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Investigation of Polydimethylsiloxane-Zinc Oxide Nanocomposites for Application to Nanogenerators

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Abstract

Hybrid nanogenerators (NGs) are emerging among the most promising approaches to leverage contact electrification and strain-induced polarization to generate electricity from everyday mechanical actions. Zinc oxide (ZnO) integrated with polydimethylsiloxane (PDMS) forms a nanocomposite exhibiting the hybrid piezo-tribo phenomenon and offers enhanced energy conversion potential. In this investigation, the scalable and cost-effective composite matrix is synthesized by incorporating ZnO nanoparticles into the PDMS matrix at 25 wt% using an ultrasonication method followed by ambient temperature curing. The characterization of the synthesized nanocomposite with X-ray diffraction and field emission scanning electron microscopy confirms the presence of wurtzite-phase ZnO and uniform nanoparticle dispersion. A flexible NG device is fabricated first by sandwiching the nanocomposite layer between two copper electrodes and then between an Indium Tin Oxide (ITO)-coated Polyethylene Terephthalate (PET) and copper electrode. A peak AC voltage of 15 V was obtained under a 2 N force at a 5 Hz tapping frequency. Replacing one copper electrode with a flexible ITO-coated PET electrode increased the output to 16.8 V, due to improved stress transfer and enhanced dipole polarization in ZnO. These results highlight the potential of ZnO-PDMS composites for flexible electronics and self-powered micro-energy systems.

Categories: Advanced Materials, Nano Materials, Nanotechnology
Keywords: tribo-electricity, pdms, nanocomposites, nano-generators, hybrid nano-generators, piezo-electricity, zno

Introduction

The increasing global demand for sustainable energy solutions has accelerated research into energy-harvesting technologies, particularly those capable of converting ambient mechanical energy, like human motion and vibrations, or tapping into electrical energy. Among these technologies, triboelectric nanogenerators (TENGs) and piezoelectric nanogenerators (PENGs) have garnered significant attention due to their high efficiency and adaptability. TENGs utilize contact electrification, while PENGs harness mechanical strain, making them suitable for powering wearable electronics, sensors, and Internet of Things devices.

Zinc oxide (ZnO), a wide-bandgap II-VI semiconductor with a wurtzite crystal structure, exhibits well-documented piezoelectric properties [1]. Its ability to generate electric dipoles under mechanical deformation, due to its non-centrosymmetric lattice structure has made it a fundamental material in piezoelectric energy harvesting [2]. Additionally, ZnO's ease of synthesis into various nanostructures further enhances its application potential. Similarly, polydimethylsiloxane (PDMS), a flexible and biocompatible silicone-based polymer, is widely recognized for its strong electron-attracting tendencies during contact electrification [3]. The integration of ZnO nanoparticles into a PDMS matrix enhances triboelectric output through improved charge separation and surface contact area, and piezoelectric response by preserving material's inherent properties, thereby improving energy harvesting performance [4].

The synthesis of ZnO-PDMS nanocomposites commonly involves hydrothermal or sol-gel methods for ZnO dispersion into a PDMS precursor, followed by thermal curing to form a mechanically robust film. Characterization techniques such as X-ray diffraction (XRD), scanning electron microscopy (SEM), and Fourier-transform infrared spectroscopy (FTIR) are used to assess crystallinity, morphology, and chemical interactions within the composite. These properties are critical to understanding how the material responds to mechanical inputs and generates electrical energy.

Testing the energy-harvesting capabilities of ZnO-PDMS nanocomposites typically involves mechanical stimulation using tapping devices, which provide a controlled means to simulate real-world interactions [5]. By varying applied force and frequency, researchers examine the interplay between triboelectric charge generation and piezoelectric polarization while evaluating material durability under cyclic loading. Literature findings suggest that key factors influencing electrical output include ZnO concentration,

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particle size, and PDMS flexibility. Moreover, frequency-dependent testing has revealed peak performance at specific mechanical resonance frequencies, highlighting the importance of dynamic conditions in practical applications. Studies have also explored enhancements such as doping with magnesium (Mg) [6] or lithium (Li) [7] and heterostructure formation [8] to improve piezoelectric and triboelectric properties and have achieved up to 186 V and 1.56 W/m² [6] and 60.1 V and 75 µA [7], respectively. Dielectric permittivity of cured ZnO-PDMS composites increases by about 80% as compared to random composites [9] leading to better results. The curing need at around 100°C compared to sintering at around 1000°C by traditional materials makes ZnO more suitable for the development of varistors. Temperature has a considerable influence on the switching field and the dielectric permittivity [10]. Further, conductivity and permittivity are dependent on filler content [10].

ZnO-PDMS nanocomposites are synthesized through various methods, including hydrothermal growth, sol-gel processing, and chemical precipitation [11]. ZnO-PDMS has reported an electrical voltage of 9 mV with a peak power of 5.34 pW [12], 5.1 V and 92.5 nA at 10 g [13]; 150 V [14]; 35.3 V and 20.82 µA [15], and 150 V and a current of ~10 µA [16]. Additional techniques such as chemical bath deposition, spin coating, spray pyrolysis, thermal evaporation, chemical vapor deposition, atomic layer deposition, pulsed laser deposition, magnetron sputtering, electrodeposition, and Electrospray Deposition have also been explored [17].

Studies indicate that exposure of ZnO-PDMS composites to UV radiation influences their surface properties, such as contact angle and hydrophobicity [18]. Additionally, integrating other materials like SiO_2 [19], TiO_2 [20], and Al_2O_3 [21] can enhance photocatalytic properties. However, the correlation between optimized ZnO functionalization and its hydrophobic application in sub-zero temperatures remains unclear in the literature, posing a challenge for commercialization [22].

Chain-like structure [23], electric flow distribution control by filler material [24,25], with 0-3 connectivity enabling homogeneous dispersion [25,26], and 1-3 anisotropic structure enabling closely aligned particles in a preferred direction to boost the electromechanical coupling [27].

Characterization of ZnO-PDMS nanocomposites is essential to understand their structural, morphological, and electromechanical properties. Several different examination conducted by different researchers to establish the material properties for the given applications include microscopic examination of alignment of doped and filler material, electric field distribution of 0-3 and 1-3, switching field analysis, temperature stability, current response (J-E characteristics), including ferroelectric polarization, capacitive behavior, and conduction mechanism-based Ohm and hopping effect, permittivity, conductivity, and dielectric losses, and mechanical characteristics-based stress-strain curve.

XRD is widely used to confirm the crystallinity of ZnO within the composite, with characteristic peaks at 31.7°, 34.4°, and 36.2° corresponding to the (100), (002), and (101) planes of the wurtzite phase [16]. SEM and transmission electron microscopy (TEM) provide insights into the dispersion and morphology of ZnO nanoparticles within the PDMS matrix. Electrical characterization, such as dielectric constant measurements, further elucidates the composite's ability to store and transfer charge, which are critical factors in tribo-piezoelectric performance [11].

Table *1* presents precise literature outcomes focusing on the synthesis, characterization, and testing of ZnO-PDMS nanocomposite layers for tribo-piezoelectricity generation. The following priorities are established from the exhaustive literature review:

· Controlled Weight Fraction (25 wt%): Prior research works mainly explored the lower ZnO concentrations (typically 10-25 wt%) with a primary focus on preserving the flexibility. Complementarily, our study investigates a higher ZnO concentration of 25 wt% with similar structural integrity.

· The authors also established the authenticity of application of ultrasonication for homogeneous dispersion of ZnO into the PDMS matrix for a higher concentration of ZnO for a consistency of the composite's dielectric and mechanical properties.

Reference	Year	Synthesis Method	Characterization Techniques	Testing Conditions (Force/Frequency)	Current, Voltage, Power Output	Key Findings	Contribution to Field
Wang and Song [1]	2006	Hydrothermal growth of ZnO nanowire arrays	SEM, XRD	AFM tip bending (force/frequency not specified)	Voltage: ~10 mV (single nanowire)	First demonstration of ZnO nanowires generating piezoelectricity	Pioneered ZnO-based piezoelectric nanogenerators

						via strain	
Fan et al. [3]	2012	PDMS film preparation (no ZnO in this study)	SEM, electrical measurements	Manual pressing (force/frequency not specified)		Introduced PDMS as a triboelectric material with high charge generation	Pioneered the use of PDMS in TENGs, setting the stage for hybrid composites
Gopakumar and Rajeev [4]	2025	ZnO and TiO_2 nanoparticles are embedded with PDMS to develop hybrid tribo/piezoelectric generator	SEM, XRD, FTIR	Finger tapping and 3N mechanical force	131 V at 20 μW/cm^2 with a load resistance of 1 MΩ and charged a 1 μF capacitor to ~6.28 V in 20 s	Piezoelectric and dielectric properties of ZnO and TiO_2 nanoparticles are explored	Developed hybrid tribo/piezoelectric energy harvester
Chen et al. [5]	2017	ZnO nanorods via hydrothermal, embedded in PDMS	TEM, XRD, dielectric analysis	Tapping device: 5 N, 5 Hz	Voltage: 10 V (peak), Current: Not specified	Hybrid mechanism outperformed single-effect systems	Validated synergy of tribo-piezo effects under tapping
Lee et al. [6]	2024	Mg-doped ZnO NFs in PDMS	XRD, SEM, electrical testing	Tapping device: 5 N, 5 Hz	Voltage: 186 V, Current: 5.23 μA, Power: 1.56 W/m²	High dielectric constant from Mg-doping boosted output	Advanced doping strategies for enhanced performance
Chowdhury et al. [7]	2019	Li-doped ZnO nanowires with PDMS-PTFE	SEM, XRD, electrical testing	Tapping device: Variable load, 5 Hz	Voltage: 60.1 V, Current: 75 μA	High output due to enhanced piezoelectricity from Li-doping	Cost-effective hybrid nanogenerator design
Qian and Kang [8]	2018	PDMS/ZnO NFs/3D Gr heterostructures using Ni foams as template substrate via a facile route	SEM, XRD, electrical testing	Tapping device: 5 N, 10 Hz	Voltage: 122 V, Current densities: 51 μA cm^{-2}, Power: 6.22 mW/cm²	Powered 68 LEDS	PDMS/ZnO NFs/3D Gr heterostructures has vast capabilities
Abdulla and Ounaies [9]	2020	ZnO nanorods via hydrothermal, embedded in PDMS	TEM, electrical testing	Tapping device: 2-8 N, 5-50 Hz	Voltage: ~10 V, Current: ~0.8 μA	Peak output at 10-15 Hz due to resonance	Highlighted frequency dependence and resonance effects
Khatun et al. [11]	2023	ZnO nanoflowers via hydrothermal, mixed with PDMS	SEM, XRD, dielectric analysis	Tapping device: 2.64 N, 5 Hz	Voltage: ~15 V, Power: 14.27 μW	PVDF filler enhanced β-phase and output	Explored ZnO-PDMS with PVDF for piezoelectric enhancement
Amangeldinova et al. [12]	2021	Changed ZnO concentration in precursor solution, and permitted elastomeric PDMS into the porous ZnO membrane	Dielectric spectroscopy, SEM	30 N to 60 N	Electrical voltage of 9 mV, 5.34 pW peak power	Adjusted porosity of the ZnO membrane from 11.6% to 35.7%	Lower dielectric constant of piezoelectric layer improves the electrical performance of piezoelectric nanogenerator
Vikas and Jeong [13]	2022	ZnO/PVDF-based nanogenerator with PDMS	XRD, FTIR, SEM	Varied load from 0 to 20 g	5.1 V, 92.5 nA at 10 g	Analyzed tribo-piezo effect in ZnO/PVDF-PDMS NGs	Triboelectric effect reduces with increase in relaxation time
Perez-Lopez et al. [14]	2021	Random dispersions of ZnO in PDMS	Dielectric test	Not specified	Voltage: 150 V	7.4 wt% exhibited highest voltage	9.4 wt% reduced output voltage

Singh and Singh [15]	2023	ZnO nanorods via hydrothermal, mixed with PDMS (adapted from MoS2 study)	XRD, SEM, electrical testing	Finger tapping	Voltage: 35.3 V, Current: 20.82 µA	MoS2-PVDF/PDMS-based HNG produced 1.6 times greater than PVDF/PDMS	Lighted 21 LED bulbs
Barras et al. [16]	2023	ZnO nanorods coated with porous PDMS	SEM, XRD, electrical testing	Tapping device: 10 N, 10 Hz	Voltage: 150 V (peak-to-peak), Current: ~10 µA	Porous PDMS coating increased surface area and output	Innovated surface modification for high voltage

TABLE 1: Precised literature outcomes of ZnO-PDMS nanocomposite layers for tribo-piezoelectricity generation

ZnO, Zinc oxide; PDMS, polydimethylsiloxane; SEM, scanning electron microscopy; XRD, X-ray diffraction; AFM, Atomic Force Microscopy; FTIR, Fourier-transform infrared spectroscopy; TEM, transmission electron microscopy; PTFE, Polytetrafluoroethylene; PVDF, Polyvinylidene Fluoride; NG, Nanogenerator; NF, Nanoflake; LED, Light Emitting Diode; TENG, triboelectric nanogenerator

The following research gaps for hybrid energy harvesting are targeted in this research article:

· Limited availability of research articles on comparative performance analysis using different electrodes in ZnO-PDMS nanocomposites: Our research article addresses this by systematically evaluating the tribo-piezoelectric response of the ZnO-PDMS nanocomposite using different electrodes during fabrication.

· Limited Experimental Validation of Hybrid nanogenerators (NGs): Available research articles primarily emphasize on the triboelectric or piezoelectric behavior in isolation. This research article analyzed hybrid effects in a composite system.

· Unclear Guidelines on Optimal Filler Loading and Dispersion Methods: The available research literature fails to clarify the influence of ZnO concentration on output performance and mechanical flexibility. We explored the 25% wt. of ZnO to add to the body of knowledge in the available literature in this research.

· Insufficient Focus on Scalable and Low-Cost Fabrication: Most of the high-performance systems used complex fabrication techniques. We focused on simple ultrasonication and ambient curing to develop the nanocomposite with scalability, cost-effectiveness, and performance in consideration.

This work investigates the methods for synthesis and detailed characterization of ZnO-PDMS nanocomposite layers, followed by a systematic study of their tribo-piezoelectric generation capabilities using a custom-designed tapping device. We explored the 25% wt. of ZnO to add to the body of knowledge in available literature in this research. We focused on simple ultrasonication and ambient curing to develop the nanocomposite with scalability, cost-effectiveness, and performance in consideration. We also explored a simplified fabrication technique using copper tape electrodes by sandwiching the ZnO-PDMS composite layer between copper foils with direct soldered wiring, providing a cost-effective, scalable, and reproducible setup suitable for practical testing under varied mechanical conditions. The performance was investigated for different electrodes.

The manuscript presents results in a logically structured format, moving from synthesis to characterization and performance testing. Comparative literature review tables and figure-based evidence (e.g., XRD peaks, NG setup, and output curves) have been included to support the claims. The conclusions are well supported by the data.

Materials And Methods

In this work, 98.5% grade zinc acetate ($Zn(CH_3COO)_2.2H_2O$), purchased from SRL chemicals, was used as the Zn^{2+} precursor for nanorods; elastomeric matrix Sylgard184 PDMS kit (base+curing agent), purchased from Sigma Aldrich; ethanol, isopropanol and De-Ionized (DI) water is used for cleaning/dispersion, and copper tape is used as the top and bottom electrode.

A total of 5 g zinc acetate was grounded manually in mortar and pestle for about an hour followed by a thermal treatment at 300°C for a duration of 4 hours for curing. The heat-treated samples were then air-quenched to room temperature. The samples were then grinded in mortar and pestle for 5 min and were then dispersed in DI water with a volume ratio of 10:1 (water volume to powder weight) at continuous magnetic stirring for 4 hours at 1000 rpm. The suspended solution was then filtered using Whatman filter paper for separation of the solid phase. The filtered particles were then dried at 70°C for about 10 hours and ash-gray colored ZnO nanorods were thus obtained. Figure 1 demonstrates the schematic for synthesis and fabrication of ZnO-PDMS layer.

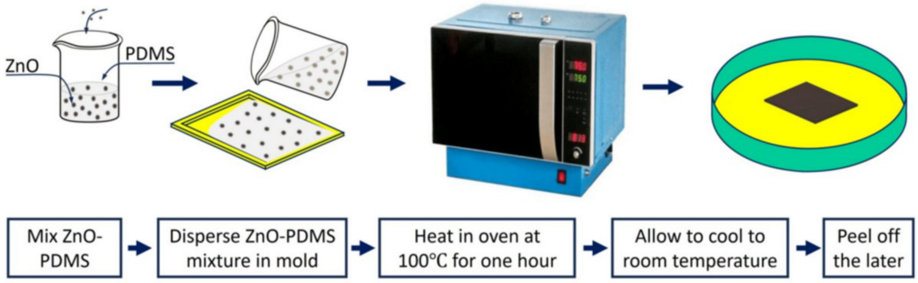

FIGURE 1: Schematic for fabrication of ZnO-PDMS layer

ZnO-PDMS, Zinc oxide-polydimethylsiloxane

The ZnO-PDMS composite film is then fabricated. ZnO powder of 25 wt.% concentration is added to a PDMS solution with the elastomer and a curing agent prepared in a mass ratio of 10:1 under continuous magnetic stirring for 15 min. The stirred homogeneous mixture is then poured into polyacrylic template and placed in vacuum to remove air bubbles from it. Curing of the ZnO-PDMS composite is then done at 100°C for about an hour. The cured ZnO-PDMS composite is peeled off. The composite material was cut into 20 cm × 70 cm piece. The material was analyzed with XRD for its physical and chemical properties. Figure 2 demonstrates the synthesized ZnO-PDMS nano-composite layer.

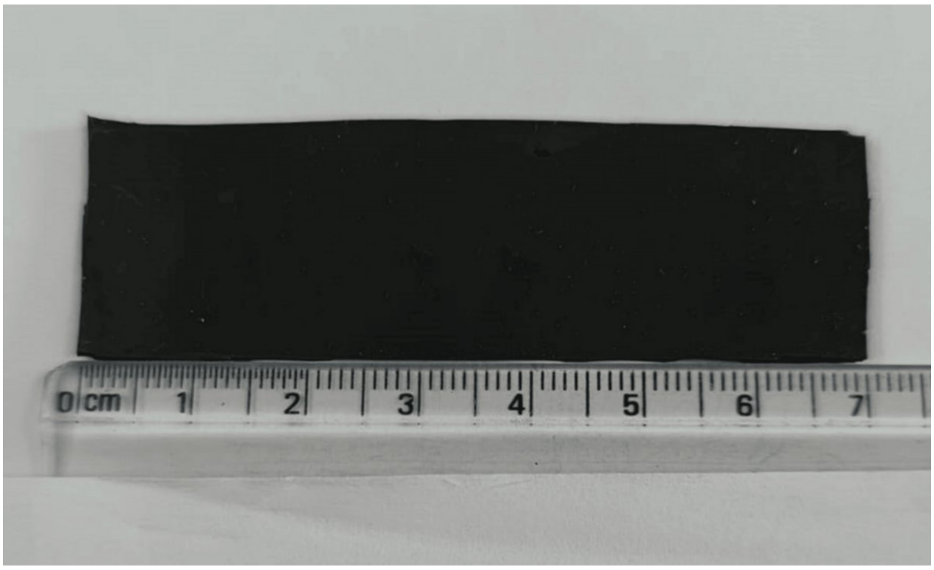

FIGURE 2: Synthesized ZnO-PDMS nano-composite layer

ZnO-PDMS, Zinc oxide-polydimethylsiloxane

XRD was performed using a PANalytical system with Cu Kα radiation (λ = 0.15418 nm), over a 2θ range of 5°-80° at a scanning rate of 0.2°/s. The crystal phases identified include (100), indicating a high degree of alignment in one direction; (002), indicating vertical alignment; and (101), indicating a high degree of alignment in one direction. Morphology and filler dispersion/alignment were analyzed using a SU8010 field-emission scanning electron microscopy (FE-SEM) from Hitachi, Japan, operated at 10 kV.

The NG was fabricated by Sandwiching the ZnO-PDMS layer between two copper foils. Copper wires are soldered with the copper foil for measurements. Figure 3 demonstrates the ZnO-PDMS layer between two copper foils.

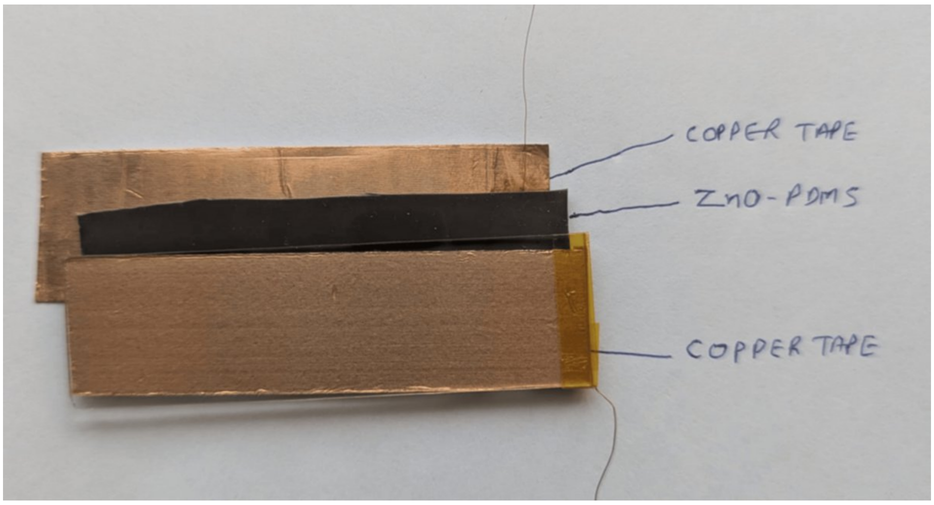

FIGURE 3: ZnO-PDMS layer between two copper foils (scale is same as Figure 2)

ZnO-PDMS, Zinc oxide-polydimethylsiloxane

The NG device is fabricated to analyze the electrical power outputs of the synthesized ZnO-PDMS nanocomposites. The soldered copper wires collects the generated charge. The electrical outcomes are discussed in next section of results of the article.

Results

The XRD results shown in Figure *4* confirm the development of homogenous composites with vertical growth of ZnO nanorods in the ZnO-PDMS composite material [16]. In XRD patterns, characteristic peaks appear at specific 2θ values. The (100) peak corresponds to weak or suppressed signals, indicating a high degree of alignment in one direction. The (002) peak corresponds to vertical alignment (c-axis perpendicular to the substrate, with nanorods aligned vertically), indicating good crystallinity and uniform rod growth. The (101) peak corresponds to weak or suppressed, indicating a high degree of alignment in one direction [16]. The dominant (002) peak, much stronger than (100) or (101), indicates vertical alignment of ZnO nanorods in the composite (c-axis perpendicular to the substrate) [16]. XRD peaks corresponding to (100), (002), (101), (101), (110), (103), (200), (112), and (201), matching with JCPDS Card No. 36-1451, are presented in Figure *4* [16]. The crystallinity of synthesized ZnO within composite is verified by this comparison.

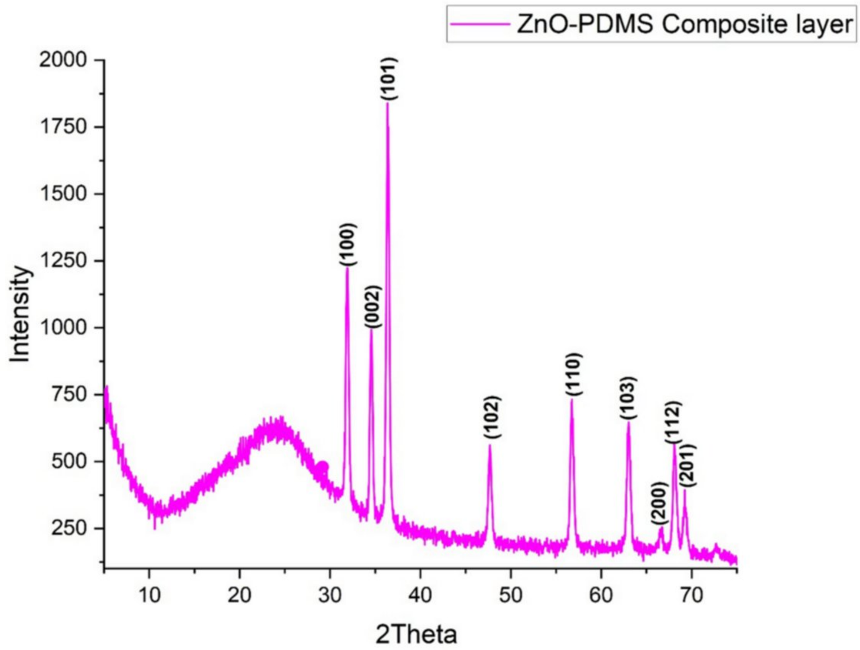

FIGURE 4: XRD of ZnO-PDMS peaks corresponding to (100), (002), (101), (101), (110), (103), (200), (112), and (201) are matching with JCPDS Card No. 36-1451

XRD, X-ray diffraction; ZnO-PDMS, zinc oxide-polydimethylsiloxane

The FE-SEM images of ZnO-PDMS at scales of 1 µm, 10 µm, and 100 nm are shown in Figures *5*, *6*, and 7, respectively.

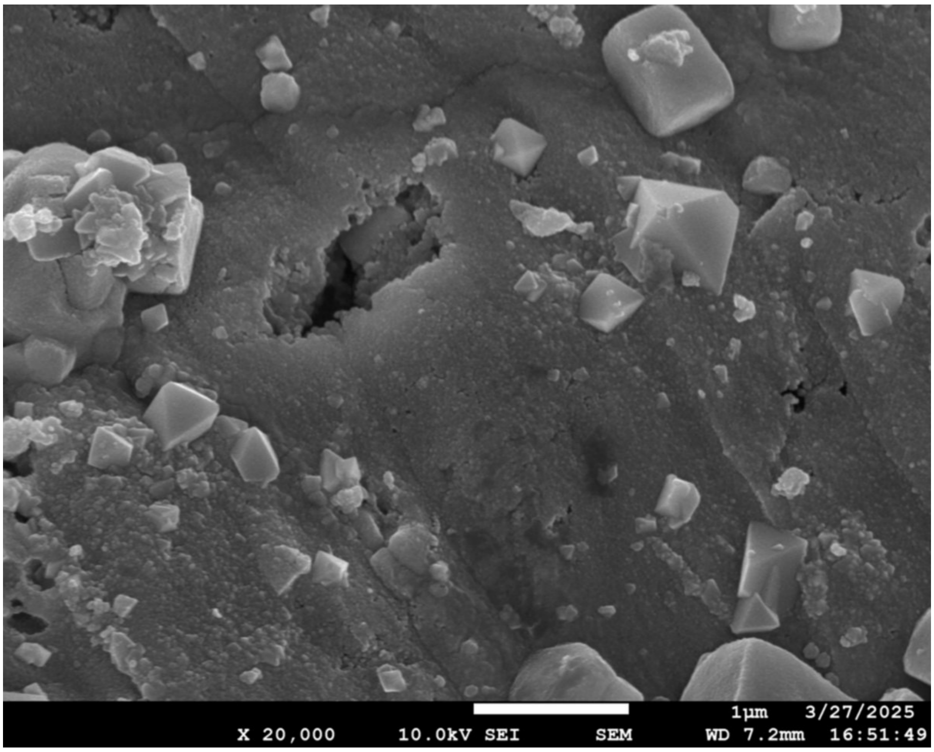

FIGURE 5: FE-SEM of ZnO-PDMS on a scale of 1 µm

FE-SEM, Field-emission-scanning electron microscopy; ZnO-PDMS, zinc oxide-polydimethylsiloxane

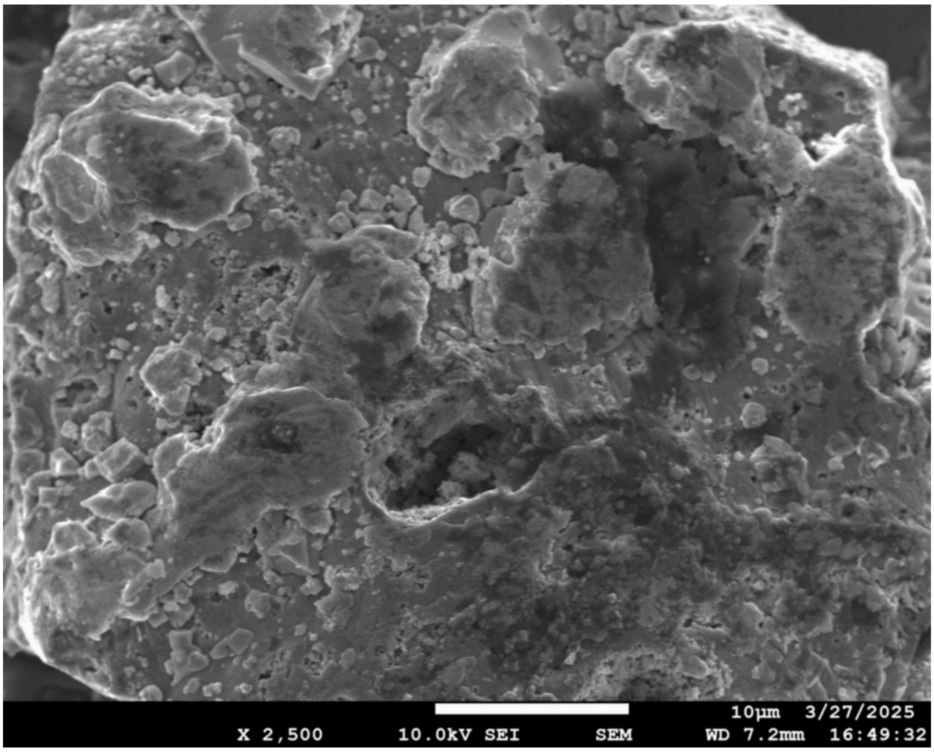

FIGURE 6: FE-SEM of ZnO-PDMS on a scale of 10 µm

FE-SEM, Field-emission-scanning electron microscopy; ZnO-PDMS, zinc oxide-polydimethylsiloxane

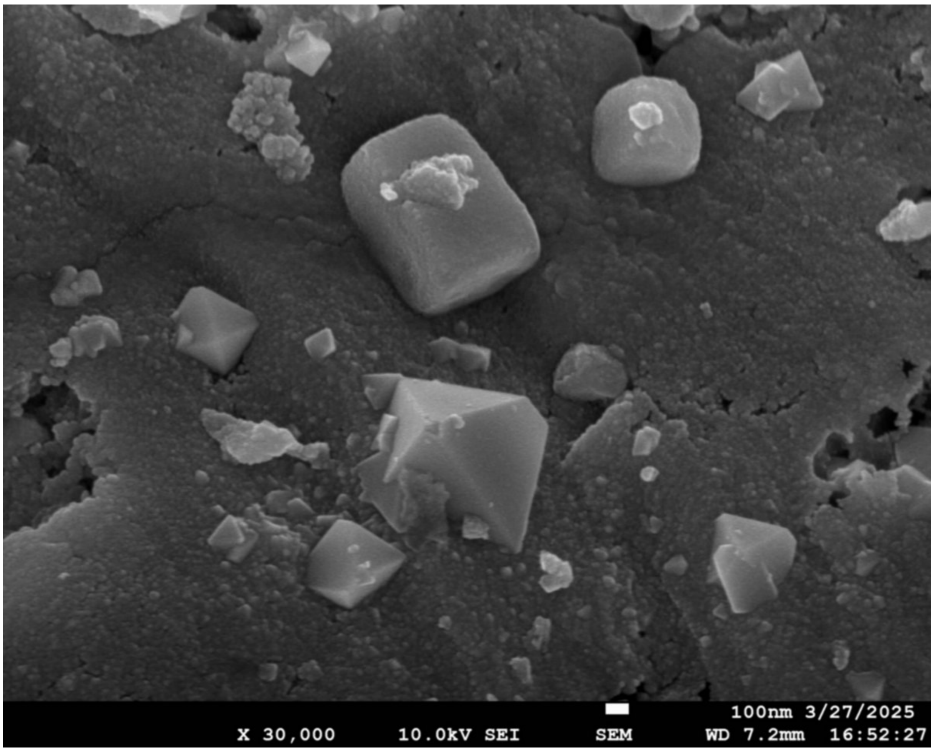

FIGURE 7: FE-SEM of ZnO-PDMS on a scale of 10 nm

FE-SEM, Field-emission-scanning electron microscopy; ZnO-PDMS, zinc oxide-polydimethylsiloxane

The development of ZnO-PDMS nanocomposites marks a significant advancement in the field of hybrid energy-harvesting systems. These composites' integration of the tribo- and piezoelectric effects of ZnO and PDMS provides the materials with higher flexibility and electrical response. The 0-3 and 1-3 connectivity enhances the alignment and charge transport pathways in the composite matrix for improved electromechanical coupling efficiency.

Discussion

Figure *8* presents the results of tapping ZnO-PDMS with copper electrodes at the top and bottom at a frequency of 5 Hz and 2 N force. Figure *9* presents results of tapping ZnO-PDMS with an Indium Tin Oxide (ITO)-coated charge collector at the top and a copper electrode at the bottom, also at a frequency of 5 Hz and 2 N force. The voltage peaked at 15 V under 2 N force and 5 Hz tapping frequency with copper electrodes at top and bottom of the composite layer. It increased to 16.8 V by replacing one copper electrode with a flexible ITO-coated Polyethylene Terephthalate electrode due to improved stress transfer and enhanced dipole polarization in ZnO. The obtained outputs have shown the potential of ZnO-PDMS composites for application in flexible electronics and self-powered micro-energy systems. Alignment is found to increase the piezoelectric contribution. The current generation capacity increases with an increase in applied force. The dielectric properties of the composites were found to improve with ZnO incorporation.

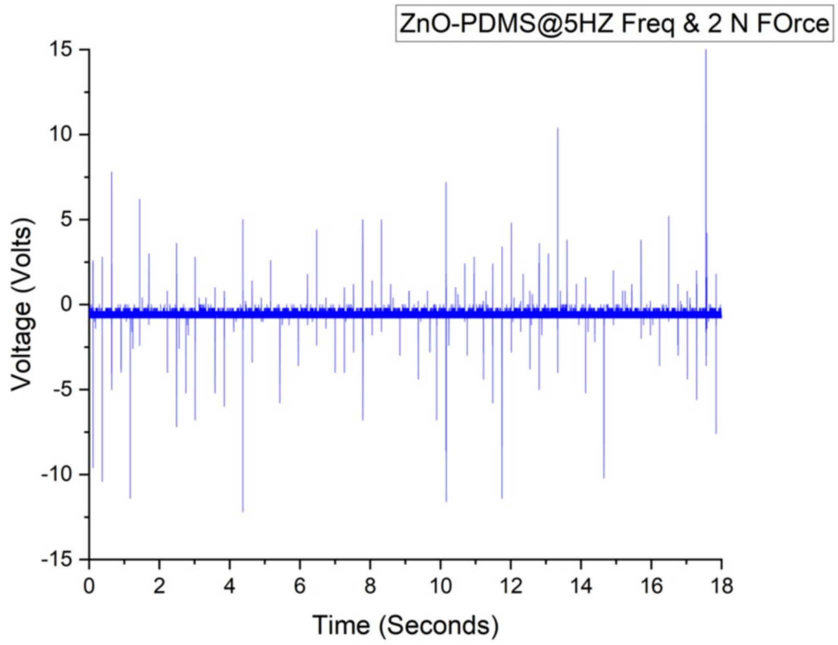

FIGURE 8: Results of tapping ZnO-PDMS with copper electrode at top and bottom at a frequency of 5 Hz and 2 N force

ZnO-PDMS, Zinc oxide-polydimethylsiloxane

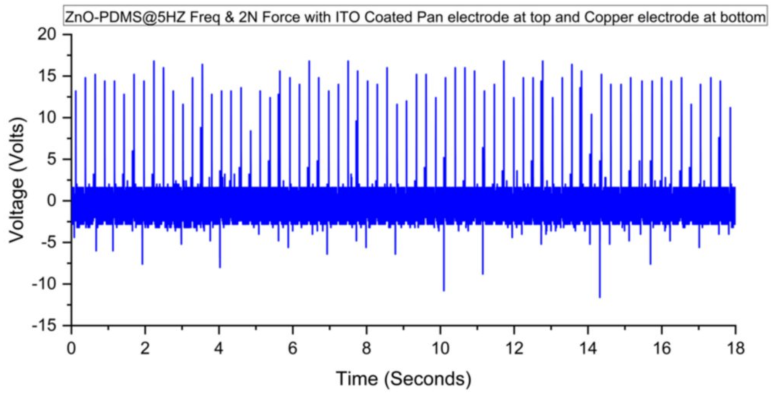

FIGURE 9: Results of tapping ZnO-PDMS with ITO-coated charge collector at top and copper electrode at bottom at a frequency of 5 Hz and 2 N force

ZnO-PDMS, Zinc oxide-polydimethylsiloxane; ITO, Indium Tin Oxide

Figure *10* presents ZnO-PDMS at 10 Hz frequency and 4 N force with an ITO-coated pan electrode at the top and copper electrode at the bottom.

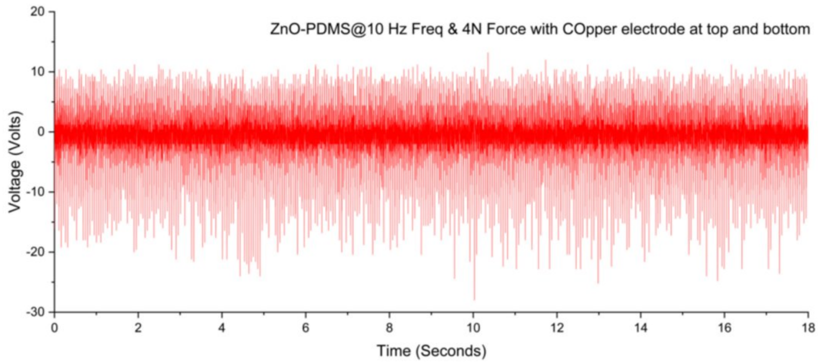

FIGURE 10: ZnO-PDMS at 10 Hz frequency and 4 N force with copper electrode at top and bottom

ZnO-PDMS, Zinc oxide-polydimethylsiloxane

ZnO-PDMS nanocomposites represent a robust and scalable solution for next-generation self-powered systems. While current research offers strong evidence for their multifunctionality and adaptability, further work is needed to overcome limitations related to mechanical integrity, environmental stability, and long-term durability. Future innovations may lie in multifunctional hybrid structures, advanced alignment techniques, and integration with other sustainable materials, pushing the boundaries of energy-harvesting technologies. Testing under dynamic mechanical stimulation using tapping devices has emerged as a standardized method to investigate the tribo-piezoelectric performance of different NG devices.

Conclusions

ZnO-PDMS nanocomposites have potential in different real-world applications for wearable electronics, flexible sensors, biosensors, and micro-varistors. Their mechanical flexibility, ease of fabrication at low temperatures, biocompatibility, and cost-effectiveness make them a competitive alternative to conventional materials like Lead Zirconate Titanate and Polyvinylidene Fluoride.

The material with a controlled weight fraction of 25 wt.% preserves a similar flexibility level in manual inspection. The authenticity of the application of ultrasonication for the homogeneous dispersion of ZnO into the PDMS matrix at a higher concentration of ZnO has been established with this study. The simplified fabrication technique involves sandwiching the ZnO-PDMS composite layer between copper foils with direct soldered wiring, providing a cost-effective, scalable, and reproducible setup suitable for practical testing under varied mechanical conditions.

Future studies could explore ZnO doping with elements such as aluminum or gallium to enhance its piezoelectric coefficient, or integrate the composite into wearable fabrics for practical energy harvesting. This study builds on existing research by synthesizing and characterizing a ZnO-PDMS nanocomposite layer and evaluating its tribo-piezoelectric performance under varying tapping forces and frequencies, aiming to address some of these gaps and contribute to the advancement of efficient hybrid NGs. Though the synthesis parameters (temperature, precursor concentration, pH, reaction time, and stirring conditions) regulate the size, shape, crystalline, and alignment of ZnO nanoparticles, due to scope constraints, we have not experimentally varied these parameters in the current work. DMA and nanoindentation could provide valuable data.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

Concept and design: Ritu ., Anubhav Agrawal, Ranbir Singh, Abhimanyu S. Rana

Drafting of the manuscript: Ritu ., Ranbir Singh

Critical review of the manuscript for important intellectual content: Anubhav Agrawal, Ranbir

Singh, Abhimanyu S. Rana

Acquisition, analysis, or interpretation of data: Abhimanyu S. Rana

Supervision: Abhimanyu S. Rana

Disclosures

Human subjects: All authors have confirmed that this study did not involve human participants or tissue. **Animal subjects:** All authors have confirmed that this study did not involve animal subjects or tissue. **Conflicts of interest:** In compliance with the ICMJE uniform disclosure form, all authors declare the following: **Payment/services info:** All authors have declared that no financial support was received from any organization for the submitted work. **Financial relationships:** All authors have declared that they have no financial relationships at present or within the previous three years with any organizations that might have an interest in the submitted work. **Other relationships:** All authors have declared that there are no other relationships or activities that could appear to have influenced the submitted work.

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