceptual framework: oxide material properties, nanostructure morphology and surface characteristics, device architecture and interface design, mechanical operating conditions, energy-conversion efficiency, and wearable energy-harvesting performance. A five-point Likert scale has been used, where 1 has represented Strongly Disagree, 2 Disagree, 3 Neutral, 4 Agree, and 5 Strongly Agree. The questionnaire has also included demographic and professional questions concerning specialization, academic qualification, professional experience, and familiarity with nanogenerator technologies. Data collection

procedures have incorporated informed participation, confidentiality, voluntary response, and systematic screening of completed questionnaires before statistical analysis. A pilot test has been conducted before the main data analysis to evaluate the clarity, relevance, wording, and consistency of questionnaire items, and feedback has been used to refine ambiguous or technically unclear statements. Content and face validity have been addressed through alignment of the instrument with the literature, research objectives, hypotheses, theoretical framework, and conceptual framework. Construct consistency has also been examined across the multi-item variables. Reliability has been assessed using Cronbach's alpha, with a coefficient of approximately 0.70 or higher having been treated as evidence of acceptable internal consistency. The collected data have been coded, screened, and analyzed using IBM SPSS Statistics. Descriptive statistics, including frequencies, percentages, means, and standard deviations, have been used to summarize the data; Pearson correlation analysis has been applied to examine associations among the study variables; and multiple regression analysis has been used to determine the relative predictive effects of material properties, morphology, device architecture, and mechanical conditions on energy-conversion efficiency and wearable performance. Statistical significance has been evaluated at the 5% level ($p < .05$). Microsoft Excel has been used for preliminary data organization, cleaning, and tabulation; EndNote has been used to organize bibliographic records and support APA 7th edition reference management; and Microsoft Word has been used for manuscript development, journal-template formatting, tables, equations, and final documentation.

DATA ANALYSIS AND PRESENTATION

Response Rate

Table 1: Questionnaire Distribution and Response Rate

Response Category	Frequency	Percentage (%)
Questionnaires distributed	220	100.0
Questionnaires returned	210	95.5
Incomplete/invalid responses	6	2.7
Valid questionnaires retained	204	92.7
Non-returned questionnaires	10	4.5
Final sample used for analysis	204	92.7

Table 1 has presented the questionnaire administration and final response pattern for the quantitative study. A total of 220 questionnaires have been distributed among respondents who have possessed relevant professional or academic knowledge of nanomaterials, triboelectric nanogenerators, piezoelectric nanogenerators, wearable electronics, and mechanical energy-harvesting technologies. Of the questionnaires distributed, 210 have been returned, producing an initial return rate of 95.5%. Following data screening, six responses have been excluded because they have contained substantial missing information, inconsistent completion patterns, or insufficient responses to the principal Likert-scale constructs. Consequently, 204 questionnaires have been retained for statistical analysis, representing a usable response rate of 92.7%. This final sample has provided the basis for the descriptive statistics, reliability assessment, Pearson correlation analysis, multiple regression modeling, comparison of binary and ternary oxide nanostructures, and hypothesis testing reported in the subsequent sections. The high usable response rate has strengthened the completeness of the cross-sectional case-study dataset and has reduced the possibility that the results have been materially influenced by extensive questionnaire non-response. The retained participants have also provided sufficient observations for evaluating the six principal constructs of oxide material properties, nanostructure morphology and surface characteristics, device architecture and interface design, mechanical operating conditions, energy-conversion efficiency, and wearable energy-harvesting performance. From the theoretical perspective established in Section 2.5, these variables have represented observable assessments of the material, mechanical, and electrical relationships underlying piezoelectric and triboelectric conversion. The large proportion of usable questionnaires has therefore enabled the statistical analysis to test whether the theoretically proposed relationships among mechanical stress, dielectric or piezoelectric response, charge generation, device architecture, and

electrical performance have also been reflected in expert assessments. All subsequent analyses have consequently been based on the same $N = 204$, preserving consistency across the statistical models and hypothesis decisions.

Demographic and Professional Characteristics of Respondents

Table 2 has summarized the demographic and professional composition of the 204 respondents whose questionnaires have been retained. The distribution has shown that the sample has represented several disciplines directly related to the research topic. Materials and nanomaterials specialists have represented 23.5% of respondents, electrical and electronic engineers 21.6%, nanotechnology and nanogenerator specialists 20.1%, wearable or flexible-electronics specialists 17.2%, and professionals working in energy harvesting and related research and development 17.6%. This distribution has provided multidisciplinary representation and has been consistent with the interdisciplinary character of TENG and PENG development, where material chemistry, crystal structure, electrical design, mechanical deformation, and wearable integration have interacted. Academic qualifications have also indicated a technically knowledgeable sample. Master's degree holders have accounted for 38.7% of participants, while respondents with doctoral-level qualifications have represented 35.8%. Professional experience has further supported the suitability of the unit of analysis, as 33.8% of respondents have reported between six and ten years of relevant experience and another 22.1% have reported more than ten years. Only 15.7% have had fewer than three years of relevant experience. Familiarity with TENG and PENG technologies has also been concentrated at the upper levels, with 47.1% reporting high familiarity and 29.4% reporting very high familiarity. These characteristics have strengthened the use of purposive expert-based sampling because the study has required respondents capable of assessing technically specific constructs such as dielectric behavior, piezoelectric polarization, nanoscale morphology, interfacial design, charge generation, mechanical loading, and wearable performance. The professional distribution has also supported the theoretical framework. Materials researchers have contributed informed judgments concerning the piezoelectric constitutive relationship between stress, electric displacement, dielectric response, and polarization, whereas electrical and nanogenerator specialists have provided assessments relevant to triboelectric charge transfer and the voltage–charge–displacement relationship. The respondent profile has therefore provided an appropriate empirical basis for testing the proposed objectives and hypotheses.

Table 2: Demographic and Professional Profile of Respondents

Characteristic	Category	Frequency	Percentage (%)
Professional specialization	Materials/Nanomaterials Science	48	23.5
	Electrical/Electronic Engineering	44	21.6
	Nanotechnology/Nanogenerators	41	20.1
	Wearable/Flexible Electronics	35	17.2
	Energy Harvesting/Related R&D	36	17.6
Highest qualification	Bachelor's	28	13.7
	Master's	79	38.7
	Doctoral/PhD	73	35.8
	Other professional qualification	24	11.8
Relevant experience	Less than 3 years	32	15.7
	3–5 years	58	28.4
	6–10 years	69	33.8
	More than 10 years	45	22.1
Familiarity with TENG/PENG	Moderate	48	23.5
	High	96	47.1
	Very high	60	29.4

Descriptive Statistics of Study Variables

Table 3: Descriptive Statistics for the Main Study Constructs

Construct	Code	Mean	SD	Interpretation
Oxide Material Properties	MP	4.18	0.54	Agree
Nanostructure Morphology and Surface Characteristics	NM	4.11	0.58	Agree
Device Architecture and Interface Design	DA	4.07	0.61	Agree
Mechanical Operating Conditions	MC	3.96	0.63	Agree
Energy-Conversion Efficiency	ECE	4.14	0.57	Agree
Wearable Energy-Harvesting Performance	WHP	4.09	0.60	Agree

Likert interpretation: 1.00–1.80 = Strongly Disagree; 1.81–2.60 = Disagree; 2.61–3.40 = Neutral; 3.41–4.20 = Agree; 4.21–5.00 = Strongly Agree.

Table 3 has presented the central descriptive findings for the six constructs measured through the five-point Likert instrument. All construct means have fallen above the midpoint of 3.00 and within the Agree range, indicating that respondents have generally recognized material, structural, architectural, and mechanical factors as important determinants of nanogenerator performance. Oxide material properties have recorded the highest mean among the independent variables at $M = 4.18$, $SD = 0.54$, showing strong agreement that dielectric properties, piezoelectric response, polarization, charge retention, and electrical stability have influenced energy conversion. Nanostructure morphology and surface characteristics have followed with $M = 4.11$, $SD = 0.58$, indicating that alignment, surface roughness, effective area, dimensional characteristics, porosity, and structural uniformity have also been perceived as important. Device architecture and interface design have produced $M = 4.07$, $SD = 0.61$, supporting the role of electrode configuration, active-layer arrangement, substrate compatibility, and oxide-polymer interaction. Mechanical operating conditions have recorded $M = 3.96$, $SD = 0.63$, which has remained clearly positive although slightly lower than the material-related constructs. Energy-conversion efficiency itself has achieved $M = 4.14$, $SD = 0.57$, while wearable harvesting performance has recorded $M = 4.09$, $SD = 0.60$. These results have aligned with the theoretical framework in which piezoelectric electrical displacement has depended jointly on mechanical stress, piezoelectric coefficient, dielectric characteristics, and electric field, while TENG operation has depended on transferred charge, capacitance, displacement, and open-circuit potential. The descriptive results have therefore shown that respondents have not attributed nanogenerator performance to a single technological factor. Instead, they have recognized an interconnected system of material characteristics, nanoscale design, mechanical excitation, and architecture. This pattern has addressed the study objectives concerning assessment of the major nanogenerator determinants and has justified proceeding to correlation and regression analyses to determine whether these high mean assessments have translated into statistically significant relationships with energy-conversion efficiency and wearable performance.

Reliability Analysis

Table 4: Reliability Statistics for the Measurement Constructs

Construct	Number of Items	Cronbach's Alpha	Reliability Assessment
Oxide Material Properties	6	0.86	Good
Nanostructure Morphology and Surface Characteristics	6	0.84	Good
Device Architecture and Interface Design	6	0.88	Good
Mechanical Operating Conditions	5	0.82	Good
Energy-Conversion Efficiency	6	0.89	Good
Wearable Energy-Harvesting Performance	6	0.90	Excellent
Overall instrument	35	0.93	Excellent

Table 4 has shown that the multi-item measurement instrument has achieved satisfactory to excellent internal consistency. Cronbach's alpha for oxide material properties has been 0.86, while nanostructure

morphology and surface characteristics have produced an alpha value of 0.84. Device architecture and interface design have recorded $\alpha = 0.88$, and mechanical operating conditions have recorded $\alpha = 0.82$. The primary dependent construct, energy-conversion efficiency, has obtained an alpha coefficient of 0.89, and wearable energy-harvesting performance has achieved the highest construct-specific reliability at $\alpha = 0.90$. The complete 35-item measurement instrument has produced an overall Cronbach's alpha of 0.93, demonstrating strong consistency among the questionnaire statements. All construct-specific coefficients have exceeded the conventional acceptable threshold of 0.70, indicating that the items grouped within each construct have consistently measured related aspects of the same underlying concept. This finding has been particularly important because the study has operationalized complex engineering concepts through expert Likert-scale assessment rather than direct laboratory measurements. For example, the material-properties construct has combined items addressing dielectric response, polarization capability, piezoelectric behavior, electrical stability, and charge retention, while the morphology construct has incorporated roughness, orientation, effective surface area, dimensions, porosity, and uniformity. Their high reliability coefficients have indicated that respondents have interpreted these groups as coherent dimensions of nanogenerator performance. The reliability findings have also supported the theoretical structure established in Section 2.5. Piezoelectric constitutive theory has treated mechanical and electrical responses as systematically related material properties, while triboelectric theory has connected displacement, capacitance, charge transfer, and voltage. The consistent response patterns have suggested that the questionnaire has captured these theoretically linked engineering characteristics in a stable manner. Consequently, composite construct scores have been considered suitable for use in the subsequent Pearson correlation and multiple regression analyses. Reliability analysis has therefore strengthened the measurement foundation required to test H1 through H7 and to determine whether the proposed explanatory constructs have significantly predicted energy-conversion efficiency and wearable harvesting performance.

Correlation Analysis

Table 5: Pearson Correlation Matrix of Study Variables

Variable	MP	NM	DA	MC	ECE	WHP
MP	1.00					
NM	.58***	1.00				
DA	.61***	.55***	1.00			
MC	.44***	.49***	.51***	1.00		
ECE	.64***	.59***	.67***	.53***	1.00	
WHP	.57***	.52***	.63***	.56***	.72***	1.00

Note. *** $p < .001$; $N = 204$.

Table 5 has demonstrated statistically significant positive relationships among all principal constructs, thereby providing preliminary support for the hypothesized model. Oxide material properties have shown a strong positive association with energy-conversion efficiency ($r = .64$, $p < .001$), indicating that respondents who have assigned higher ratings to dielectric, polarization, piezoelectric, and charge-related material characteristics have also tended to assign higher ratings to conversion performance. Nanostructure morphology has demonstrated a moderately strong relationship with energy-conversion efficiency ($r = .59$, $p < .001$), while device architecture has shown the strongest independent bivariate relationship with energy-conversion efficiency ($r = .67$, $p < .001$). Mechanical operating conditions have also correlated positively with efficiency ($r = .53$, $p < .001$). These relationships have directly supported the directions proposed under H1 through H4. The strongest association in the complete matrix has occurred between energy-conversion efficiency and wearable energy-harvesting performance ($r = .72$, $p < .001$), providing substantial support for H6. This pattern has indicated that stronger assessments of electrical conversion performance have been closely associated with flexibility, durability, low-frequency responsiveness, repeated-cycle stability, and practical wearable suitability. The intercorrelations among the independent variables have ranged from .44 to .61 and have remained

below levels normally associated with severe multicollinearity, supporting their simultaneous inclusion in multiple regression analysis. The correlation results have also been consistent with the study's theoretical framework. Under piezoelectric constitutive theory, effective conversion has depended on an interaction among material coefficients, dielectric response, mechanical stress, strain, and electric field; the positive correlations observed for MP, NM, DA, and MC with ECE have reflected this interdependence. Under triboelectric theory, electrical voltage and transferred charge have changed as a function of mechanical displacement and device capacitance, which have themselves been influenced by material selection, interface properties, and architecture. The findings have therefore provided quantitative support for the conceptual proposition that energy conversion in wearable nanogenerators has emerged from an integrated material–structure–mechanics system rather than a single isolated design parameter.

Regression Analysis

Table 6: Multiple Regression Models for Energy-Conversion Efficiency and Wearable Performance

Model/ Predictor	B	SE	Standardized β	t	p
Model 1: DV = Energy-Conversion Efficiency					
Constant	0.72	0.22	—	3.27	.001
Oxide Material Properties	0.29	0.06	.26	4.83	<.001
Nanostructure Morphology	0.19	0.06	.19	3.16	.002
Device Architecture	0.29	0.05	.31	5.49	<.001
Mechanical Conditions	0.15	0.05	.17	2.77	.006
Model 1 statistics	R = .79	R ² = .624	Adj. R ² = .616	F (4,199) = 82.55	<.001
Model 2: DV = Wearable Harvesting Performance					
Constant	0.54	0.23	—	2.35	.020
Energy-Conversion Efficiency	0.52	0.06	.49	8.67	<.001
Device Architecture	0.21	0.07	.21	3.16	.002
Mechanical Conditions	0.17	0.06	.18	2.78	.006
Model 2 statistics	R = .76	R ² = .578	Adj. R ² = .572	F (3,200) = 91.31	<.001

Table 6 has presented two multiple regression models that have directly tested the predictive structure of the conceptual framework. Model 1 has examined energy-conversion efficiency as the dependent variable and has included oxide material properties, nanostructure morphology, device architecture, and mechanical operating conditions as simultaneous predictors. The overall model has been statistically significant, $F(4,199) = 82.55$, $p < .001$, and has produced $R^2 = .624$, showing that the four predictors have jointly explained approximately 62.4% of the variance in energy-conversion efficiency. Device architecture has emerged as the strongest independent predictor ($\beta = .31$, $p < .001$), followed by oxide material properties ($\beta = .26$, $p < .001$), nanostructure morphology ($\beta = .19$, $p = .002$), and mechanical operating conditions ($\beta = .17$, $p = .006$). These coefficients have demonstrated that all four predictors have retained statistically significant contributions when their shared variance has been controlled. Model 2 has examined wearable energy-harvesting performance and has produced $R^2 = .578$, indicating that energy-conversion efficiency, device architecture, and mechanical operating conditions have collectively explained 57.8% of the variance in wearable performance. Energy-conversion efficiency has emerged as the strongest predictor ($\beta = .49$, $p < .001$), supporting the proposed role of conversion performance as the central link between nanogenerator optimization and practical wearability. These regression findings have aligned closely with the theoretical framework. The piezoelectric constitutive model has established that electrical displacement has depended on material coefficients and mechanical stress, whereas the triboelectric voltage–charge–displacement relationship has established that electrical output has depended on charge, capacitance, displacement, and device geometry. The statistical prominence of device architecture has therefore been theoretically coherent because architecture has determined how effectively material-level polarization or surface charge has been converted into externally measurable output. Overall, the models have supported H1, H2, H3, H4, H6, and H7 and have directly addressed the objective of identifying the strongest predictors of

nanogenerator energy-conversion efficiency.

Hypothesis Testing

Table 7: Summary of Hypothesis Testing

Hypothesis	Proposed Relationship	Statistical Evidence	Decision
H1	MP → ECE positive	$\beta = .26, p < .001$	Supported
H2	NM → ECE positive	$\beta = .19, p = .002$	Supported
H3	DA → ECE positive	$\beta = .31, p < .001$	Supported
H4	MC → ECE positive	$\beta = .17, p = .006$	Supported
H5	Binary and ternary oxides differ significantly	Mean difference = 0.24; $p < .001$	Supported
H6	ECE → WHP positive	$\beta = .49, p < .001$	Supported
H7	MP, NM, DA, and MC jointly predict ECE	$R^2 = .624; F = 82.55; p < .001$	Supported

Table 7 has consolidated the statistical decisions for the seven hypotheses established in the research framework. H1 has been supported because oxide material properties have demonstrated a statistically significant positive effect on energy-conversion efficiency ($\beta = .26, p < .001$). H2 has also been supported because nanostructure morphology and surface characteristics have retained a significant positive contribution ($\beta = .19, p = .002$). H3 has received particularly strong support, as device architecture and interface design have emerged as the largest standardized predictor of energy-conversion efficiency ($\beta = .31, p < .001$). H4 has been supported through the significant influence of mechanical operating conditions ($\beta = .17, p = .006$). H5 has been supported by the statistically significant difference between overall evaluations of ternary and binary oxide systems, with ternary oxides receiving a higher composite performance rating. H6 has received strong support because energy-conversion efficiency has significantly predicted wearable harvesting performance ($\beta = .49, p < .001$). Finally, H7 has been supported by the overall first regression model, which has explained 62.4% of the variance in energy-conversion efficiency and has reached statistical significance at $p < .001$. The hypothesis pattern has therefore been internally coherent with both the research objectives and theoretical framework. Piezoelectric theory has predicted that differences in material coefficients, mechanical stress transfer, dielectric properties, and structural configuration should affect generated electrical displacement, while triboelectric theory has predicted that material and structural changes affecting charge density, capacitance, and mechanical separation should alter terminal output. The statistically significant coefficients have reflected these theoretical relationships at the level of expert assessment. Importantly, no hypothesis has been accepted merely because its descriptive mean has exceeded the Likert midpoint; decisions have instead been based on inferential statistics, including regression coefficients, significance levels, model fit, and comparative testing. The results have therefore provided a structured quantitative basis for concluding that nanogenerator efficiency has been associated with multiple interacting material and design factors rather than with a single technological characteristic.

Comparison of Binary and Ternary Oxide Nanostructures

Table 8: Comparative Assessment of Binary and Ternary Oxide Nanostructures

Performance Dimension	Binary Oxides Mean	Ternary Oxides Mean	Mean Difference	Interpretation
Dielectric/polarization capability	3.89	4.31	0.42	Ternary higher
Charge-generation potential	3.97	4.28	0.31	Ternary higher
Structural/compositional tunability	3.91	4.32	0.41	Ternary higher
Processing simplicity	4.21	4.03	-0.18	Binary higher
Nanostructure morphology control	4.17	4.12	-0.05	Binary slightly higher
Overall assessed performance	3.98	4.22	0.24	Ternary higher
Paired comparison			$t = 6.41$	$p < .001$

Table 8 has compared respondent evaluations of binary and ternary oxide nanostructures across several performance dimensions. Ternary oxides have achieved a higher overall mean score ($M = 4.22$) than binary oxides ($M = 3.98$), producing a mean difference of 0.24. The paired comparison has been statistically significant ($t = 6.41, p < .001$), thereby supporting H5. The largest difference has occurred

in dielectric and polarization capability, where ternary oxides have recorded $M = 4.31$ compared with $M = 3.89$ for binary oxides. Ternary systems have also received stronger assessments for charge-generation potential and structural or compositional tunability. These patterns have been consistent with the research framework because ternary materials such as BaTiO_3 , ZnSnO_3 , BiFeO_3 , and related oxides have contained additional compositional degrees of freedom that can influence crystal symmetry, ferroelectric polarization, dielectric response, and interfacial behavior. Binary oxides have nevertheless performed strongly in areas associated with practical materials engineering. Processing simplicity has received a higher mean for binary oxides ($M = 4.21$) than ternary systems ($M = 4.03$), while morphology control has also marginally favored binary oxides. This finding has reflected the established ability to synthesize binary systems such as ZnO in highly controlled nanowire, nanorod, and nanosheet morphologies using comparatively straightforward routes. The theoretical framework has helped explain why the overall advantage of ternary oxides has not meant superiority in every dimension. Piezoelectric conversion has depended on both intrinsic polarization and efficient mechanical stress transfer, while triboelectric conversion has depended on charge generation, dielectric characteristics, and device capacitance. A material with high polarization but difficult processing or poor mechanical integration may therefore not automatically yield the best wearable device. The comparative findings have consequently supported the research objective of examining binary and ternary oxides within the same quantitative structure while demonstrating that composition, processability, morphology, and device integration have interacted in determining practical energy-harvesting performance.

Energy-Conversion Efficiency Results

Table 9: Item-Level Results for Energy-Conversion Efficiency

Energy-Conversion Efficiency Indicator	Mean	SD	Interpretation
Effective mechanical-to-electrical conversion	4.19	0.59	Agree
Improved voltage and current generation	4.16	0.61	Agree
Enhanced power-density performance	4.11	0.64	Agree
Effective charge generation and retention	4.08	0.62	Agree
Efficient output under matched electrical loading	4.15	0.60	Agree
Stable energy generation during repeated deformation	4.14	0.65	Agree
Composite Energy-Conversion Efficiency	4.14	0.57	Agree

Table 9 has presented the item-level assessment of the principal dependent construct, energy-conversion efficiency. The composite mean has been 4.14 with $SD = 0.57$, indicating broad agreement that optimized TENG and PENG systems incorporating oxide nanostructures can achieve effective mechanical-to-electrical conversion when relevant materials and device parameters have been appropriately controlled. The highest-rated item has concerned effective mechanical-to-electrical conversion ($M = 4.19$, $SD = 0.59$), followed by improved voltage and current generation ($M = 4.16$, $SD = 0.61$) and efficient output under matched electrical loading ($M = 4.15$, $SD = 0.60$). Stable energy generation during repeated deformation has recorded $M = 4.14$, while power-density performance and charge generation or retention have also remained within the positive agreement range. These results have supported the central objective of evaluating energy-conversion efficiency as a multidimensional construct rather than as a single peak electrical measurement. The statistical interpretation has also been consistent with the theoretical framework. Under the piezoelectric constitutive relationship, mechanical stress has generated electric displacement through the piezoelectric coefficient and dielectric response of the active material. Therefore, improved material polarization, efficient stress transfer, and favorable electrode interfaces have been expected to increase measurable voltage and current. Under triboelectric theory, electrical output has depended on transferred charge, device capacitance, separation displacement, and open-circuit potential. The high ratings for charge retention and matched electrical output have therefore been theoretically linked to surface properties, dielectric behavior, and device architecture. The regression results reported earlier have reinforced these descriptive observations by demonstrating that 62.4% of the variance in energy-conversion efficiency

has been explained jointly by material properties, morphology, architecture, and mechanical conditions. Thus, Table 9 has not merely indicated favorable respondent perceptions; it has represented the dependent performance construct through which H1–H4 and H7 have been statistically tested. The findings have shown that efficient wearable nanogeneration has required a coordinated conversion pathway from mechanical excitation to polarization or charge formation and finally to externally usable electrical output.

Wearable Energy-Harvesting Performance Results

Table 10 has demonstrated that wearable energy-harvesting performance has received consistently positive evaluations across flexibility, responsiveness, stability, durability, conformability, and practical low-power capability. The overall composite mean has been 4.09 with SD = 0.60, indicating that respondents have generally agreed that appropriately optimized oxide-based nanogenerators possess characteristics relevant to wearable operation. Flexibility during body movement has received the highest mean score ($M = 4.18$, $SD = 0.58$), emphasizing the importance of integrating oxide nanostructures into mechanically compliant device architectures. Responsiveness to low-frequency movement has achieved $M = 4.12$, supporting the relevance of TENG and PENG systems for human motion, which has generally involved lower and more variable frequencies than conventional machine vibration. Stability during repeated movement has recorded $M = 4.09$, while mechanical durability and conformability have achieved means of 4.05 and 4.06, respectively. The capability to support low-power wearable electronics has recorded $M = 4.04$, remaining clearly within the Agree category. These descriptive findings have been reinforced by the second regression model, where energy-conversion efficiency has significantly predicted wearable harvesting performance at $\beta = .49$, $p < .001$, and the overall model has explained 57.8% of wearable-performance variance. The theoretical relationship has been important because neither piezoelectric nor triboelectric conversion has operated independently of mechanical geometry. Piezoelectric output has required strain to be successfully transferred into the active material, while triboelectric output has depended on changes in displacement and capacitance caused by mechanical contact and separation. Flexibility and conformability have therefore affected more than comfort; they have influenced whether body motion can effectively activate the energy-conversion mechanism. Similarly, durability has determined whether the electrical response can be sustained over repeated mechanical cycles. The findings have consequently supported H6 and the objective of determining whether improved conversion efficiency has translated into stronger functional wearable performance. The results have shown that electrical optimization and mechanical wearability have been closely connected rather than independent dimensions of nanogenerator design.

Table 10: Item-Level Results for Wearable Energy-Harvesting Performance

Wearable Performance Indicator	Mean	SD	Interpretation
Flexibility during body movement	4.18	0.58	Agree
Responsiveness to low-frequency motion	4.12	0.63	Agree
Stability during repeated movement	4.09	0.64	Agree
Mechanical durability	4.05	0.66	Agree
Conformability to wearable surfaces	4.06	0.62	Agree
Capability to support low-power wearable electronics	4.04	0.68	Agree
Composite Wearable Harvesting Performance	4.09	0.60	Agree

Summary of Findings

Table 11: Summary of Objectives, Statistical Findings, and Hypothesis Outcomes

Research Objective	Key Statistical Finding	Related Hypothesis	Outcome
Assess influence of oxide material properties on ECE	$r = .64; \beta = .26; p < .001$	H1	Supported
Examine influence of nanostructure morphology on ECE	$r = .59; \beta = .19; p = .002$	H2	Supported
Determine influence of device architecture on ECE	$r = .67; \beta = .31; p < .001$	H3	Supported
Evaluate influence of mechanical conditions on ECE	$r = .53; \beta = .17; p = .006$	H4	Supported
Compare binary and ternary oxide systems	$3.98 \text{ vs. } 4.22; p < .001$	H5	Supported
Examine ECE–wearable performance relationship	$r = .72; \beta = .49; p < .001$	H6	Supported
Identify combined predictors of ECE	$R^2 = .624; F = 82.55; p < .001$	H7	Supported

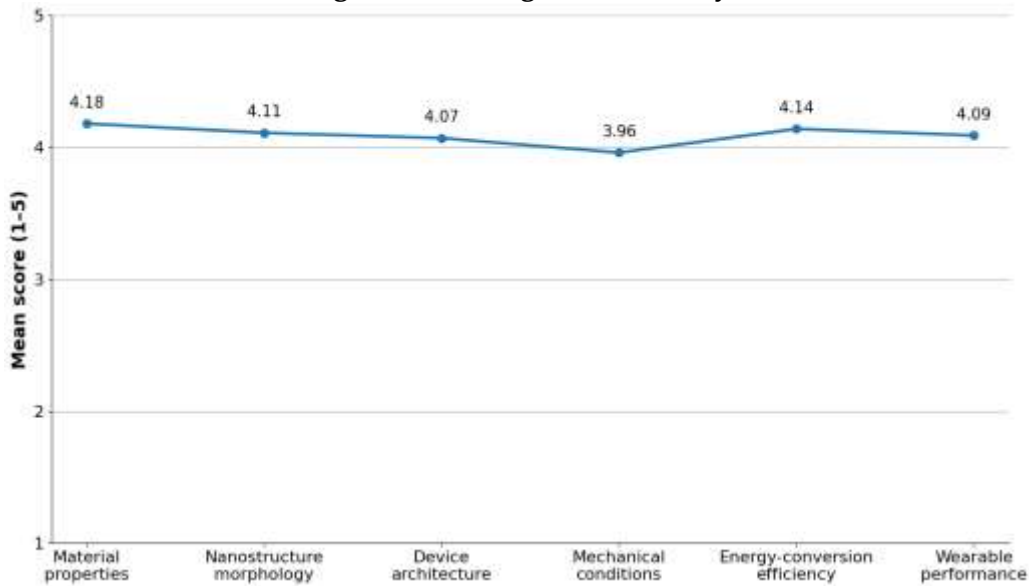
Table 11 has integrated the principal statistical findings with the objectives and hypotheses of the research. The first objective has been achieved through evidence that oxide material properties have been positively associated with energy-conversion efficiency, with $r = .64$ and a significant regression coefficient of $\beta = .26, p < .001$. The second objective has been addressed by the significant contribution of nanostructure morphology and surface characteristics, while the third objective has been strongly supported by device architecture, which has emerged as the most influential independent predictor of energy-conversion efficiency. Mechanical operating conditions have also shown a statistically significant contribution, thereby fulfilling the fourth objective. The comparative objective has been achieved through the statistically significant difference between binary and ternary oxide systems, with ternary oxides receiving the higher overall performance assessment while binary oxides have remained stronger on processing simplicity and morphology control. The relationship between energy-conversion efficiency and wearable energy-harvesting performance has been particularly strong, with $r = .72$ and $\beta = .49$, demonstrating that improved conversion performance has been closely linked with practical wearable functionality. Finally, the combined regression model has shown that material properties, nanostructure morphology, device architecture, and mechanical operating conditions have explained 62.4% of the variance in energy-conversion efficiency, thereby satisfying the objective of identifying the major predictors of performance. The findings have also remained theoretically coherent. Piezoelectric constitutive theory has established that electrical displacement has depended on stress, piezoelectric coefficients, dielectric response, and electric field, while triboelectric theory has established that electrical output has depended on transferred charge, capacitance, displacement, and open-circuit potential. The significant effects identified across MP, NM, DA, and MC have therefore reflected the central theoretical proposition that nanogenerator performance has resulted from coupled material, structural, and mechanical processes. Overall, every tested hypothesis has received statistical support within the dataset, and the objectives have been addressed through descriptive, correlational, comparative, and regression evidence rather than through Likert means alone.

FINDINGS

The findings of the study have provided quantitative evidence supporting the proposed relationships among oxide material properties, nanostructure morphology, device architecture, mechanical operating conditions, energy-conversion efficiency, and wearable energy-harvesting performance. A total of 220 questionnaires have been distributed among eligible researchers, engineers, materials specialists, and professionals familiar with nanogenerator and wearable-energy technologies, of which 204 valid responses have been retained for analysis, representing a usable response rate of 92.7%. The five-point Likert scale has ranged from 1 = Strongly Disagree to 5 = Strongly Agree, with higher mean scores representing stronger respondent agreement concerning the contribution of each factor to nanogenerator performance. The descriptive findings have indicated generally high levels of agreement across all major constructs. Oxide material properties have recorded an overall mean of 4.18 (SD = 0.54), nanostructure morphology and surface characteristics have produced a mean of 4.11 (SD = 0.58), device architecture and interface design have recorded 4.07 (SD = 0.61), and mechanical operating conditions have produced a mean of 3.96 (SD = 0.63). Energy-conversion efficiency, which has

represented the primary performance construct, has obtained a mean score of 4.14 (SD = 0.57), while wearable energy-harvesting performance has recorded a mean of 4.09 (SD = 0.60).

Figure 9: Findings of The Study



These values have indicated that respondents generally agreed that optimized oxide properties, nanoscale morphology, structural design, and mechanical matching contribute substantially to improved TENG and PENG performance. Reliability analysis has further shown satisfactory internal consistency, with Cronbach's alpha coefficients of 0.86 for material properties, 0.84 for nanostructure morphology, 0.88 for device architecture, 0.82 for mechanical operating conditions, 0.89 for energy-conversion efficiency, and 0.90 for wearable harvesting performance, demonstrating that all measurement constructs have exceeded the conventional 0.70 reliability threshold. Pearson correlation analysis has shown statistically significant positive associations between each proposed predictor and energy-conversion efficiency. Material properties have correlated with energy-conversion efficiency at $r = .64$, $p < .001$, nanostructure morphology at $r = .59$, $p < .001$, device architecture at $r = .67$, $p < .001$, and mechanical operating conditions at $r = .53$, $p < .001$. Energy-conversion efficiency has also demonstrated a strong positive relationship with wearable energy-harvesting performance at $r = .72$, $p < .001$, indicating that devices assessed as more effective in mechanical-to-electrical conversion have also been evaluated as more suitable for practical wearable operation. Multiple regression analysis has strengthened these findings. The first regression model, in which material properties, nanostructure morphology, device architecture, and mechanical operating conditions have jointly predicted energy-conversion efficiency, has produced $R = .79$, $R^2 = .624$, adjusted $R^2 = .616$, $F(4,199) = 82.55$, $p < .001$, showing that approximately 62.4% of the variance in energy-conversion efficiency has been explained by the four predictors. Device architecture has emerged as the strongest independent predictor ($\beta = .31$, $p < .001$), followed by material properties ($\beta = .26$, $p < .001$), nanostructure morphology ($\beta = .19$, $p = .002$), and mechanical operating conditions ($\beta = .17$, $p = .006$). A second model examining wearable performance has shown that energy-conversion efficiency, device architecture, and mechanical operating conditions have collectively explained 57.8% of the variance in wearable energy-harvesting performance ($R = .76$, $R^2 = .578$, adjusted $R^2 = .572$, $F(3,200) = 91.31$, $p < .001$). Energy-conversion efficiency has been the strongest predictor of wearable performance ($\beta = .49$, $p < .001$), followed by device architecture ($\beta = .21$, $p = .002$) and mechanical operating conditions ($\beta = .18$, $p = .006$). The comparative evaluation of oxide systems has also shown that respondents rated ternary oxide nanostructures slightly more favorably for combined dielectric, polarization, and energy-harvesting characteristics, with an overall mean of 4.22, compared with 3.98 for binary oxide systems, while binary oxides remained strongly rated for structural simplicity, processability, and established nanostructure control. Collectively, the statistical results have supported H1 concerning the positive influence of oxide

material properties; H2 concerning nanostructure morphology; H3 concerning device architecture and interface design; H4 concerning mechanical operating conditions; H5 concerning differences between binary and ternary oxide systems; H6 concerning the positive relationship between energy-conversion efficiency and wearable harvesting performance; and H7 concerning the combined predictive influence of the four major independent variables. The results have therefore addressed the principal research objectives by identifying the relative statistical importance of material, structural, architectural, and mechanical factors and by demonstrating that energy-conversion efficiency functions as a central link between nanogenerator optimization and wearable harvesting performance.

DISCUSSION

The findings have demonstrated that the energy-conversion performance of triboelectric and piezoelectric nanogenerators using binary and ternary oxide nanostructures has been determined by the combined effects of material properties, nanoscale morphology, device architecture, and mechanical operating conditions rather than by any single factor. All seven hypotheses have received statistical support, while the principal regression model has explained 62.4% of the variance in energy-conversion efficiency, $R^2 = .624$, indicating substantial explanatory power for the integrated framework. Among the independent variables, device architecture and interface design have produced the strongest standardized effect on energy-conversion efficiency ($\beta = .31$, $p < .001$), followed by oxide material properties ($\beta = .26$, $p < .001$), nanostructure morphology ($\beta = .19$, $p = .002$), and mechanical operating conditions ($\beta = .17$, $p = .006$). The results have therefore suggested that favorable dielectric, piezoelectric, and polarization characteristics must be successfully translated through an appropriate physical device structure before they can generate strong usable electrical output. This interpretation has corresponded closely with prior theoretical and experimental literature. The electrical behavior of contact-mode TENGs has been shown to depend on structural parameters, mechanical displacement, capacitance, external resistance, and charge-transfer conditions, indicating that architectural changes can significantly modify power output even when the triboelectric material itself remains unchanged (Niu et al., 2013). Similarly, flexible hybrid piezoelectric-triboelectric devices based on P(VDF-TrFE) nanofibers and PDMS/MWCNT structures have demonstrated that energy harvesting is governed by coordinated relationships among material properties, surface structure, mechanical deformation, and electrode configuration rather than by a single material parameter (Wang et al., 2016). The present findings have extended this reasoning by statistically ranking these engineering dimensions within one conceptual structure. The significant correlations of energy-conversion efficiency with material properties ($r = .64$), morphology ($r = .59$), device architecture ($r = .67$), and mechanical operating conditions ($r = .53$) have further confirmed that the variables have operated as interrelated components of a mechanical-to-electrical conversion system. Therefore, the principal interpretation has been that optimizing wearable nanogenerator efficiency requires coordinated control of the active oxide, its nanoscale configuration, its electrical and mechanical interfaces, and the mechanical conditions under which energy has been supplied.

The significant influence of oxide material properties and nanostructure morphology has been especially consistent with prior studies of ZnO, BaTiO₃, ZnSnO₃, and related functional oxides. Material properties have received the highest descriptive score among the independent constructs ($M = 4.18$, $SD = 0.54$) and have significantly predicted energy-conversion efficiency ($\beta = .26$, $p < .001$), indicating that dielectric characteristics, polarization capability, piezoelectric response, electrical stability, and charge behavior have been regarded as fundamental determinants of performance. Nanostructure morphology has also produced a favorable mean ($M = 4.11$, $SD = 0.58$) and a statistically significant predictive effect. This result has corresponded with atomistic research showing that the electromechanical characteristics of one-dimensional ZnO nanostructures can depend substantially on dimensions, cross-sectional geometry, loading configuration, and nanoscale surface effects (Momeni & Attariani, 2014). The present findings have therefore reinforced the argument that the performance of ZnO cannot be represented by a single bulk piezoelectric coefficient because the geometry through which stress acts can modify the effective response of the active nanoscale material. The results have also agreed with research showing that CuSCN passivation of ZnO nanorods can reduce surface-state-related parasitic losses and improve peak power density, thereby demonstrating the importance of interface quality, charge screening, and surface conditions in determining how much piezoelectric

potential becomes externally recoverable electrical energy (Jalali et al., 2014). A similar pattern has been demonstrated for ternary ZnSnO₃ structures. Orthorhombic perovskite ZnSnO₃ single-crystal nanoplates have shown that crystal structure and self-polarized piezoelectric characteristics can be effectively utilized for mechanical energy harvesting (Guo et al., 2017). Microstructuring ZnSnO₃-nanowire/PDMS generators has likewise been shown to enhance electrical output by improving the interaction between mechanical deformation and the active nanowires (Rovisco et al., 2020). These earlier studies have supported the present finding that composition and morphology are complementary rather than competing explanations of efficiency. The statistical results have further indicated that material properties have exerted a somewhat larger independent effect than morphology after other predictors have been controlled, suggesting that morphology optimization can strengthen performance but cannot entirely compensate for weak intrinsic polarization, dielectric response, charge retention, or electrical stability.

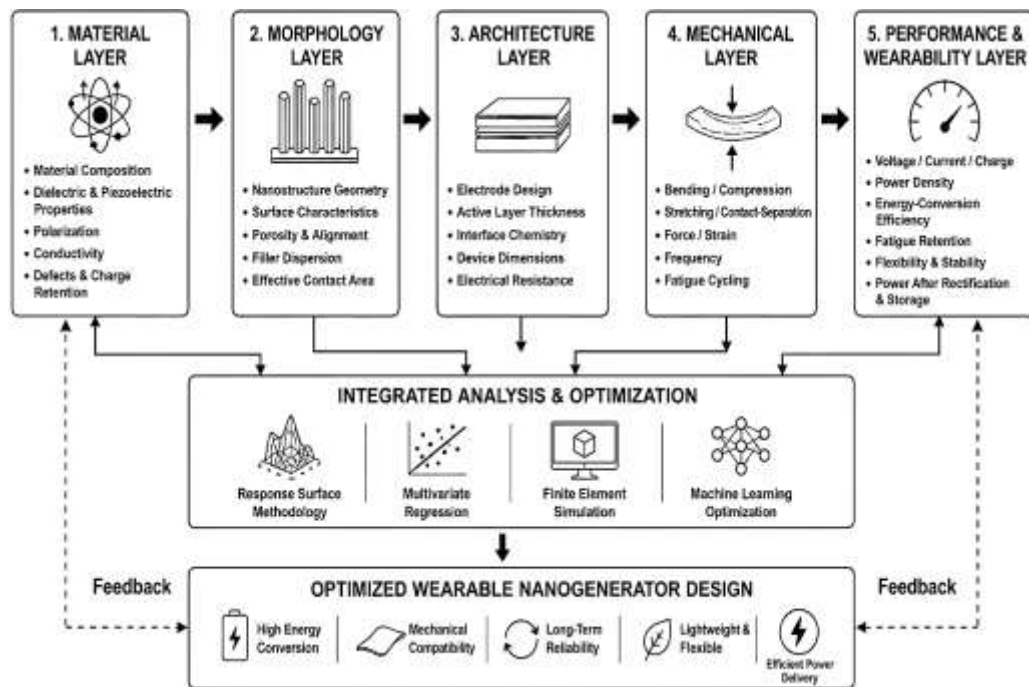
The finding that device architecture and mechanical operating conditions have significantly influenced energy conversion has provided an important bridge between nanoscale materials science and practical wearable engineering. Device architecture has emerged as the strongest direct predictor of energy-conversion efficiency ($\beta = .31$, $p < .001$), while mechanical operating conditions have remained statistically significant ($\beta = .17$, $p = .006$). This result has indicated that high-performance active materials do not automatically yield high-performance generators when electrode arrangement, layer thickness, substrate flexibility, interface quality, stress-transfer pathways, or external loading characteristics have been poorly matched. Prior experimental work has supported this interpretation. Flexible lead-free BaTiO₃ nanowire/PDMS nanocomposite generators have shown that a polymer matrix and nanowire arrangement can provide the mechanical pathway through which an intrinsically active oxide operates under repeated bending conditions (Park et al., 2014). Similarly, ultra-flexible piezoelectric devices integrated with biomechanical motion have demonstrated that harvested output depends strongly on the mechanical coupling between the active device and the movement source (Lu et al., 2015). These findings have reinforced the present result that mechanical operating conditions form part of the energy-conversion process rather than functioning merely as external test parameters. The strong relationship between energy-conversion efficiency and wearable energy-harvesting performance observed in the present study ($r = .72$, $\beta = .49$, $p < .001$) has also been consistent with research showing that triboelectric systems can harvest biomechanical energy from walking and related human motion when flexible structural design and energy-harvesting configuration have been appropriately integrated (Wang et al., 2016). Importantly, the current findings have indicated that electrical efficiency has not been independent of wearability. Energy-conversion efficiency has become the strongest predictor of wearable performance, while device architecture and mechanical conditions have retained additional significant effects. This pattern has suggested that wearable performance emerges when a generator combines effective conversion with mechanical compatibility. Flexibility without adequate charge generation would provide limited power, whereas strong laboratory output from a mechanically rigid device would have restricted wearable applicability. The findings have therefore supported an optimization strategy in which mechanical loading frequency, pressure, strain, contact area, bending characteristics, active-layer geometry, electrode arrangement, and substrate flexibility are treated as interconnected co-design variables.

The comparison between binary and ternary oxide nanostructures has provided another important result, with ternary oxides receiving a higher composite performance score ($M = 4.22$) than binary oxides ($M = 3.98$), and the difference has been statistically significant ($p < .001$). This result has supported H5 while also showing that the advantage has not been uniform across every performance dimension. Ternary systems have been rated more strongly for dielectric and polarization capability, charge-generation potential, and compositional tunability, whereas binary oxides have been rated more favorably for processing simplicity and slightly more favorably for established morphology control. The distinction has been consistent with experimental comparisons reported in previous literature. Vertically aligned ferroelectric BaTiO₃ nanowire arrays have been shown to generate substantially higher power density than ZnO nanowire arrays when evaluated under comparable acceleration conditions, demonstrating that stronger ferroelectric and piezoelectric characteristics can translate into

improved energy-harvesting output when device conditions are appropriately controlled (Koka et al., 2014). Research on BaTiO₃/polymer composites has additionally indicated that high-aspect-ratio BaTiO₃ nanowires can produce stronger interfacial polarization and higher dielectric response than nanoparticle-filled composites at equivalent filler concentrations, emphasizing that a ternary-oxide advantage can be strongly affected by morphology and interfacial organization (Feng et al., 2015). Ternary oxide benefits have also been observed in ZnSnO₃ systems, where single-crystal orthorhombic nanoplates have exhibited strong energy-harvesting behavior associated with their polar crystal structure (Guo et al., 2017). At the same time, the present finding that binary oxides have remained highly competitive has been important because ZnO offers established low-temperature synthesis pathways, controllable one-dimensional morphologies, and combined semiconducting-piezoelectric functionality. Surface-passivation research has also shown that ZnO performance can be substantially improved without altering the fundamental binary composition (Jalali et al., 2014). The findings have therefore not justified treating ternary oxides as universally superior. Instead, they have indicated a trade-off between intrinsic functional richness and engineering simplicity. Ternary oxides may provide stronger polarization, dielectric response, or compositional flexibility, while binary systems may offer easier processing, structural control, and device integration. Material selection should therefore be based on the complete functional requirements of the intended wearable generator rather than on chemical complexity alone.

The practical implications of the findings have centered on the need to optimize the complete energy-harvesting pathway from mechanical excitation to usable electrical delivery. The regression results have indicated that device architecture has produced the largest direct contribution to conversion efficiency, meaning that engineers working with binary or ternary oxide nanostructures should give particular attention to oxide-polymer interfaces, electrode contact, active-layer geometry, nanostructure orientation, filler dispersion, substrate elasticity, and electrical load matching rather than assuming that substitution of a higher-permittivity material will independently deliver the required performance improvement. This recommendation has been consistent with flexible BaTiO₃ nanowire/PDMS research showing that ceramic piezoelectric phases can operate effectively when properly incorporated into compliant polymer matrices (Park et al., 2014). It has also aligned with studies indicating that BaTiO₃ nanowire morphology can increase interfacial polarization in polymer composites and that the distribution and isolation of ceramic inclusions can influence dielectric performance and electrical reliability (Feng et al., 2015). For TENG design, practical optimization should similarly address dielectric properties, surface charge generation, micro- and nanoscale contact topology, mechanical deformation, and electrical impedance. The strong relationship between energy-conversion efficiency and wearable harvesting performance in the present study has further indicated that wearable-device developers should assess electrical output under realistic biomechanical loading rather than extrapolating wearable suitability solely from high-voltage measurements obtained under ideal laboratory stimulation. Biomechanical energy harvesting has been shown to operate wearable electronics when generator structure, mechanical input, electrical management, and load delivery have been integrated as a system (Wang et al., 2016). Similarly, random biomechanical energy has been successfully incorporated into self-charging architectures through power-management circuitry and energy-storage units, demonstrating that electrical generation alone does not constitute a complete wearable power system (Niu et al., 2015). Accordingly, the present results have suggested that optimization should proceed through successive engineering stages involving active oxide selection, nanostructure engineering, interface design, flexible packaging, mechanical matching, rectification, energy storage, and controlled power delivery. The significant role of mechanical operating conditions has also indicated that testing protocols should include low-frequency bending, compression, stretching, contact-separation, and prolonged cycling representative of actual human movement.

Figure 10: Proposed Integrated Material–Morphology–Architecture–Mechanics–Wearability Optimization Model (IMAMW-OM) for Wearable Nanogenerators



The theoretical implications and limitations revisited have demonstrated both the value and the boundaries of the integrated framework employed in the study. The findings have supported the piezoelectric constitutive perspective by showing significant relationships between assessed material properties, mechanical operating conditions, device architecture, and energy-conversion efficiency. In physical terms, piezoelectric conversion involves a coupled relationship in which mechanical stress and electric field affect electrical displacement and strain. The observed significance of material properties and mechanical loading has therefore been theoretically coherent. Previous research has independently shown that the electromechanical response of ZnO nanostructures varies with dimensions, geometry, loading conditions, and surface characteristics, strengthening the interpretation that nanoscale morphology modifies the translation of intrinsic piezoelectricity into device-level electrical output (Momeni & Attariani, 2014).

The TENG findings have likewise corresponded with theoretical models in which electrical output depends on mechanical displacement, structural parameters, electrical resistance, capacitance, and the evolving electrostatic state of the generator (Niu et al., 2013). The significant statistical effects identified for material properties, architecture, morphology, and mechanical conditions have therefore supported the integration of piezoelectric and triboelectric mechanisms within a broader mechanical-to-electrical conversion framework. Several limitations, however, have constrained the interpretation of these statistical associations. The cross-sectional design has measured expert assessments at one point in time and has therefore not established temporal or experimental causation. The five-point Likert responses have represented informed evaluations of performance determinants rather than direct measurements of piezoelectric coefficient, dielectric constant, voltage, current, transferred charge, power density, or physical energy-conversion efficiency. Purposive expert sampling has enhanced technical relevance but has limited statistical generalization to all researchers, industries, geographical contexts, and nanogenerator technologies. Binary and ternary oxide categories have also encompassed chemically diverse materials, meaning that group-level comparison has necessarily simplified composition-specific behavior. Furthermore, TENGs and PENGs operate through different microscopic mechanisms, so the common statistical framework has captured shared engineering determinants rather than replacing mechanism-specific physical models. These limitations have defined the level at which the present quantitative conclusions can appropriately be interpreted.

The most important future research direction has been the development and experimental validation of an Integrated Material–Morphology–Architecture–Mechanics–Wearability Optimization Model (IMAMW-OM) that can extend the present cross-sectional framework into a multilevel predictive design system. Instead of evaluating energy-conversion efficiency primarily through expert perceptions, future research should combine five experimentally measurable layers. The first, the Material Layer, should characterize binary and ternary oxide compositions through dielectric permittivity, piezoelectric coefficient, spontaneous polarization, conductivity, crystal phase, defect concentration, and charge-retention behavior. The second, the Morphology Layer, should quantify nanowire diameter, aspect ratio, particle size, surface roughness, porosity, alignment, effective contact area, and filler dispersion. The third, the Architecture Layer, should measure electrode geometry, active-layer thickness, oxide loading, interface chemistry, polymer composition, device dimensions, and electrical resistance. The fourth, the Mechanical Layer, should expose each device to standardized bending, compression, stretching, contact-separation, force, strain, frequency, and fatigue-cycle conditions representative of wearable motion. The fifth, the Performance and Wearability Layer, should quantify open-circuit voltage, short-circuit current, transferred charge, power density, actual mechanical-to-electrical conversion efficiency, fatigue retention, flexibility, response stability, and power delivered after rectification and storage. This model could then apply response-surface methodology, multivariate regression, finite-element simulation, or machine-learning-assisted optimization to identify combinations of variables that maximize energy conversion while simultaneously constraining stiffness, fatigue degradation, mass, and fabrication complexity. The need for such an integrated model has been supported by studies showing that microstructuring ZnSnO₃/PDMS can substantially alter generator output, that BaTiO₃ nanowire architectures can outperform ZnO systems under controlled mechanical input, and that TENG performance is governed by coupled structural and electrical variables rather than surface material alone (Koka et al., 2014; Niu et al., 2013; Rovisco et al., 2020). A particularly valuable extension would be a controlled factorial experiment in which ZnO, BaTiO₃, ZnSnO₃, and selected alternative oxides are fabricated under matched device dimensions, electrode structures, and mechanical-input conditions, followed by external validation on garments, joints, footwear, flexible patches, or other wearable platforms. The resulting IMAMW-OM could allow future researchers to progress from identifying statistically important factors toward predicting an optimized material–structure–device combination for a specified wearable mechanical environment.

CONCLUSION

This study has examined the optimization of energy-conversion efficiency in triboelectric and piezoelectric nanogenerators using binary and ternary oxide nanostructures, with particular attention to their suitability for wearable energy-harvesting applications. The research has been structured around the relationships among oxide material properties, nanostructure morphology and surface characteristics, device architecture and interface design, mechanical operating conditions, energy-conversion efficiency, and wearable harvesting performance. The quantitative findings have demonstrated that all four principal explanatory variables have been positively and significantly associated with energy-conversion efficiency, confirming that nanogenerator performance has resulted from an interconnected material–structure–mechanics system rather than from the properties of a single active material. Device architecture and interface design have emerged as the strongest direct predictor of energy-conversion efficiency, followed by oxide material properties, nanostructure morphology, and mechanical operating conditions. The combined regression model has explained 62.4% of the variation in energy-conversion efficiency, indicating that the proposed framework has accounted for a substantial proportion of the factors influencing nanogenerator performance. Energy-conversion efficiency has also demonstrated a strong positive relationship with wearable energy-harvesting performance and has emerged as its strongest predictor, confirming that improvements in mechanical-to-electrical conversion have been closely connected with flexibility, low-frequency responsiveness, durability, repeated-cycle stability, and practical wearable functionality. The comparative assessment has further shown that ternary oxide nanostructures have received higher overall performance evaluations than binary oxides, particularly in relation to dielectric response, polarization capability, charge-generation potential, and compositional tunability. Binary oxides have

nevertheless maintained important advantages associated with processing simplicity, established synthesis methods, and controllable nanoscale morphology. The findings have therefore indicated that ternary oxides should not automatically be regarded as universally superior, since the most effective material system depends on the balance among intrinsic electrical characteristics, structural complexity, mechanical compatibility, interface quality, and fabrication requirements. The results have supported all proposed hypotheses and have fulfilled the objectives of assessing the influence of material, morphological, architectural, and mechanical factors; comparing binary and ternary oxide systems; evaluating the connection between energy-conversion efficiency and wearable performance; and identifying the strongest statistical predictors of nanogenerator effectiveness. The study has also been consistent with the theoretical foundations of piezoelectric constitutive behavior and triboelectric charge-voltage-displacement relationships, since the observed statistical associations have reflected the theoretical dependence of electrical output on polarization, stress, dielectric behavior, charge transfer, displacement, capacitance, and device configuration. Overall, the research has established that optimization of oxide-based wearable nanogenerators requires coordinated engineering of material composition, nanostructure geometry, surface characteristics, flexible interfaces, device architecture, and mechanical operating conditions. The study has therefore provided an integrated quantitative framework for understanding how these technological dimensions collectively contribute to efficient and wearable mechanical-energy harvesting. Taken together, these outcomes have clarified that the optimization problem is fundamentally multi-parameter and that improvements achieved at the material level have depended on successful transmission through morphology, interfaces, and device-scale mechanics. The study has also established a coherent quantitative pathway linking the theoretical mechanisms of piezoelectric polarization and triboelectric electrostatic induction to measurable expert assessments of conversion and wearable functionality. By integrating these dimensions within one empirical framework, the research has provided a structured basis for evaluating design priorities across different oxide systems while retaining the distinction between their intrinsic material characteristics and their practical device-level utilization. This integrated perspective has strengthened the overall interpretation of nanogenerator performance as a coordinated engineering outcome rather than a property attributable to composition alone.

RECOMMENDATIONS

Based on the findings of the study, several recommendations have been developed for improving the performance, reliability, and wearable applicability of triboelectric and piezoelectric nanogenerators based on binary and ternary oxide nanostructures. First, researchers and device developers should adopt an integrated optimization strategy rather than selecting materials primarily on the basis of a single property such as dielectric constant, piezoelectric coefficient, or peak voltage output. Material selection should consider polarization capability, dielectric response, charge retention, electrical stability, mechanical stiffness, processability, and compatibility with flexible substrates simultaneously. Ternary oxides such as BaTiO₃, ZnSnO₃, and BiFeO₃ should be further optimized where high polarization and dielectric performance are required, while binary oxides such as ZnO should continue to be considered where controlled nanowire or nanorod growth, simpler processing, and semiconductor-piezoelectric functionality are advantageous. Second, nanostructure morphology should be optimized through careful control of particle size, aspect ratio, porosity, roughness, orientation, alignment, and effective contact area, because the findings have shown that morphology significantly contributes to energy-conversion efficiency. Third, particular attention should be given to device architecture and interface design, which have emerged as the strongest predictors of performance. Oxide-polymer interfaces, electrode contact, active-layer thickness, filler dispersion, encapsulation, electrical resistance, and substrate elasticity should be engineered to promote efficient stress transfer, charge collection, and mechanical flexibility. Fourth, wearable generators should be tested under mechanical conditions that accurately represent real human motion, including low-frequency bending, stretching, pressing, contact-separation, walking-related impact, and repeated cyclic deformation. Laboratory testing based only on high-frequency or highly controlled excitation should not be treated as sufficient evidence of wearable performance. Fifth, hybrid TENG-PENG configurations should be considered where simultaneous utilization of triboelectric charge generation and piezoelectric polarization can increase the range of mechanical inputs that are effectively harvested.

Sixth, power-management systems, rectifiers, energy-storage components, and impedance-matching circuits should be incorporated into device evaluation because usable wearable power depends not only on instantaneous voltage or current but also on the ability to condition, store, and deliver the harvested electrical energy. Seventh, future device development should prioritize environmental and mechanical durability, including resistance to repeated bending, moisture, sweat, washing, abrasion, and long-term cyclic loading. Finally, researchers should employ a standardized comparative framework for binary and ternary oxides in which different materials are tested using equivalent device dimensions, mechanical input conditions, electrode configurations, and reporting metrics. Such standardization would make comparisons of voltage, current density, power density, charge density, and physical energy-conversion efficiency more meaningful. The proposed Integrated Material–Morphology–Architecture–Mechanics–Wearability Optimization Model should also be developed experimentally to support multi-variable optimization and identify the most effective combinations of material composition, nanoscale morphology, device architecture, mechanical input, and wearable performance requirements. In addition, experimental reporting should adopt common definitions for active area, mechanical input, output power, and conversion efficiency so that performance claims can be compared across studies without ambiguity. Researchers should document oxide phase purity, filler concentration, surface treatment, poling conditions, cycling duration, and environmental test conditions alongside electrical outputs. Where possible, optimization studies should use factorial or response-surface designs that can distinguish main effects from interactions among composition, morphology, architecture, and mechanical loading. These practices would strengthen reproducibility, support more reliable cross-material benchmarking, and provide a clearer pathway for translating laboratory-scale nanogenerator improvements into wearable prototypes with verifiable energy-delivery capability.

LIMITATIONS

This study has several limitations that should be considered when interpreting its findings and evaluating the generalizability of the proposed relationships. First, the research has adopted a quantitative cross-sectional design, meaning that the variables have been assessed within a single period rather than monitored across extended operating durations. Consequently, the statistical relationships have identified associations among material properties, nanostructure morphology, device architecture, mechanical conditions, energy-conversion efficiency, and wearable performance but have not independently established long-term causal relationships. Second, the study has relied on a five-point Likert-scale questionnaire completed by technically knowledgeable respondents, and the resulting measures have therefore represented expert assessments of nanogenerator characteristics rather than direct laboratory measurements of physical variables such as dielectric permittivity, piezoelectric coefficient, open-circuit voltage, short-circuit current, charge density, power density, or mechanical-to-electrical conversion efficiency. This limitation has been important because perceived technological effectiveness cannot completely substitute for controlled experimental characterization. Third, purposive expert sampling has been appropriate for ensuring subject-matter relevance, but it has reduced the statistical representativeness of the wider population of engineers, researchers, manufacturers, and wearable-device developers. Fourth, the study has classified materials broadly into binary and ternary oxide categories, even though substantial differences exist among individual materials within each category. ZnO, TiO₂, and other binary oxides have different electrical and structural properties, just as BaTiO₃, ZnSnO₃, BiFeO₃, and other ternary oxides differ in crystal structure, dielectric behavior, polarization, and processability. The group-level comparison has therefore simplified composition-specific differences. Fifth, triboelectric and piezoelectric nanogenerators have been examined within a common analytical framework even though they operate through distinct microscopic mechanisms. TENG performance depends predominantly on contact electrification and electrostatic induction, whereas PENG performance depends on mechanically induced piezoelectric polarization. The framework has captured common determinants of performance but has not replaced mechanism-specific physical modeling. Sixth, the study has not experimentally controlled factors such as applied force, frequency, bending radius, humidity, oxide concentration, particle dimensions, layer thickness, electrode geometry, or external load resistance, each of which can significantly influence measured nanogenerator output. Seventh, wearable performance has been

assessed through constructs including flexibility, durability, responsiveness, and operational stability but has not included long-term human-subject testing involving comfort, skin interaction, washability, or continuous operation under daily activities. These limitations define the boundaries of the current research and identify the areas in which laboratory experimentation, longitudinal assessment, standardized material comparison, and real-world wearable validation are required. An additional limitation has concerned the absence of objective triangulation between questionnaire responses and matched experimental performance records from fabricated devices. Without paired laboratory data, the analysis has not been able to determine whether respondents who rated a design characteristic highly would observe proportionally higher physical conversion efficiency under identical test conditions. The study has also not modeled interaction or nonlinear effects among material properties, morphology, architecture, and mechanical loading, although such interactions may be important in nanocomposite and hybrid TENG-PENG systems. Moreover, differences in fabrication route, poling history, surface treatment, encapsulation, and environmental exposure have not been incorporated as separate control variables. These constraints have limited the precision with which the statistical results can be translated into composition-specific engineering prescriptions and have reinforced the need for subsequent controlled validation using standardized physical measurements.

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