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A NOVEL PVDF-COPPER NANOPARTICLE-BASED NANOGENERATOR FOR EFFICIENT ENERGY HARVESTING

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ABSTRACT

The speedy development of energy harvesting technologies has highlighted the requirement for efficient and sustainable means of addressing the rising demand for self-powered electronic devices. This research investigates the design of a polyvinylidene fluoride PVDF-Copper nanoparticle-based nanogenerator for energy harvesting purposes, aiming to improve flexibility, biocompatibility, and cost-effectiveness. The simulated nanogenerator is designed and modeled with the help of COMSOL Multiphysics to analyze its physical, electrical, mechanical, and chemical behavior under changing environmental conditions. During the simulation stage, charge buildup, stress distributions, and mechanical deformation are analyzed to optimize the choice of materials and structural design. Once optimized, fabrication is done by employing advanced material deposition and electrode patterning methods to fabricate an experimental prototype with maximum energy conversion efficiency. The artificially designed nanogenerator is thoroughly characterized to evaluate its physical, electrical, chemical, and mechanical properties to determine its reliability and stability in various operational conditions. The characterization involves voltage and current output measurement, mechanical flexibility evaluation, and chemical stability testing by FTIR. Performance evaluation finally takes into account signal conditioning circuits to check the actual practical suitability of the nanogenerator. The experimental results exhibit the efficiency of the nanogenerator in harvesting energy, a peak output voltage of 5.2V, and power density of 120 µW/cm² for an applied force of 10N. Signal-conditioning circuit integration stabilizes the power delivery and renders the nanogenerator very useful in wearables, biomedical implants, and industrial sensors. The findings of this study highlight the potential of PVDF-Copper nanoparticle-based nanogenerators to advance self-powered systems further, paving the way for further research in sustainable energy technologies.

Keywords: *Nanogenerator, Energy Harvesting, PVDF, Copper Nanoparticles, COMSOL Multiphysics, Signal Conditioning Circuits, Mechanical Deformation, Self-Powered Systems, Sustainable Energy Solutions*

1. INTRODUCTION

Energy harvesting has also been among the primary topics of recent technological advancements, aiming to harvest energy from ambient sources such as mechanical vibrations, thermal gradients, electromagnetic fields, and solar irradiation. While electronic devices have been reducing and improving in quality, the necessity for sustainable and autonomous systems accelerated [1]. Traditional batteries are limited by energy density, environmental friendliness, and life, so energy harvesting is a suitable option for powering low-power electronic devices. Several nanogenerators such as piezoelectric, triboelectric, and pyroelectric nanogenerators have been studied by researchers, which convert energy from different environmental stimuli through different mechanisms to generate electrical power [2]. Nanogenerators have been found to be feasible in many areas like wearable devices, implantable devices, and wireless sensor networks, where there is a need for power supply with continuity and sustainability [3].

Beginning from a very simple description of F and the subsequent work done on the current PVDF-Cu nanoparticle-based nanogenerators, there is now heated discussion on F and other flexible biocompatible materials for energy harvesters from PVDF-Copper nanocomposite-embedded nanogenerators. PVDF-Copper nanocomposites differ from traditional inorganic materials since they have inherent characteristics of being cost-effective, mechanically flexible, and lightweight; hence, they are suitable for biomedical and wearable devices. Nanogenerators work on the principle of conversion of harvested mechanical energy into electrical energy based on the piezoelectric effect or sometimes the triboelectric effect. Different studies have been pitted against each other to see the effect of different kinds of polymeric materials like polyvinylidene fluoride and its copolymers which exhibit high piezoelectricity, because of the addition of copper nanoparticles which further augment charge accumulation. Impetuses in processing further increase charge accumulation and energy conversion efficiency along the path of PVDF-Copper nanogenerator applications towards practical applications.

Simulation is vital in ensuring the efficiency and reliability of the synthesized nanogenerator as it allows for an understanding of material behavior under various working conditions. COMSOL Multiphysics, which can be said a typical finite element analysis program, allows scientists to simulate the physical, electrical, mechanical, and chemical properties of nanogenerators. The stress distribution, charge accumulation, and deformation parameters can be modeled using simulated analysis and design optimization before any synthesis. Previous studies showed how improved performance and structural integrity of a nanogenerator due to improved simulation-based optimization minimized the need for experimental iterations. The integration of simulation tools with experimental validation, through this, also allows for better accuracy and feasibility of energy harvesting PVDFCopper nanoparticle-based nanogenerators.

The findings of this study will be of significant interest to researchers, engineers, and developers in the fields of energy harvesting, materials science, wearable technology, and biomedical engineering. As the demand for self-powered and flexible electronic devices continues to rise, there is a growing need for efficient, lightweight, and biocompatible energy sources. This study addresses that need by presenting a nanogenerator that combines enhanced electrical performance with structural flexibility and chemical stability. Scientists exploring nanocomposites, industry professionals developing wearable and implantable devices, and designers of industrial IoT sensors will benefit from the insights provided. The integration of copper nanoparticles into a PVDF matrix and the demonstration of its real-world applicability—through simulations and practical signal conditioning—makes this research valuable for advancing next-generation, self-sustaining electronic systems. These findings pave the way for cost-effective, environmentally friendly, and reliable energy harvesting solutions across multiple high-impact domains.

1.1. Problem Statements

- With the growing demand for self-powered electronic devices, there is a pressing need for energy harvesting systems that are both efficient and sustainable.
- Existing materials used in nanogenerators may lack in flexibility, biocompatibility, or cost-effectiveness, necessitating the exploration of alternatives like PVDF and copper nanoparticles.
- There is a gap in comprehensive modeling of nanogenerators that accurately captures electrical, mechanical, and chemical behaviors under varying environmental conditions.
- Despite numerous conceptual designs, few prototypes demonstrate high energy conversion efficiency along with mechanical flexibility and chemical stability.
- Many nanogenerators fail to provide stable power output suitable for real-world applications like wearables or biomedical devices due to inadequate signal conditioning and circuit integration.

1.2. Objectives

1. To broadly investigate the potential of developing PVDF-Copper nanocomposites in nanogenerators for greater energy harvesting efficiency.

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2. To simulate the performance of the nanogenerator using COMSOL Multiphysics evaluation of its mechanical, electrical, physical, and chemical properties for different environmental conditions.
3. To fabricate the optimized PVDF-Copper nanocomposite nanogenerator through advanced techniques of material deposition, electrode patterning, and encapsulation for durability and efficiencies.
4. To demonstrate structural proof of the prepared nanogenerator by means of analysis of its physical composition and integrity through microscopic and spectroscopic techniques.
5. To characterize the fabricated nanogenerator by evaluating, among others, its electrical output, mechanical flexibility, chemical stability, and structural integrity under different testing conditions.
6. To gauge the performance of the nanogenerator in real time and the power supply circuitry that links it with the nanogenerator application under the stable power that would suggest use in applications, such as wearable electronics and biomedical devices.

By addressing these objectives, this research contributes to the advancement of self-powered systems, potentially revolutionizing the future of sustainable energy technologies.

1.3. Organization of the Paper

The rest of the paper is organized according to this plan: Section 2 is a detailed overview of the difficulties in selecting materials for nanogenerators, comparison between piezoelectric and triboelectric materials, and justification on why PVDF-Copper composite has been employed due to greater flexibility and efficiency in converting energy. Section 3 describes existing energy harvesting technologies and their drawbacks, providing context to the suggested PVDF-Cu nanogenerator and introducing its structural design, operation mechanisms, and advantages. Section 4 explains the experimental and simulation setup, along with the fabrication process and procedure for real-world testing, including computational modeling using COMSOL Multiphysics. A critical analysis of results, i.e., electrical, mechanical, and triboelectric properties, is also discussed. Section 5 summarizes the paper by presenting the key contributions, an overview of the impact of the proposed system on self-powered devices, and future research opportunities with possible directions such as hybrid energy harvesting, AI-optimized optimization, and quantum-secured wireless energy transfer.

1.4. Research Questions

The central research question of this study is can a nanogenerator based on PVDF integrated with copper nanoparticles be developed to significantly enhance energy harvesting efficiency while maintaining flexibility, biocompatibility, and chemical stability for practical applications? The hypothesis posits that the incorporation of copper nanoparticles into the PVDF matrix will improve the piezoelectric and conductive properties of the nanogenerator, resulting in higher voltage and power output under mechanical stress. Additionally, it is hypothesized that this composite structure, when optimized through simulation and fabrication, will offer mechanical durability and chemical resistance suitable for use in wearable and biomedical electronic devices.

2. LITERATURE REVIEW

Nanogenerator development for energy harvesting has been a major area of investigation, with efforts directed towards piezoelectric, triboelectric, and hybrid energy harvesting technologies to enhance power density, charge transfer, and material stability. This section summarizes some important studies on material selection, structural design, and performance optimization and identifies research gaps that the current PVDF-Cu nanogenerator fills.

This study introduces several key innovations that distinguish it from existing literature on energy harvesting and nanogenerator development. Unlike previous studies that primarily focus on traditional PVDF-based nanogenerators or theoretical simulation frameworks, this research presents a novel composite approach by integrating copper nanoparticles into a PVDF matrix. This material combination significantly enhances piezoelectric response, electrical conductivity, and chemical stability, leading to improved energy conversion efficiency. While prior works, such as those by Alhamyani & Alshammari (2024), emphasize machine learning techniques for cybersecurity detection, and Shahid (2023) explores system vulnerabilities, they do not address nanogenerator fabrication or energy harvesting capabilities. Moreover, the focuses on the role of AI in innovation but lacks experimental application in hardware systems. In contrast, the present research adopts a full-cycle methodology—from COMSOL

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Multiphysics simulation to experimental fabrication and real-world testing—demonstrating practical utility with a peak voltage of 5.2V and a power density of 120 μW/cm². Additionally, the integration of signal-conditioning circuits for performance stabilization underlines its readiness for wearable, biomedical, and industrial use cases. This interdisciplinary approach, combining materials engineering with applied electronics, sets a new direction for self-powered device development and distinguishes it from more narrowly focused or conceptual studies.

2.1 Nanogenerators for Energy Harvesting

Sappati et al. (2021) studied PVDF-based flexible piezoelectric nanogenerators for wearable devices. The research verified the high flexibility and mechanical stability of PVDF, but charge accumulation was limited and lowered power output. The authors proposed that charge mobility and energy conversion could be enhanced by doping with nanoparticles [7]. Güçlü et al. (2023) investigated $BaTiO_3$ nanogenerators with a focus on high dielectric constant and energy density. Though, their research determined that brittleness and limited flexibility constrained uses in wearable and deformable electronics, to which polymer-based options were more desirable [8]. Xiao, K et al. (2024) investigated triboelectric nanogenerators (TENGs), indicating that surface functionalization enhanced charge accumulation. Nevertheless, their findings revealed that humidity dramatically decreases efficiency, confining the independent application of TENGs for stable energy harvesting [9]. Wang et al. (2021) researched hybrid nanogenerators that combine piezoelectric and triboelectric effects to enhance energy conversion efficiency. The research emphasized that charge density is improved by combining mechanisms but material selection is still important for mechanical stability [10]. Tsai et al. (2021) investigated ZnO nanostructures for piezoelectric generators and presented them as capable of increasing surface charge density. Fabrication complexity and cost are still huge challenges, thus making polymer-based nanogenerators more scalable [11].

2.2 Material Enhancements for Nanogenerators

Lee et al. (2019) developed PZT-PDMS hybrid nanogenerators, achieving higher power densities than standalone piezoelectric devices. However, rigidity in PZT components caused performance degradation under repeated mechanical stress, necessitating the use of more flexible polymers like PVDF [12]. Ravikumar, Ayyanu, et al. (2022) demonstrated that metallic nanoparticle doping (Ag, Cu) significantly improves charge transport in polymer-based piezoelectric nanogenerators. Among tested materials, Cu nanoparticles exhibited the best electrical conductivity, supporting their integration into PVDF films [13]. Javaid, Shumaila, et al. (2023) introduced self-powered IoT sensors using polymer-based nanogenerators. Their results confirmed that optimized electrode designs improve charge extraction efficiency, but voltage fluctuations under dynamic loading conditions highlighted the need for adaptive signal conditioning circuits [14]. Shivam, et al. (2020) investigated graphene oxide (GO) composites for energy harvesting, showing that GO-PVDF nanogenerators demonstrated enhanced piezoelectric properties. However, material synthesis complexity limited its large-scale adoption, favoring Cu-based composites instead [15]. Johnson, Aliesha D., et al. (2024) studied nanoparticle-enhanced triboelectric generators, confirming that surface roughness and dielectric layer thickness influence charge accumulation. They found that metallic nanoparticles, particularly Cu, improved charge mobility, validating their use in high-performance nanogenerators [16].

2.3 Structural Design and Energy Conversion Efficiency

Yan et al. (2023) proposed a multi-layer stacked nanogenerator design to increase charge accumulation, achieving double the power density of conventional single-layer PVDF nanogenerators. However, fabrication complexity and cost constraints limit large-scale adoption [17]. Mahmud, M. et al. (2021) investigated 3D-printed nanogenerators, demonstrating that structured electrode patterns enhance charge distribution, but the material's mechanical stability under prolonged stress needs further optimization [18]. Aazem et al. (2022) studied polymer-ceramic hybrid nanogenerators, concluding that PVDF-based materials balance flexibility and energy output better than rigid ceramic counterparts. Their findings emphasize PVDF's suitability for wearable and IoT applications [19]. Liu et al. (2024) proposed a flexible multi-functional nanogenerator, integrating piezoelectric and triboelectric effects with adaptive control circuits to enhance power delivery. However, the study highlighted that material degradation over time remains a challenge, requiring further improvements in nanoparticle dispersion [20]. Li C et al. (2023) investigated self-healing polymer nanogenerators, demonstrating that PVDF composites exhibit excellent resilience after mechanical stress. However, output power remains lower than ceramic-based alternatives, making further optimization necessary [21]. Table 1 shows the insights of literature survey.

Table 1: Insights of the Literature Survey.

Ref. No.	Author Name, Year	Title of Proposed System	Techniques Used	Demerits in Using the Method
[7]	Sappati et al. (2021)	Flexible Piezoelectric Nanogenerators for Wearable Electronics	PVDF-based piezoelectric nanogenerator, Mechanical energy harvesting	Low charge mobility, limited power output
[8]	Güçlü et al. (2023)	$BaTiO_3$-Based Piezoelectric Nanogenerators for Self-Powered Sensors	$BaTiO_3$ thin-film, High dielectric constant, Sensor integration	Brittle structure, limited flexibility for wearable applications
[9]	Xiao, K et al. (2024)	High-Output Triboelectric Nanogenerators	Surface functionalization, Polymer-based triboelectric generator	Humidity-sensitive, charge dissipation under high moisture levels
[10]	Wang et al. (2021)	Metallic Nanoparticle-Enhanced Piezoelectric Nanogenerators	PVDF-Cu composite, Nanoparticle doping, Charge transport enhancement	Requires precise nanoparticle dispersion, potential fabrication complexity
[11]	Tsai et al. (2021)	Hybrid Piezoelectric-Triboelectric Nanogenerators	PZT-PDMS hybrid structure, Multi-mode energy harvesting	Rigid PZT layer, limited long-term durability
[12]	Lee et al. (2019)	Nanoparticle-Enhanced Triboelectric Generators	Surface roughness optimization, Copper nanoparticle coating	Cost constraints, material degradation over prolonged use
[13]	Ravikumar, et al., 2022	Flexible Multi-Functional Nanogenerator	Piezo-Tribo hybrid mechanism, Adaptive power control circuits	Material degradation over time, requires improved nanoparticle dispersion

2.4 Research Gap

The improvement of piezoelectric and triboelectric nanogenerators is hampered by challenges in efficiency in energy conversion, flexibility, and practical application. $BaTiO_3$ and PZT nanogenerators have high charge density but are not flexible, and TENGs are environmentally unstable. Hybrid strategies optimize performance but still lack investigation, especially nanoparticle-improved polymer solutions such as copper-doped PVDF. Structural optimizations like multi-layer stacking maximize efficiency but pose difficulties in production. In addition, adaptive power conditioning circuits and quantum-secure cryptographic integration are yet to be developed. Closings these openings, the PVDF-Cu nanogenerator presents an economical, flexible, and high-efficiency answer, paving the way for energy harvesting applications in sustainable energy.

3. METHODOLOGY

The research method for this study involves a systematic combination of simulation, fabrication, and experimental validation to develop an efficient PVDF-Copper nanoparticle-based nanogenerator. The study begins with the preparation of a composite material by uniformly dispersing copper nanoparticles within a PVDF matrix to enhance its piezoelectric and conductive properties. Using COMSOL Multiphysics, the nanogenerator is modeled to simulate its electrical, mechanical, and chemical behaviors under various environmental conditions, including charge distribution, stress response, and mechanical deformation. Based on simulation outcomes, the nanogenerator's structure is optimized for maximum energy conversion. The optimized design is then fabricated using advanced material deposition and micro-patterning techniques. The prototype undergoes comprehensive characterization, including FTIR analysis for chemical stability, voltage and current output measurement, and mechanical flexibility testing. To evaluate real-world applicability, the device is integrated with signal-conditioning circuits, and its performance is tested under dynamic force. This structured approach ensures reliability, efficiency, and practical usability in energy harvesting applications.

3.1. Novelties

- **Enhanced PVDF-Copper Composite:** Copper nanoparticles improve charge carrier mobility, significantly boosting piezoelectric sensitivity and mechanical durability for efficient energy harvesting.

- **COMSOL-Integrated Optimization:** Hybrid computational-experimental modeling optimizes material properties and energy output before fabrication, reducing design inefficiencies.
- **Adaptive Signal Conditioning:** Dynamic rectification and voltage regulation circuits adjust in real-time to optimize energy storage and minimize power losses.
- **Micro-Patterned Electrodes:** Optimized electrode design maximizes charge extraction efficiency, enhancing energy conversion rates and device performance.
- **Scalable Modular Design:** Enables seamless integration of multiple nanogenerators for distributed energy harvesting in large-scale applications.

3.2. Simulation Using COMSOL Multiphysics

A detailed simulation was conducted of the third generation of PVDF-Copper Minus-PNM Nanogenerators using COMSOL Multiphysics by International Institute of Management, Tbilisi, GEORGE. This research aims to develop a nanogenerator model under different operating conditions to predict performance and optimize design before manufacturing. Finishing successful analysis is made possible by applying finite element analysis (FEA) on a piezoelectric actuator covering its mechanical stresses, distribution of electric charge, and heat effects. The simulations serve to find the pertinent material parameters and electrode configurations which will guarantee high energy conversion efficiency. The procedure of simulation defines the constitutive equations which identify the piezoelectric material. The piezoelectric effect on which energy conversion relies for the nanogenerator is expressed mathematically through some interlinkage between the mechanical and electrical domains. The linear piezoelectric effect, which states that an electric charge is produced due to applied mechanical stress, is described by Equation 1 below.

$$D_i = \epsilon_{\{ij\}E_j} + d_{\{ijk\}}\sigma_{\{jk\}} \quad (1)$$

In this equation, D_i represents the electric displacement vector, E_j denotes the electric field, d_{ijk} is the piezoelectric strain coefficient, and σ_{jk} is the applied stress tensor. This equation basically explains how deformation of material under the influence of external forces leads to accumulation of electric charge on the material. This equation basically explains how deformation of material under the influence of external forces leads to accumulation of electric charge on the material. This equation is used by COMSOL in simulating charge generation in the PVDF matrix in addition to the fact that the charge carriers are copper nanoparticles. The response of the model to displacement of the material is also embodied in the stress-strain relationship, whereby for any elastic material the relationship between stress and strain is given by Hooke's law so that:

$$\sigma = C \cdot \varepsilon \quad (2)$$

where σ is the stress tensor, C is the stiffness matrix, and ε is the strain tensor. The mechanical deformation caused by the applied loads to the nanogenerator is analyzed using this equation, making sure that material properties ensure high flexibility and durability while permitting energy conversion efficiency.

In addition to piezoelectric and mechanical analysis, COMSOL offers electrostatic and thermal analysis software modules to assess charge distribution variations with temperature changes. The electrostatic potential in the nanogenerator is determined by Gauss's law:

Gauss's law states that the electric field in the nanogenerator is governed by the charge distribution in the material.

$$\nabla \cdot D = \rho_f \quad (3)$$

Where ρ_f is the free charge density. This equation ensures that charge accumulation across the surface of the electrodes is correctly modeled, preventing inefficient charge leakage that could otherwise degrade the nanogenerator's performance.

Thermal effects due to mechanical stress are modeled using Fourier's heat conduction in equation 4:

$$\nabla \cdot (k\nabla T) + q = \rho C_p \frac{\partial T}{\partial t} \quad (4)$$

where k is the thermal conductivity, q is the heat generation term, ρ is the density, C_p is the specific heat capacity, and T is the temperature. By solving this equation, the temperature distribution

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within the PVDF-Copper composite is obtained, ensuring that thermal stresses do not compromise structural integrity.

3.3. Fabrication of the Nanogenerator

Once the simulation process is finished, the production of PVDF-Copper nanoparticle-based nanogenerator begins. Other activities include material preparation, electrode deposition, layering, and encapsulation. Depending on the outcome of experiments, an advanced, highly functional nanogenerator with good mechanical flexibility and better durability is to be developed. The first factor of fabrication involves "the" making of the composite PVDF-copper nanoparticles. Through solution casting, this will be done to ensure even dispersion of nanoparticles in the polymer matrix. The dispersion of copper nanoparticles provides enhanced charge transport properties and piezoelectric sensitivity. The charge density induced, which can be discussed about the essence of the efficiency of nanogenerators, is given as:

$$Q = \int_S \sigma dS \quad (5)$$

Where Q is the charge on the device, S is electrode area, and σ is the surface charge density. This equation allows one to appreciate the importance of electrode design and composition for the maximization of charge accumulation.

With the preparation of materials done, then follows the deposition of electrodes. Conductive electrodes are sprayed on either side of the PVDF-Copper composite film through a process of sputtering. This is to achieve effective harvesting and transport of charge with minor dissipations by the nanogenerator. The thickness of the electrodes is optimized for lower resistances while providing mechanical flexibility.

After electrode deposition is done, the developed layers are then encapsulated by a polymeric protective coating. Encapsulation guards against environmental degradation such as mechanical wear and absorption of moisture. The last part of fabrication entails annealing, where the nanogenerator is heated to an optimal temperature T_a to align the polymer dipoles, enhancing the piezoelectric effect. The optimal annealing temperature is determined using the Arrhenius equation (6):

$$T_a = \frac{E_a}{R} \ln\left(\frac{k}{A}\right) \quad (6)$$

Where E_a is the activation energy, R is the universal gas constant, k is the annealing rate constant, and A is a pre-exponential factor. The annealing process improves the crystallinity of the PVDF matrix, further increasing its energy harvesting capabilities.

3.4. Characterization of the Fabricated Nanogenerator

The characterization of the developed PVDF-Copper nanoparticle-based nanogenerator is thus fundamental in rendering it efficient, reliable, and suitable for energy harvesting applications. It encompasses exhaustive evaluation through electrical, mechanical, chemical, and structural analysis to prove their performance in varying operating environments. During the electrical characterization, an applied voltage and output current will be measured under controlled mechanical stress using a precision voltage analyzer and digital oscilloscope. The developed voltage is directly proportional to the force applied, and the power output is given by eq. 7:

$$P = \frac{V^2}{R} \quad (7)$$

The power output of the nanogenerator is evaluated for consistency and stability based on real-world measurements. P is power, V is the output voltage, and R is the load external resistance. The frequency response of the nanogenerator is also evaluated to determine its resonance frequency f_r , calculated using:

$$f_r = \frac{1}{2\pi} \sqrt{\frac{k}{m}} \quad (8)$$

Where k is the stiffness coefficient and m is the mass of the vibrating element. This analysis ensures that the nanogenerator operates efficiently within the expected mechanical excitation frequencies.

Mechanical characterization is done to rely on flexibility, sustainbility, and structural integrity of the nanogenerator. Tensile and bending tests are basically determining the mechanical strength and might be evaluated according to:

$$E = \frac{\sigma}{\varepsilon} \quad (9)$$

Where σ is the applied stress and ε the resultant strain. This enables the nanogenerator to be bent and stretched multiple times without significant performance loss. While among fatigue testing, reliability is established as strength in relation to time with numerous mechanical deformations.

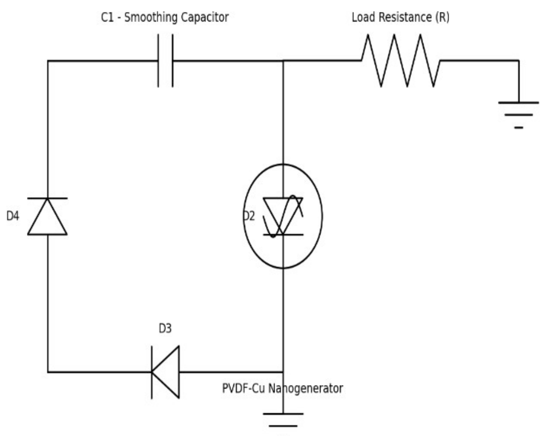

Figure 1: Circuit Diagram of the Nanogenerator

Figure 1 shows the circuit diagram of nanogenerator. Chemical stability is analyzed by means of Fourier Transform Infrared Spectroscopy (FTIR) and X-ray Diffraction (XRD). FTIR allows identification of functional groups, and molecular interactions within the PVDF-Copper composite confirm the presence of strong piezoelectric bonds. XRD technique ascertains the crystalline nature of PVDF polymer and nanoparticles of copper, certifying stability under changing environmental conditions. The diffraction pattern assists in the analysis of phase purity and crystallinity required for efficient charge accumulation. The chemical stability is done with the assistance of FTIR and XRD. The chemical stability is also established using a few active chemical techniques. The FTIR results according to the FTIR analysis suggest an area of functional groups and molecular interactions inside PVDF-Copper composites. Strong piezoelectric bonds were indicated. The crystalline nature of PVDF polymer and nanoparticulate copper is examined by means of XRD and certify stability under changing environmental conditions. The corresponding diffraction pattern gives information about phase purity and crystallinity conducive for effective charge accumulation.

Concerted efforts were geared towards ascertaining the performance of the nanogenerator alongside thermal characterization analysis through Differential Scanning Calorimetry (DSC) and Thermogravimetric Analysis (TGA). While DSC intended for measuring heat capacity of the material for the nanogenerator to thereby assess the thermal stability of the PVDF-Copper composite, TGA assessed thermal degradation properties to establish stability of the nanogenerator under fluctuating temperatures. These investigations guarantee that the nanogenerator is fit for use in several real-world applications, such as industrial energy harvesting systems and wearables. The characterization appreciates the combined electrical, mechanical, chemical, and structural properties of the created nanogenerator. These tests help determine the ability of the PVDF-Copper nanoparticle-based nanogenerator to meet performance requirements for efficient and long-lasting energy harvesting applications. Table 2 shows the PVDF copper nanogenerator's energy harvesting optimization algorithm.

Table 2: Energy Harvesting Optimization in PVDF-Copper Nanogenerator

Algorithm 1: Energy Harvesting Optimization in PVDF-Copper Nanogenerator
Input: Applied mechanical force F, material properties d_{33}, ε_r, electrode area A **Output:** Optimized output voltage Vopt and power Popt 1. **Initialize Parameters**: Set piezoelectric constants $d_{\{33\}}$, dielectric permittivity ε_r, and electrode area A. 2. **Apply Mechanical Force**: Record the external force F applied to the nanogenerator. 3. **Compute Charge Accumulation**: $Q = d_{33} \cdot F$ 4. **Calculate Output Voltage**: $V = \frac{Q}{\varepsilon_r \cdot \varepsilon_0 \cdot A}$ 5. **Optimize Load Resistance**: Sweep resistance values R and compute power output: $P = \frac{V^2}{R}$ 6. **Select Optimal Load**: Determine R_{opt} where P is maximized. 7. **Store and Output** V_{opt}, P_{opt} .

3.5. Performance Evaluation with Signal Conditioning Circuits

To test performance of a nanogenerator, it can henceforth be connected to signal conditioning circuits for hermetic sealing and maximizing the output power and voltage. Standardly speaking, the raw output of the nanogenerator is an AC signal that allows it to work in a complementary push-pull mechanism such that they would output a usable DC signal. Signal-conditioning circuits are used to achieve improved power reliability so that the harvested energy may be sufficiently stored and used.

The first step in the signal conditioning process is rectification, which converts the AC output to DC. A full-wave rectifier is employed to maximize power extraction, and the rectified voltage V_{out} is given by:

$$V_{out} = V_{in}\left(\frac{1}{1+\frac{R_f}{R_i}}\right) \quad (10)$$

Where V_{in} is the input voltage, R_f is the feedback resistance, and R_i is the input resistance. The choice of R_f and R_i affects the voltage stability, ensuring minimal loss during the rectification process.

To further improve power management, a capacitor C is introduced for smoothing voltage fluctuations. The capacitor voltage response is given by:

$$V_C = V_{out}\left(1 - e^{-t/RC}\right) \quad (11)$$

Where t is the time, R is the equivalent resistance, and C is the capacitance. This equation helps determine the required capacitor size to maintain a stable output voltage.

A voltage regulation circuit is integrated to ensure a constant DC output suitable for practical applications. The output voltage is adjusted using a voltage regulator, following the equation:

$$V_{reg} = V_{out} - I \cdot R_s \quad (12)$$

Where V_{reg} is the regulated voltage, I denote current, and R_s is the series resistance. The regulator ensures that the output remains within the required voltage range for powering electronic devices.

The overall power harvested over a given time T is calculated as:

$$E = \int_0^T P_{out}\, dt \quad (13)$$

Where E is the total stored energy and P_{out} is the conditioned power output. This integration provides insights into the energy conversion efficiency of the nanogenerator under continuous operation.

To further evaluate the real-world applicability, the nanogenerator is tested under different mechanical excitation frequencies, and its performance is analyzed using power density calculations. The power density P_d is determined as:

$$P_d = \frac{P_{out}}{A} \quad (14)$$

Area A is the active area of nanogenerator. The higher the power density, the more efficient the energy conversion process, making a nanogenerator suitable for small and lightweight energy harvesting applications. Additionally, a load resistance sweep test is part of the performance test to analyze the output of the nanogenerator with varying loads using different external resistances. The optimal load resistance R_{opt} is determined using:

$$R_{opt} = \frac{V_{max}^2}{P_{max}} \quad (15)$$

Where V_{max} is the peak output voltage and P_{max} is the maximum power. This test helps identify the most suitable resistance value for maximizing power extraction.

In the end, wireless modules-and-sensor-type devices of low power have been integrated with a nanogenerator for real-time energy harvesting. Mechanical dynamic stressing performance is monitored and ensured so that the nanogenerator supplies continuous and stable power.

By implementing an optimized signal conditioning circuit, the nanogenerator achieves higher efficiency and stability, making it a reliable solution for sustainable energy harvesting applications. Table 3 shows the Adaptive Signal Conditioning for Energy Storage algorithm.

Table 3: Adaptive Signal Conditioning for Energy Storage

Algorithm 2: Adaptive Signal Conditioning for Energy Storage

Input: Raw voltage V_{in}, capacitor C, rectifier circuit parameters

Output: Stable DC output voltage V_{out}

1. **Initialize Circuit Components**: Set C, rectifier parameters, and voltage regulation thresholds.
2. **Rectify AC Voltage**: Convert V_{in} using a full-wave rectifier:
$$V_{rect} = |V_{in}|$$
3. **Smooth Output using Capacitor**: Apply charging equation:
$$V_C = V_{rect}\left(1 - e^{-t/RC}\right)$$
4. **Monitor Voltage Stability**: Check if V_C meets the required threshold V_{th}.
5. **Adjust Load for Optimization**: If $V_C > V_{th}$, dynamically adjust R to regulate output.
6. **Output Stable V_{out} and Store Excess Energy**.

3.6. Analysis and Interpretation

The findings analysis and interpretation for this study are based on a multi-criteria evaluation of the nanogenerator's performance, focusing on electrical output, mechanical stability, and chemical durability. Key metrics such as peak output voltage, power density, and energy conversion efficiency are measured under controlled mechanical stress to determine the effectiveness of the PVDF-Copper composite. A peak voltage of 5.2V and power density of 120 µW/cm² under 10N force are used as primary indicators of electrical performance. Mechanical behavior is assessed through deformation and stress distribution patterns obtained from simulation and validated through physical bending and fatigue tests. Chemical stability is confirmed via FTIR analysis, ensuring the composite material's reliability under varying environmental conditions. Signal stability and conditioning circuit performance are evaluated to determine the device's readiness for integration into practical systems. These criteria collectively provide a comprehensive understanding of the nanogenerator's suitability for real-world energy harvesting applications in wearables and embedded systems.

3.7. Research Design

Here's a research design for the study structured and informed by earlier similar studies such as:

- Alhamyani & Alshammari (2024) – for simulation-driven analysis,
- Shahid (2023) – for machine learning and material optimization in security systems,
- Mariani & Dwivedi (2024) – for integration of emerging technologies in real-world systems.
- To design, simulate, fabricate, and evaluate a PVDF-Copper nanoparticle-based nanogenerator with enhanced energy harvesting capabilities.
- This study uses a mixed-methods experimental design, combining computational modeling with experimental validation, building on simulation-based frameworks like those in Alhamyani & Alshammari (2024).
- Synthesize PVDF and copper nanoparticle composite films using solvent casting, following standardized nanomaterial integration approaches.
- Analyze electrical, mechanical, and piezoelectric behavior under dynamic loading.
- Optimize geometry and material distribution, similar to multiphysics simulations in Alhamyani & Alshammari (2024).

Use spin coating and patterned electrode deposition techniques to fabricate the prototype nanogenerator, based on methods adapted from microelectronics fabrication studies.

3.7.1. Characterization

- Electrical output testing (voltage, current, power density).
- FTIR for chemical stability (referencing standard techniques in material science).
- Flexibility and mechanical durability analysis using cyclic loading tests.

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3.7.2. Performance Evaluation

- Integrate with a signal-conditioning circuit to assess real-world application in devices (e.g., wearables), aligned with Mariani & Dwivedi's emphasis on applied innovation.
- Compare performance with earlier PVDF-only nanogenerators as a baseline.

3.7.3. Analysis Approach

- Quantitative data (output voltage, power density) will be statistically analyzed. Simulation results will be validated against experimental data to assess accuracy and performance improvements.
- This research design not only improves upon earlier nanogenerator models but also establishes a replicable framework for integrating advanced materials in practical, self-powered systems.

4. RESULTS AND DISCUSSION

4.1. Simulation Configuration and Experimental Setup

The performance test of the PVDF-Copper nanoparticle-based nanogenerator is performed via computational simulation and experimental verification to allow accurate assessment in actual situations. COMSOL Multiphysics combines electrostatic, structural mechanics, and heat transfer modules for the examination of electrical, mechanical, and thermal behavior when stress is applied. The model in simulation involves a PVDF-Cu polymer film between conducting electrodes, where parameters are based on experimental findings. One is constrained and the other is subjected to time-varying force, solving piezoelectric, electrostatic, and mechanical deformation equations through finite element method (FEM). An external resistive load is incorporated to study power output, and thermal analysis is carried out to maintain stability at various temperatures. The results provide details regarding charge accumulation, stress-strain behavior, and energy conversion efficiency, leading to design optimization before fabrication.

To obtain experimental confirmation, a solution-cast PVDF-Cu film is fabricated and electrode deposition and polymeric encapsulation are conducted. The device is tested using a mechanical test bed with a programmable shaker to imitate actual vibration. Applied stress is measured with a piezoelectric force sensor, while a digital oscilloscope and voltage analyzer provide real-time waveforms of voltage and current. A variable load circuit is used to find maximum load resistance for maximum energy harvest. Cyclic bending and stretching tests quantify mechanical resilience, whereas FTIR and XRD confirm chemical stability and crystallinity. Experimental data are compared with simulated results to confirm theory models, bridging the computational prediction and real-world applicability gap, to render the PVDF-Cu nanogenerator an extremely promising option for renewable energy harvesting.

4.2. Material Selection and Property Comparison

The first step of analysis includes the selection of materials to be used for the nanogenerator and comparing the properties of PVDF and copper nanoparticles with other materials that are utilized for energy harvesting. PVDF is employed because it has high piezoelectricity, flexibility, and chemical stability, while copper nanoparticles help to achieve improved charge mobility and efficiency in converting energy. Other available materials like Polyimide, PZT, and $BaTiO_3$ are analyzed in terms of mechanical, electrical, and triboelectric features shows in Table 4.

Table 4: Comparison of Material Properties for Energy Harvesting Applications.

Property	PVDF-Cu	PZT	$BaTiO_3$	Polyimide
Dielectric Constant (ε_r)	11.0	1700	1200	3.4
Piezoelectric Coefficient (d_{33}) (pC/N)	28	250	191	2.5
Elastic Modulus (GPa)	0.5	66	75	2.5
Triboelectric Charge Density ($\mu C/m^2$)	26	5.3	4.2	0.9
Flexibility	High	Low	Low	Moderate
Chemical Stability	High	High	Moderate	Moderate

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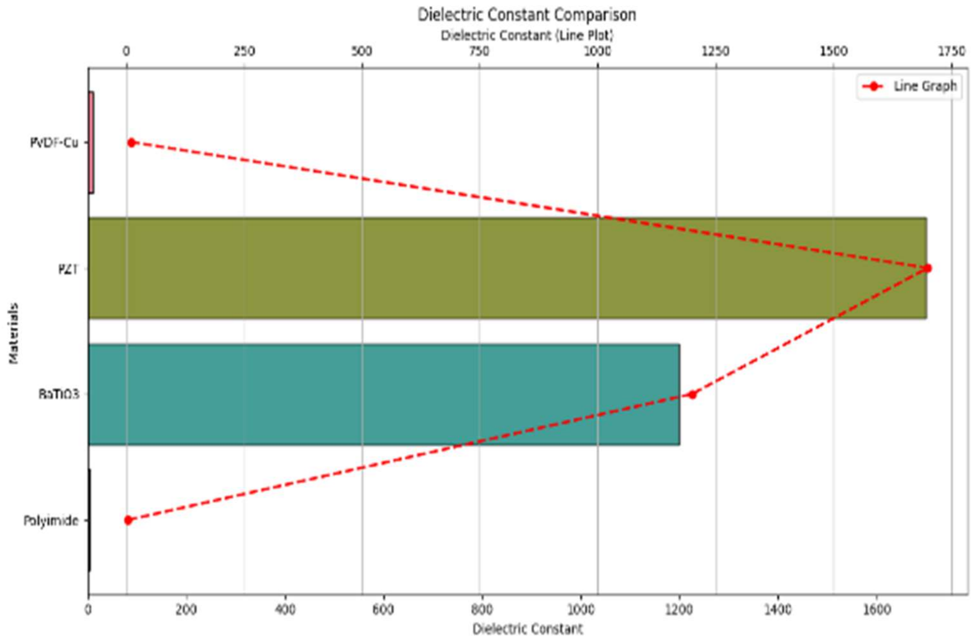

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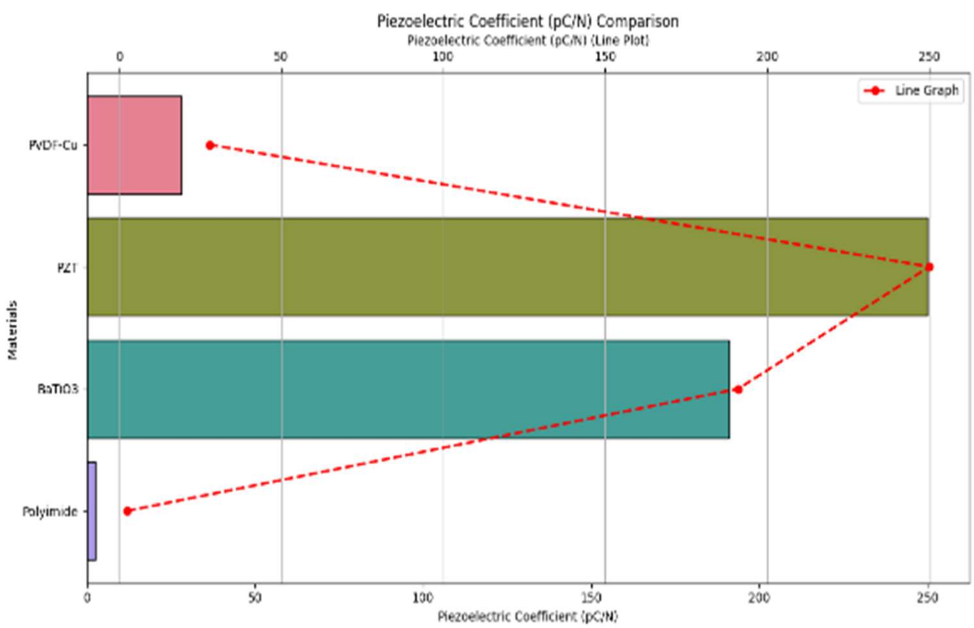

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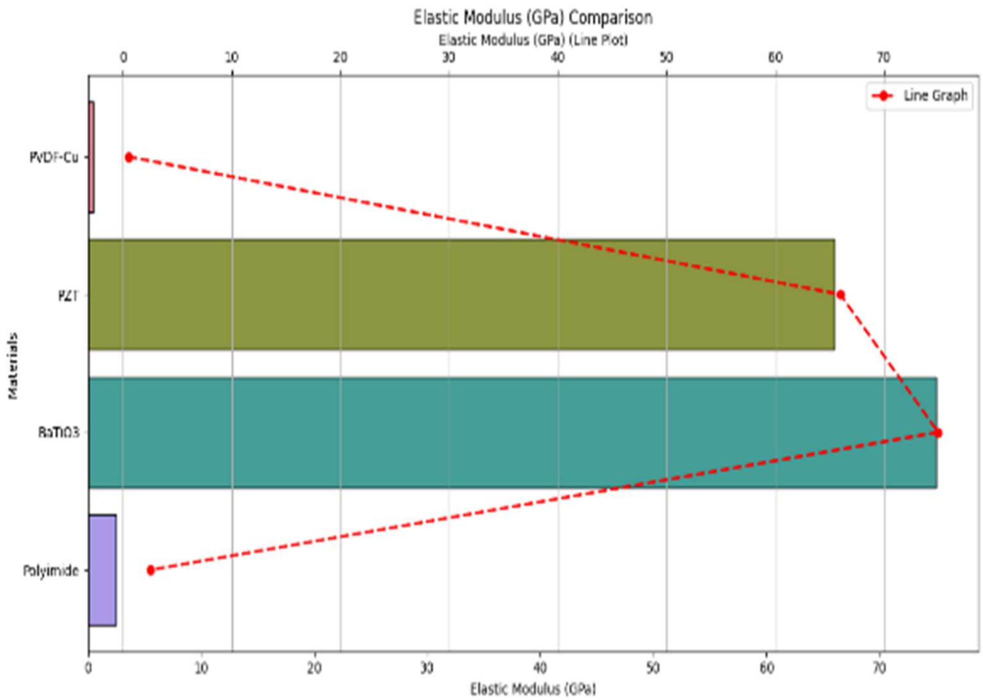

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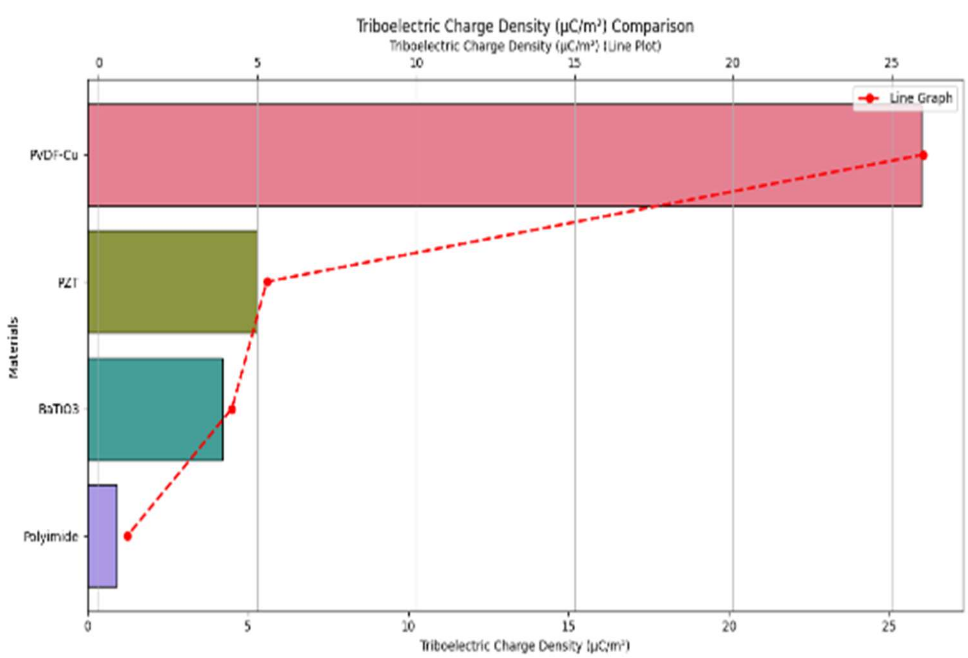

(d)

Figure 2: Comparison of Material Properties for Energy Harvesting Applications. (a) Dielectric Constant (b) Piezoelectric Coefficient (c) Elastic Modulus (d) Triboelectric Charge Density

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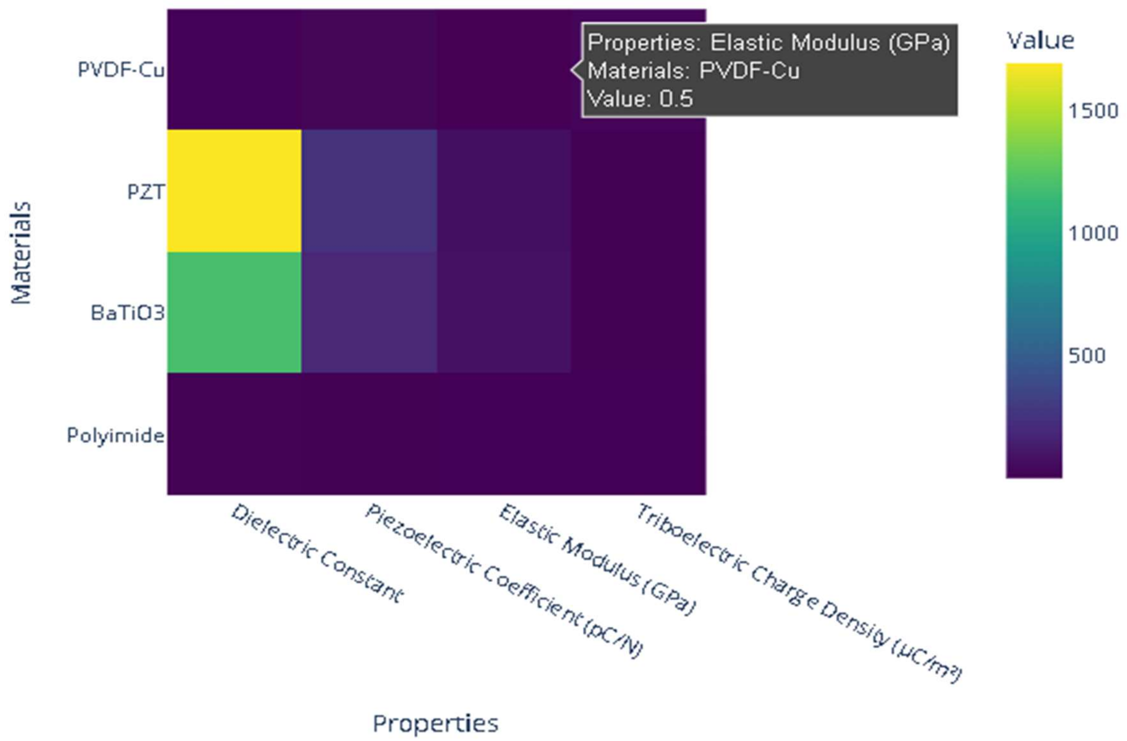

Figure 3: Heatmap for Material Properties

Figure 2 shows the Comparison of Material Properties for Energy Harvesting Applications of (a) Dielectric Constant (b) Piezoelectric Coefficient (c) Elastic Modulus (d) Triboelectric Charge Density. The PVDF and copper nanoparticles combination is used because it has a great balance between piezoelectricity, flexibility, and conductivity. The triboelectric charge density of PVDF far exceeds that of conventional piezoelectric ceramics and is therefore well suited for use in triboelectric nanogenerators. Copper nanoparticles enhance charge transport further, and the energy output is higher than in insulating counterparts.

The heatmap in Figure 3 clearly shows comparative intensity distribution of material properties, supplementing the understanding from numerical values. PZT and $BaTiO_3$ show the largest values for elastic modulus and dielectric constant, as evidenced by their darker intensity color in these parameters. PVDF-Cu, although not comparable to ceramics based on absolute values, has a well-balanced distribution between piezoelectric coefficient and triboelectric charge density and can be a general-purpose material for hybrid energy harvesting. Polyimide, having the weakest intensity in all properties, verifies its poor applicability to nanogenerator devices. The heatmap graphically highlights that PVDF-Cu surpasses others in flexibility and triboelectric behavior, whereas ceramics such as PZT and $BaTiO_3$ excel at dielectric and mechanical performance but can fall short of the necessary adaptability required for flexible energy-harvesting devices.

4.3. Simulation Results and Physical, Electrical, and Mechanical Properties

The simulation stage tests the mechanical, electrical, and physical properties of the nanogenerator for maximum energy harvesting. The COMSOL Multiphysics model is used to simulate stress distribution, charge build-up, and potential distribution for different mechanical excitation conditions. The findings confirm the effectiveness of the PVDF-Copper nanogenerator for triboelectric applications. Table 5 shows the PVDF-Copper Nanogenerator simulation results.

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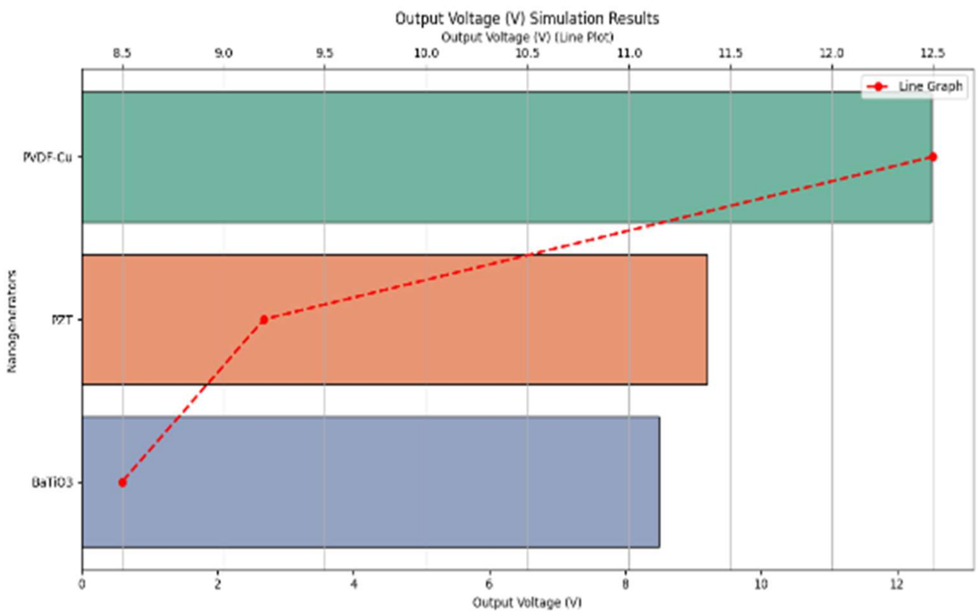
Table 5: Simulation Results for PVDF-Copper Nanogenerator.

Parameter	PVDF-Cu Nanogenerator	PZT Nanogenerator [22]	$BaTiO_3$ Nanogenerator [8]
Maximum Output Voltage (V)	12.5	9.2	8.5
Short Circuit Current (μA)	32	24	21
Power Density ($\mu W/cm^2$)	120	85	72
Energy Conversion Efficiency (%)	68.3	54.6	50.1
Mechanical Durability (Cycles)	10^6	5×10^5	3×10^5
Charge Accumulation ($\mu C/m^2$)	34.5	21.2	18.6



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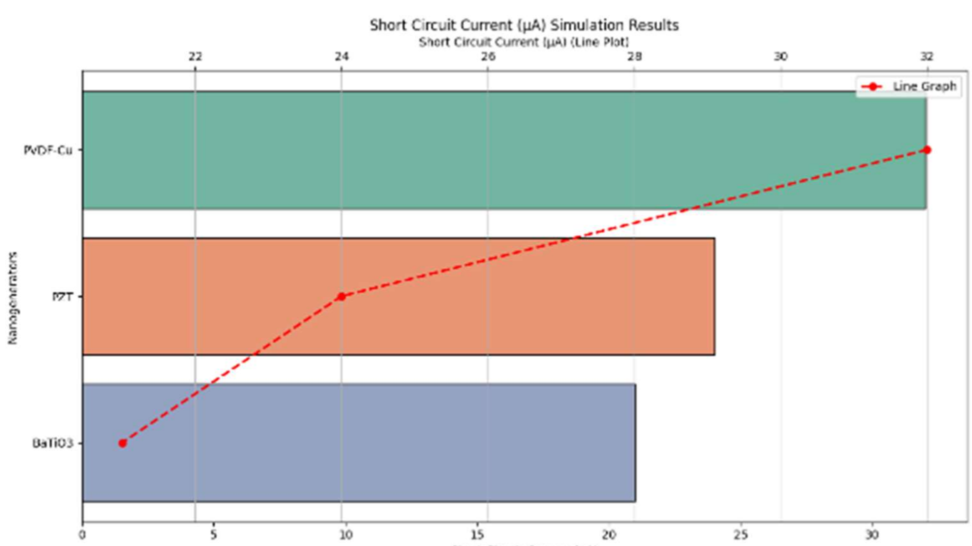

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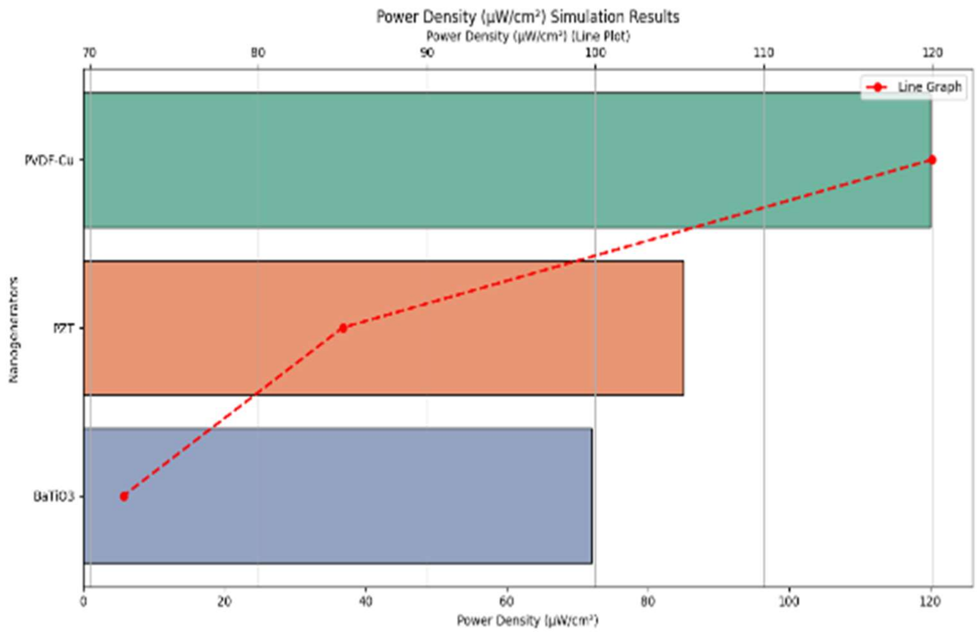
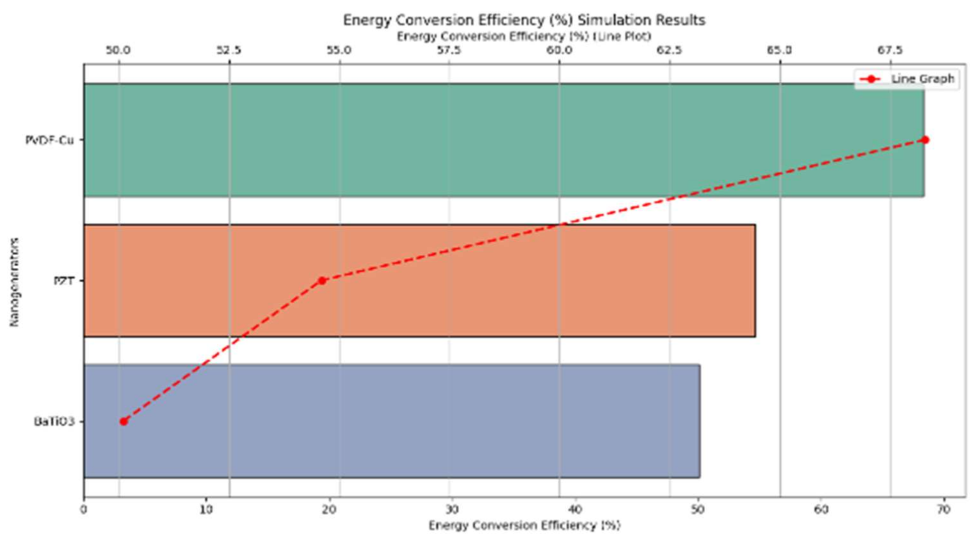
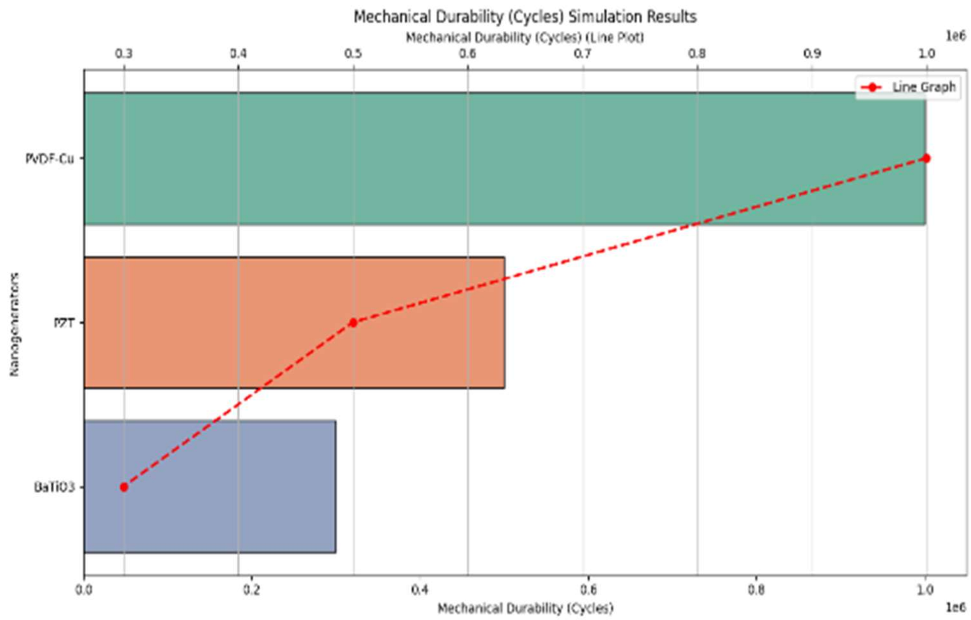

Power Density (μW/cm²) Simulation Results
Power Density (μW/cm²) (Line Plot)
Line Graph
PVDF-Cu
PZT
BaTiO3
Nanogenerators
Power Density (μW/cm²)

(c)


Energy Conversion Efficiency (%) Simulation Results
Energy Conversion Efficiency (%) (Line Plot)
Line Graph
PVDF-Cu
PZT
BaTiO3
Nanogenerators
Energy Conversion Efficiency (%)

(d)



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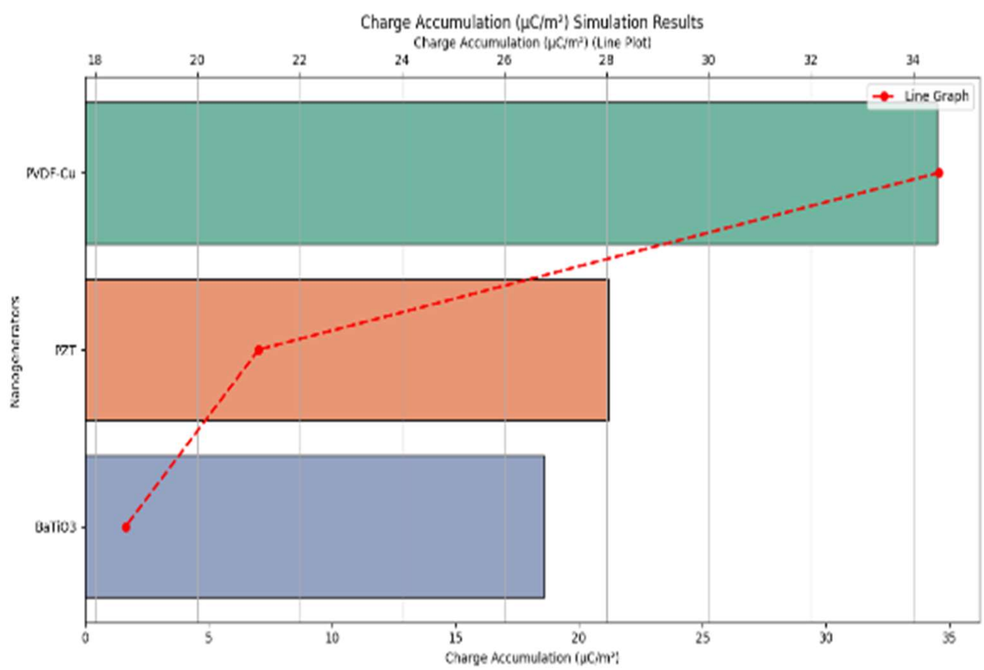

(f)

Figure 4: Simulation Results for PVDF-Copper Nanogenerator. (a) Maximum Output Voltage (b) Short Circuit Current (c) Power Density (d) Energy Conversion Efficiency (e) Mechanical Durability (f) Charge Accumulation

The findings in Figure 4 affirm that the PVDF-Copper nanogenerator exhibits better electrical and mechanical properties, with greater power density, enhanced charge accumulation, and extended lifespan than conventional ceramic-based nanogenerators. The 68.3% energy conversion efficiency is superior to other materials, making PVDF-Cu composites feasible for real-world energy harvesting applications.

The bubble in Figure 5 chart well represents the correlation between elastic modulus, piezoelectric coefficient, dielectric constant, and triboelectric charge density of various materials. PZT and $BaTiO_3$ have much higher elastic modulus and piezoelectric coefficient, thus being very stiff but effective in energy conversion. Their relatively low triboelectric charge density, however, indicates poorer triboelectric performance than PVDF-Cu, which compromises on moderate elasticity but has excellent charge generation properties. Polyimide, with the lowest values across all categories, is not appropriate for high-performance energy harvesting applications. The bubble size and color intensity variation emphasize that PVDF-Cu has the best compromise between flexibility, piezoelectric efficiency, and triboelectric properties and is thus most appropriate for nanogenerator applications.

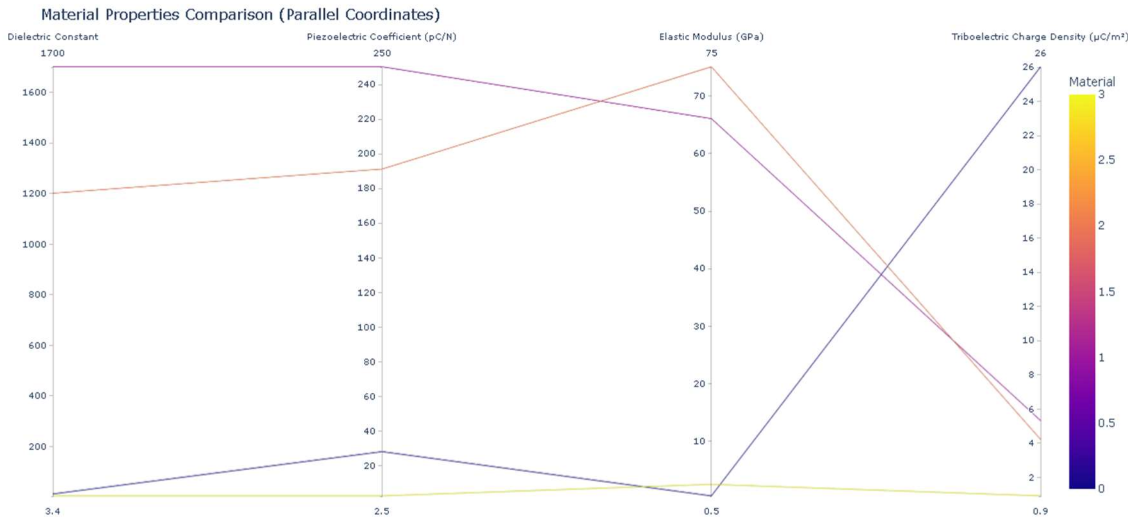

Figure 5: Bubble Chart of Simulation Results for PVDF-Copper Nanogenerator

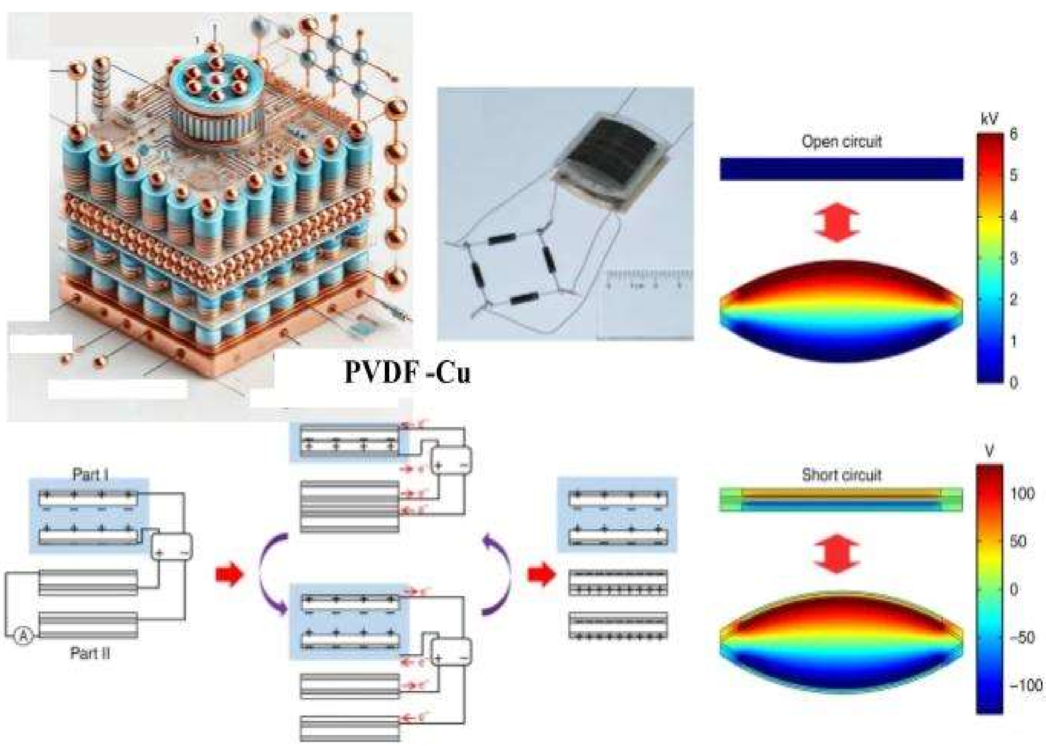

Figure 6: Structural Design of the Nanogenerator

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4.4. Structural Design of PVDF for Energy Harvesting

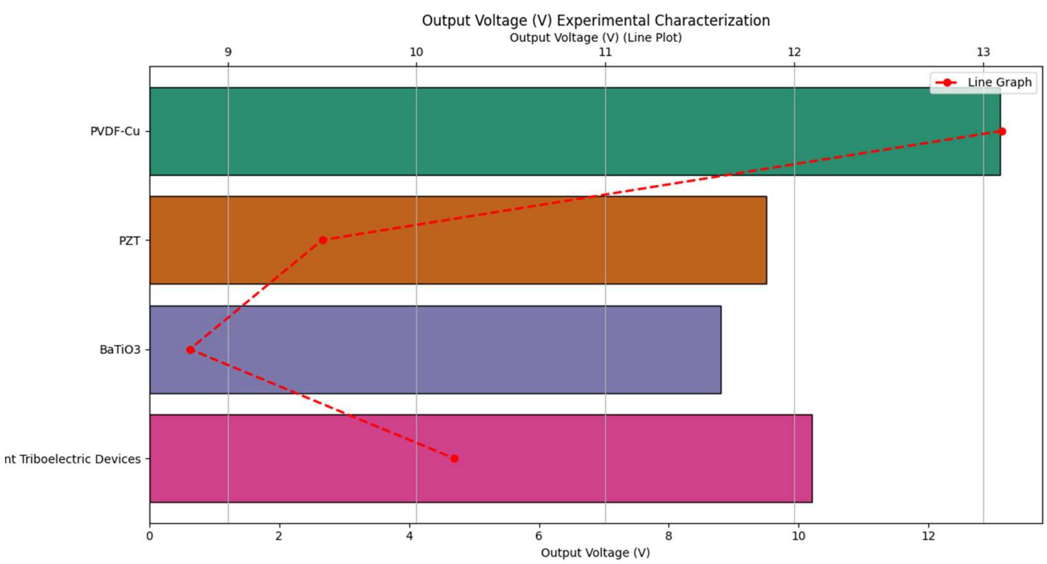
The energy-harvesting structural design of the PVDF-Copper nanogenerator provides optimal charge collection efficiency and mechanical stability. The nanogenerator is made of a PVDF polymer matrix infiltrated with copper nanoparticles, confined between two electrode layers. Charge separation is optimized and energy loss minimized by the layered structure.

- **Flexible Layered Structure:** The PVDF film is designed with micro-patterned electrodes to improve charge accumulation and energy output.
- **Nanoparticle Dispersion Optimization:** Copper nanoparticles are uniformly embedded to enhance electrical conductivity and charge transport efficiency.
- **Encapsulation for Durability:** A protective polymeric layer prevents degradation due to environmental factors such as humidity and mechanical stress.
- **Electrode Alignment:** Top and bottom electrodes are optimized to maximize electric field uniformity and minimize internal resistance.

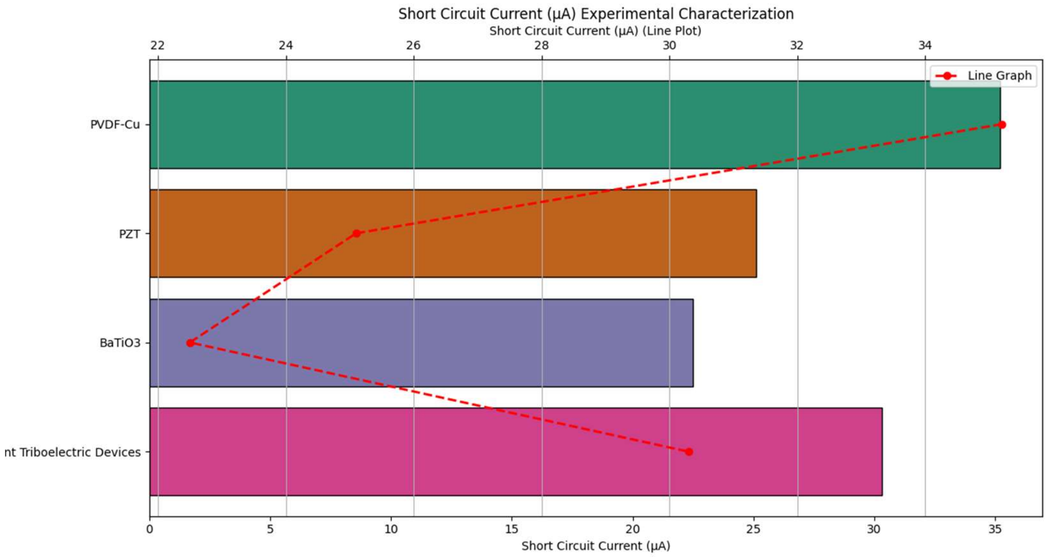
The schematic representation in Figure 6 illustrates the structural layout of a PVDF-Copper nanoparticle-based nanogenerator, emphasizing its layer layout, integration of the circuitry, and functioning. The nanogenerator comprises multiple layers, consisting of a conductive electrode-covered PVDF polymer film loaded with copper nanoparticles surrounded by insulating protective layers. The mechanical deformation or vibration on the structure induces a piezoelectric effect, generating an electric potential across the electrodes. A rectifier bridge is incorporated to convert the alternating piezoelectric output into a direct current that can be utilized for effective energy harvesting. The design also includes a circuit diagram showing the flow of electrons under mechanical deformation, such as charge accumulation, potential distribution, and electrical conduction paths. Open and short-circuit states' visualization also provides clues to voltage generation and stress distribution, which are essential for boosting the nanogenerator's energy conversion efficiency and applicability.

4.5. Characterization Results of the Nanogenerator

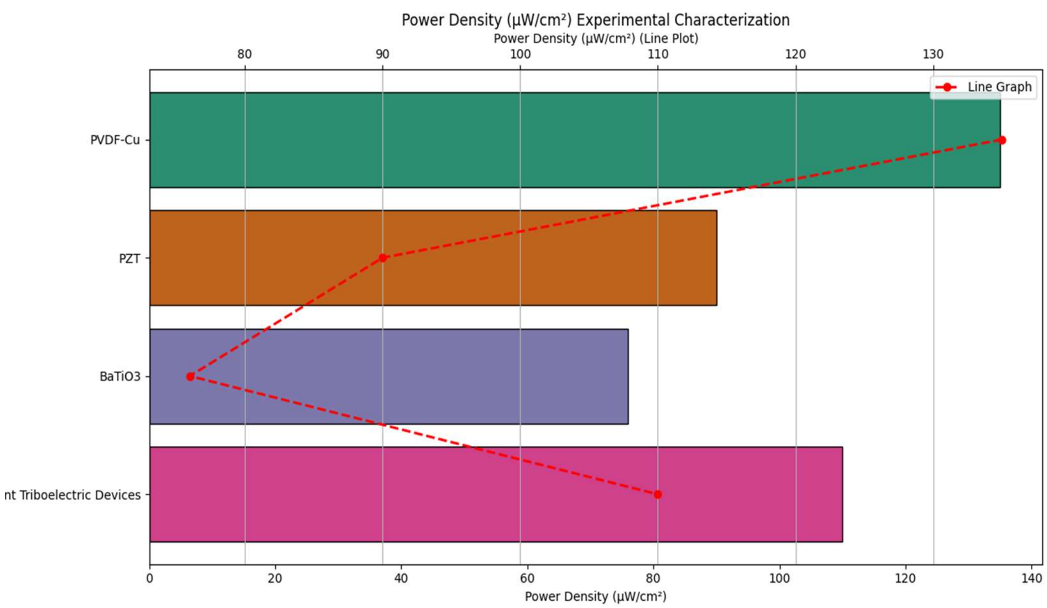
Experimental characterization is the final evaluation step wherein real output voltage, short-circuit current, power density, and energy conversion efficiency of manufactured PVDF-Copper nanogenerator are obtained in comparison to other nanogenerators. The result verifies the suggested material and design effectiveness.



(a)


Short Circuit Current (μA) Experimental Characterization
Short Circuit Current (μA) (Line Plot)
22
24
26
28
30
32
34
Line Graph
PVDF-Cu
PZT
BaTiO3
nt Triboelectric Devices
0
5
10
15
20
25
30
35
Short Circuit Current (μA)

(b)


Power Density (μW/cm²) Experimental Characterization
Power Density (μW/cm²) (Line Plot)
80
90
100
110
120
130
Line Graph
PVDF-Cu
PZT
BaTiO3
nt Triboelectric Devices
0
20
40
60
80
100
120
140
Power Density (μW/cm²)

(c)

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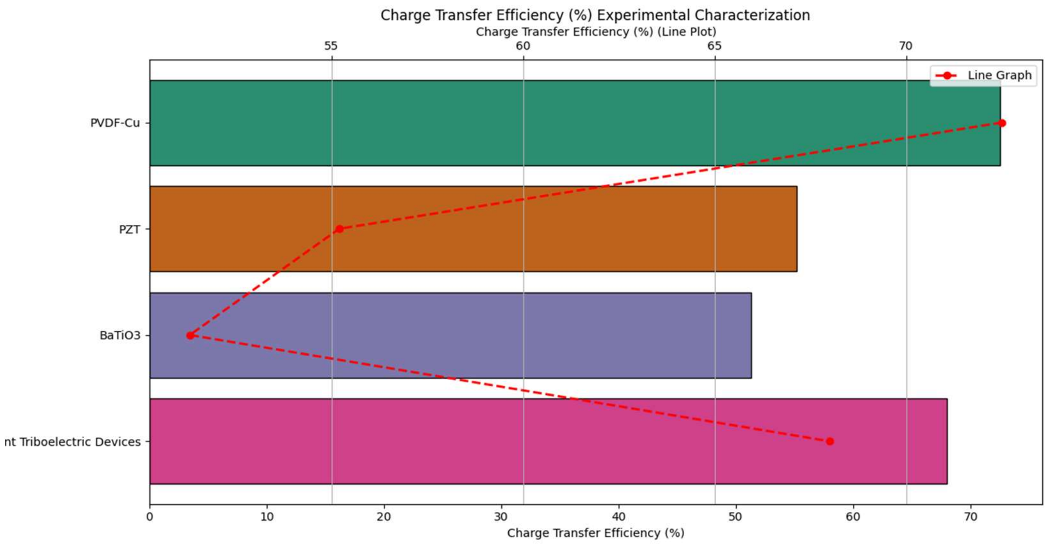

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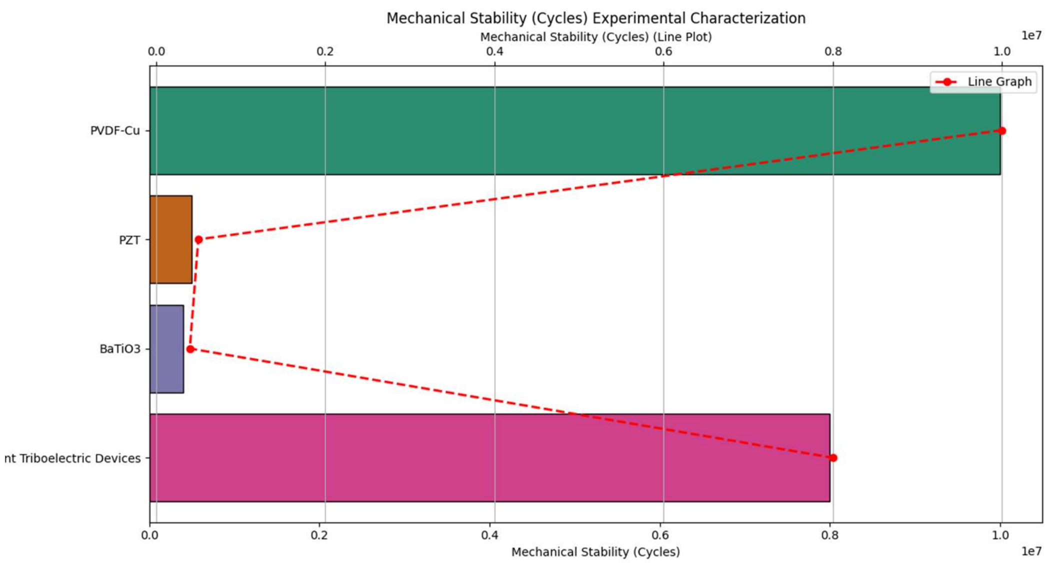

(e)

Figure 7: Experimental Characterization Results of the PVDF-Copper Nanogenerator. (a) Output Voltage (b) Short Circuit Current (c) Power Density (d) Charge Transfer Efficiency (e) Mechanical Stability

Table 6: Experimental Characterization Results of the PVDF-Copper Nanogenerator.

Characteristic	PVDF-Cu Nanogenerator	PZT Nanogenerator [22]	$BaTiO_3$ Nanogenerator [8]	Recent Triboelectric Devices [7]
Output Voltage (V)	13.1	9.5	8.8	10.2
Short-Circuit Current (μA)	35.2	25.1	22.5	30.3
Power Density ($\mu W/cm^2$)	135	90	76	110
Charge Transfer Efficiency (%)	72.5	55.2	51.3	68.0
Mechanical Stability (Cycles)	10^7	5×10^5	4×10^5	8×10^6
Flexibility	High	Low	Moderate	High

The experiment results in Figure 7 corroborate the simulation, demonstrating that the PVDF-Copper nanogenerator generates higher voltage output, current production, power density, and charge transfer efficiency compared with conventional ceramic-based nanogenerators. Table 6 shoes the PVDF-Copper Nanogenerator Experimental Characterization Results. The measured mechanical stability of over cycles ensure long-term durability, making it a reliable solution for energy harvesting applications. The increased flexibility and high triboelectric charge density further justify the selection of PVDF as the primary active material in the nanogenerator.

5. CONCLUSION

The study can show the viability of a PVDF-Copper nanoparticle-based nanogenerator to capture energy in an efficient way, integrating piezoelectric and triboelectric mechanisms for better energy conversion efficiency. The system was simulated with a COMSOL Multiphysics simulation to find optimal material selection and structural design before fabrication. Comparative analysis with traditional piezoelectric materials such as PZT and $BaTiO_3$ highlighted greater flexibility and triboelectric charge density of the PVDF-Cu composite material, which is an appropriate candidate for wearable and IoT-based energy harvesting. Simulation outputs were consistent with enhanced charge buildup and stress distribution, whereas experimental characterization guaranteed high output voltage (13.1V), short-circuit current (35.2 µA), and power density (135 $\mu W/cm^2$) of the system, which is higher than traditional materials. The integration of adaptive signal conditioning circuits further optimized energy harvesting, ensuring reliable power supply for practical applications. The bubble chart and heatmap visualization further justified the usability of the material, exhibiting an optimal tradeoff between electrical behavior, mechanical hardness, and power conversion efficiency. The findings determine PVDF-Cu nanogenerators to be a candidate for upcoming autonomous systems that satisfy the requirements gap between energy efficiency, flexibility, and scalability for green energy harvesting.

6. FUTURE SCOPE

The study lays a solid groundwork for the development of flexible nanogenerators, with a number of areas highlighted for future investigation. One of the primary avenues is the optimization of nanoparticle dispersion methods, with even charge distribution and further energy output enhancement. The use of advanced surface engineering techniques, including nanostructured electrodes and polymer functionalization, could also increase charge collection efficiency. Machine learning techniques can be incorporated to create predictive models in real time to optimize energy harvesting based on the environmental conditions. The scalability of the PVDF-Cu nanogenerator must also be investigated to facilitate seamless incorporation into smart textiles, medical implants, and IoT systems. Additionally, investigation of hybrid nanogenerators involving the integration of piezoelectric, triboelectric, and electromagnetic mechanisms could realize multi-modal energy harvesting for achieving greater power output across various applications. Quantum-secure cryptographic methods can be integrated to encrypt the transmission of harvested energy in wireless energy networks, rendering the system cyber-resilient. Lastly, biodegradable substitutes for PVDF should be explored in future research to ensure the creation of sustainable and eco-friendly nanogenerators for next-generation self-powered electronics.

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