Lead-Free BCZT-PDMS Piezoelectric Energy Harvester

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ABSTRACT

This article presents the synthesis and characterisation of lead- free BCZT (Ba₀.₈₅Ca₀.₁₅Ti₀.₉Zr₀.₁O₃) nanopowder produced by the solid-state reaction technique, employing between four to five cycles of grounding to enhance crystallinity. X-ray diffraction (XRD) and field emission scanning electron microscopy (FESEM) verified that grounding the materials five times yielded a highly crystalline BCZT with a cubic perovskite structure. The BCZT powder was filled into a polydimethylsiloxane (PDMS) matrix at different weight percentages (1%, 3%, 5%, and 10%) to investigate the performance in terms of piezoelectric coefficient and generated voltage. The BCZT-PDMS composites displayed an amorphous form attributable to the polymer matrix. While preserving the functional piezoelectric characteristics of the ceramic filler, the result shows that the 10% wt sample exhibits higher d33 measurement with 45 pC/N which increased approximately 50% compared to 5% wt. Furthermore, the performance was assessed using d₃₃ measurements and voltage production during mechanical excitation utilising a solenoid with a constant force of 2 N and a frequency of 10 Hz. The findings indicated that the piezoelectric generate voltage well with BCZT-PDMS composite with 10 wt%, yielding a maximum output voltage of 8 V. Finally, the capability of BCZT-PDMS to harvest energy has been presented in this paper.

**Keywords:** BCZT-PDMS, piezoelectric coefficient, solenoid tapping technique, energy harvester

# INTRODUCTION

Piezoelectric materials are vital in modern technology, enabling applications in sensors, actuators, and energy harvesting devices through their ability to convert mechanical stress into electrical energy [1]. Traditionally, lead-based materials like lead zirconate titanate (PZT) have been widely used due to their superior piezoelectric properties in exhibiting a balanced combination of robustness, high piezoelectric coefficients, and good thermal properties [2]. However, the environmental and health hazards of lead, including toxicity and pollution risks during manufacturing, usage, and disposal, have driven the search for safer alternatives.

Considering the environmental issues related to lead-based piezoelectric materials, significant research efforts have focused on developing lead-free alternatives that exhibit similar piezoelectric properties. Barium Titanate (BaTiO₃) has been studied extensively among lead-free piezoelectric materials due to its outstanding piezoelectric and dielectric characteristics. It has been recognized for achieving the highest sensing voltage among lead-free materials [3]. It has also shown the highest mechanical stress (6.09 MN/m² at 140 Hz), electric potential (12.2 V), and power dissipation (1.86 mW at 100 Hz) compared to Zinc Oxide (ZnO) and Barium Sodium Niobate (BNN) [4]. The excellent energy harvesting capability of BaTiO₃ corresponds to its high piezoelectric coefficients and dielectric constant, which enhance its efficiency in converting mechanical energy into electrical energy [5]. Among these coefficients, d33, the piezoelectric charge coefficient is commonly used to evaluate material performance, as it quantifies the electric charge generated per unit of mechanical stress applied along the same axis, and is expressed in picoCoulombs per Newton (pC/N).

BaTiO₃ has notable advantages in piezoelectric characteristics but it exhibits greater crystallite growth at higher temperatures, making it particularly ideal for applications that require larger crystalline structures. Meanwhile, Barium Calcium Zirconate Titanate (BCZT) demonstrates a smaller crystalline size at higher calcination temperatures. The characteristics of BCZT offer a significant benefit for applications requiring smaller crystalline sizes, as these small crystalline may enhance certain mechanical and electrical properties by improving material homogeneity and minimizing flaws [6]. The incorporation of Ca²⁺ and Zr⁴⁺ into BaTiO3 enhanced energy harvesting efficiency, illustrating the advantages of A-site and B-site doping within the perovskite structure thereby transforming it into BCZT. In addition, BCZT demonstrates major potential as a lead-free material for flexible nanogenerators, providing higher output voltage and power density in comparison to conventional BaTiO₃ and BZT [7][8].

To improve the flexibility of BCZT, a polymer matrix is integrated into the composite. Polydimethylsiloxane (PDMS) is widely used as the polymer matrix due to its incredible flexibility and biocompatibility [9]. Furthermore, the microelectrodes established in the composite exhibit incredible flexibility, enabling them to be bent or folded without sustaining any structural damage [10]. The BCZT-PDMS composite successfully harvested energy from biomechanical activities, including walking and finger tapping, generating output voltages of approximately 16.8 V when tested under walking excitation. This indicates that flexible and wearable devices are important for biomedical applications [11]. Although BCZT-based ceramics have gained attention as lead-free alternatives to conventional piezoelectric materials, limited studies have investigated compatibility with flexible polymer matrices like PDMS for low filler content applications. Most earlier studies have concentrated on either solid material, which reduces flexibility and durability, or high ceramic loading, usually greater than 15%. Furthermore, the impact of ceramic grounding cycles on crystalline and subsequent piezoelectric performance has not been thoroughly explored. Additionally, while PDMS offers excellent mechanical flexibility, its interaction with varying concentrations of BCZT filler and the influence on electrical output remain underexplored.fese

In this project, BCZT ceramic powder is synthesized by the solid-state reaction method. In fact, this technique is very preferable since it is simple and eases the fabrication process using a marble mortar and furnace for mixing, grounding, and calcination processes. The production of BCZT powder using the solid-state reaction method will produce strong mechanical properties and a stable crystalline structure, making it ideal for energy harvesting applications which need durable materials. The number of grounding cycles plays a critical role in enhancing the crystallinity of the BCZT powder, where increasing the grounding steps leads to sharper XRD peaks and more uniform grain morphology, thereby improving piezoelectric performance. In addition, PDMS is used as a polymer matrix due to its flexible and biocompatible properties. Therefore, the aim of this project is to demonstrate the characteristics of BCZT powder and BCZT-PDMS composite and to evaluate its performance in generating usable power by developing efficient piezoelectric materials for energy harvesting that can lead to self-powered devices. This research presents a novel approach by optimizing the crystalline of BCZT ceramic through a few grounding processes and integrating it into a PDMS matrix at low weight percentages ranging from 1 to 10%. At the end of the research, the performance of BCZT-PDMS is evaluated by mimicking biomechanical behaviors using solenoid tapping.

# METHODS AND MATERIAL

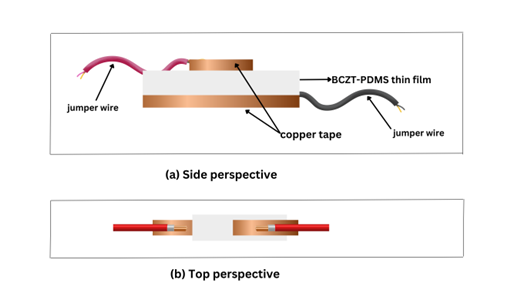
This project focuses on the development of flexible lead-free piezoelectric material using BCZT as the piezoelectric component. To enhance the material’s flexibility, PDMS is combined with BCZT powder. The development of piezoelectric material involves the fabrication and synthesis of BCZT powder, preparation of the BCZT-PDMS composite, and testing of the piezoelectric samples in terms of piezoelectric composite and output voltage. These steps are defined to ensure that the resulting material meets both piezoelectric properties and flexibility, suitable for energy harvesting applications. The methodology includes precise control over the material and testing preparation, ensuring consistency sample characteristic for testing and evaluation. Each step in the process is carefully explained to ensure the reproducibility and reliability of the final product. BCZT ceramics powder is prepared using the conventional solid state reaction method. The BCZT ceramics powder consists of Barium Carbonate (BaCO3), Calcium Carbonate (CaCO3), Zirconium (IV) Oxide (ZrO2) and Titanium (IV) Oxide (TiO2) from Sigma Aldrich (St. Louis, Missouri, United States) were composite weigh using stoichiometric composition of Ba(0.85)Ca(0.15)Zr(0.1)Ti(0.9). Then, the composites are mixed and poured into a mortar for grounding process. A small amount of acetone is used to mix the composite until a uniform BCZT ceramic powder is synthesized. The ceramics powder is then heated at 80⁰C for 15minutes to remove the residual moisture from the ceramics powder and make sure it thoroughly dried. Based on previous study, the repeatable grounding process is needed to get the fine crystal structure of BCZT [6]. The grounding and drying process are repeated four and five times to achieve homogeneity in the material. Lastly, the dried ceramics powder is poured into a crucible to be calcined by heating again at 1200⁰C for 5 hours. The temperature of 1200⁰C is used since it is an optimum temperature for BCZT ceramics powder to crystallize [6]. The BCZT sample was then synthesized for material properties using X-ray Diffraction (XRD) (RIGAKU/D/MAX-2000/PC, Akishima, Tokyo, Japan) and FESEM(JEOL, JSM-7600F,Akishima, Tokyo, Japan) to observe the crystalline and surface morphology.

Then, the PDMS solution serves as a polymer matrix to enhance the flexibility of the BCZT ceramic powder. To fabricate the BCZT-PDMS composite, BCZT ceramics powder is weighed to the desired weight percentage, from 1%, 3 %, 5% and 10% as depicted in Figure 1 (b). Based on previous studies, the weight percentage was tested between 10% and 20%, with the optimum performance observed at 15%. Therefore, in this research, the weight percentage was intentionally kept below 15%[12]. These percentages are calculated based on the weight of the PDMS solution. Then, the PDMS solution and its bonding agent (silicone elastomer curing agent) weighed in 10:1 ratio. The bonding agent is added into PDMS solution to facilitate the hardening process and transform the solution into a solid and flexible material. The weight percentage of BCZT ceramics powder is then mixed into the solution to ensure even distribution. The BCZT ceramics powder is spread to achieve a uniform layer of thin film as it is essential for consistent material properties. To eliminate air bubbles and ensure the thin film is well-compressed, the mixture is subjected to a degassing process using vacuum chamber for 15 minutes. Lastly, the solution is cured by heating the mixture in the furnace for 45 minutes to produce a BCZT-PDMS thin film. The thin film cools down at the room temperature before peeling off the BCZT-PDMS sample from the petri dish.

A diagram of a diagram of a weighting process

AI-generated content may be incorrect.Figure 1: The fabrication process a) BCZT fabrication b) BCZT-PDMS thin film fabrication

The BCZT-PDMS composite requires conductive components such as copper tape and jumper wires to exhibit the electrical charge. The preparation of the sample for the testing process is shown in figure 2. The sample preparation begins by cutting the BCZT-PDMS thin films into 2 cm x 1 cm sizing. Then, the copper tape is attached to the samples. A 2 cm x 1 cm of copper tape is attached to the top which indicates the positive side of the sample while a 1cm x 1cm of copper tape is attached at the bottom to indicate the negative side of the sample. Copper wires are then connected to both sides of the samples to ensure proper electrical contact. Lastly, the sample is sealed with a plastic cover and tape to secure it.



1. Cross section
2. Top side

Figure 2: The device consists of a BCZT-PDMS composite thin film placed between two copper tape electrodes.: a) cross section perspectives, b) top side perspectives

## Piezoelectric Coefficient

The piezoelectric coefficient (d33) has been constructed using d33 meter to evaluate the performance of BCZT-PDMS composite through the integration of mechanical force and precise electrical measurement. Firstly, the sample is properly positioned between the upper and lower probes of the testing equipment to ensure a constant pressure application on the sample. The force head serves to control the applied force, while the adjusting knob allows a precise measurement of the mechanical force exerted. The mechanical energy generated by the pressure applied can lead to the production of electrical charges in the piezoelectric material. The upper and lower probes function as electrodes to capture the electrical charge generated by the samples. The signal conditioning unit will amplify the electrical signal in precise measurement by filtering out undesired noise, thereby ensuring that the processed data is accurate and appropriate for analysis. The data was subsequently transmitted to the readout chassis, where the piezoelectric coefficient results were calculated and displayed in picoCoulombs per Newtons (pC/N), allowing direct observation for analysis. The experiment is conducted again for the samples with 1%, 5%, and 10% weight percentage of BCZT. Based on the previous study, the optimal percentage was found to be 15% [12]. Therefore, this experiment was conducted with values below 15% to investigate whether the optimum can be achieved at a lower value.

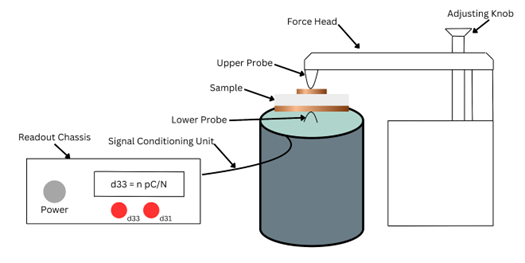


Figure 3: Piezoelectric Coefficient Testing Set up

## Voltage Output

To evaluate the piezoelectric performance, the experiment was conducted using solenoids and operated at a fixed frequency and force. In this setup, the solenoid served as a tapping mechanism, applying a mechanical force of 2 N at 10 Hz, with a displacement of approximately 2 mm and an actuation duration of 50 ms per cycle. This controlled impact was repeated continuously to simulate periodic mechanical stress for energy harvesting evaluation as shown in Figure 4. Oscilloscope (KEYSIGHT/DSOX2022A, Santa Rosa, California, U.S)

A diagram of a machine

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Figure 4: Characterisation setup

# RESULTS AND DISCUSSION

The atomic structure, phase purity and quality of fabricated BCZT ceramics powder can be determined by X-Ray Diffraction (XRD) analysis. The pattern shown in figure 5 demonstrates the comparison between four to five times ground process which shows the sharp and well-defined peaks of the synthesized BCZT powder indicating the BCZT powder is well-synthesized. The BCZT powder possesses a high crystalline structure due to the presence of high intensity peaks at 2-theta values, particularly the prominent peak at approximately 32⁰ shows that the cubic crystal structure of BCZT was formed in the calcination temperatures of 1100°C and the diffraction peaks match the patterns expected for perovskite structures, which represent the crystal structure of BCZT ceramics [6]. Figure 5 presents the diffraction pattern of the sample ground five times, exhibiting significantly sharper and more intense peaks compared to the sample subjected to four grounding cycles. This indicates that the higher number grounded process possesses higher crystal structure, and a well-defined crystal structure. Perovskite structure exhibits high phase purity, with no additional or unexpected peaks, indicating that the sample is solely BCZT with minimal impurities. The crystallite size of BCZT was determined using the Scherrer equation based on the XRD peaks at 2θ = 31.500° for the sample ground five times, and at 2θ = 31.440° for the sample ground four times. The results indicate an approximate size of 263 Å = 26.3 nm for the five-time ground sample, and 304 Å =30.4 nm for the four-time ground sample. This nanometric grain size is indicative of fine crystallite formation, which is desirable in piezoelectric ceramics for enhanced electromechanical properties. A quantitative comparison of peak broadening was performed via Full Width at Half Maximum (FWHM) analysis. The FWHM of the main peak for BCZT ground was found to be lower than that of BCZT ground four times which is 0.2980 and 0.3420 suggesting a relatively larger crystallite size and/or lower micro strain in the five times ground sample. This implies improved crystallinity and possibly enhanced ferroelectric or piezoelectric performance. Such peak narrowing in the XRD profile can be attributed to optimized synthesis conditions, which promote better grain growth and phase formation. The presence of impurities could negatively impact the piezoelectric properties. Since the capability of converting mechanical energy to electrical energy is dependent upon the crystallinity of BCZT, a high-crystallinity structure facilitates better interaction with the polymer in the composite, thereby enhancing the performance of the BCZT-PDMS composite in energy harvesting applications. The XRD pattern proves the results align with the expected properties of BCZT materials, hence validating the effectiveness of the synthesis process in producing the crystalline material.



Figure 5: XRD comparison results between five times and four times ground process for BCZT powder

The surface morphology, microstructure and topography of materials with high resolution of BCZT powder is employed by characterization technique. Field emission scanning electron microscopy (FESEM) is utilized to ascertain these characteristics of the materials. The FESEM demonstrates a granular morphology that possesses a rough and grainy structure, exhibiting particles of irregular shapes and sizes which a typical characteristic of synthesized powders [13]. Figure 6 (a) displays a rough, granular morphology with a wide distribution of particle sizes. The presence of both fine and coarse particles suggests incomplete particle breakdown and partial agglomeration, likely due to insufficient grounding or the high-temperature calcination step. The irregular particle shapes and rough surface texture are characteristic of typical ceramic powders post-synthesis. Figure 6(b), although at the same magnification, highlights larger, faceted grains with clearer crystalline edges, indicative of the material’s inherent crystallinity. In contrast, Figures 6(c) and 6(d) illustrate the microstructure of powders ground five times. Image 6(c) reveals more uniform and finer particles, with improved dispersion and reduced agglomeration, which is beneficial for sintering and homogeneity in composites. Image 6(d), taken at higher magnification, shows well-defined, densely packed crystalline grains with smoother surfaces, suggesting improved particle uniformity and crystallinity because of the extended grounding process. For quantitative comparison, the particle size for four and fivetimes ground was estimated from FESEM images. The average crystallite size for BCZT five times ground was found to be approximately 6.1 nm, compared to 6.6 nm for BCZT four times ground, confirming the observed refinement in particle size. Unfortunately, surface roughness was not quantified in this study, as no AFM or profilometry measurements were conducted. As the comparison in XRD the grain size for five times grounded process is smoother and uniform compared to four times grounded process in line with the theoretical. Based on the FESEM it also shows that the number and the intensity of grounding steps effect the grain size of BCZT. However, over grounding may introduce defects or contamination from the mortar or pestle which can affect the grain boundary behaviours. These morphological characteristic matches the requirement for piezoelectric applications due to direct impact on the material’s ability to convert mechanical energy into electrical energy. The crystalline and homogeneous structure of BCZT particles enhance the performance of the final BCZT-PDMS composite for energy harvesting.

Close-up of several different types of crystals

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Figure 6: The structure of BCZT powder under FESEM: a) four times ground, b) four times ground c) five times ground d) five times ground

Table 1: Summary of results four times and five times ground BCZT

|  |  |  |
| --- | --- | --- |
| Parameter | 4× Ground | 5× Ground |
| 2θ (main peak) | 31.440° | 31.500° |
| Crystallite size (Scherrer) | 304 Å (30.4 nm) | 263 Å (26.3 nm) |
| FWHM | 0.3420 | 0.2980 |
| Morphology (FESEM) | Larger, irregular grains | Smaller, more uniform grains |
| Estimated grain size (FESEM) | 6.6 nm | 6.1 nm |
| Crystallinity | Lower, more agglomeration | Higher, better phase purity |

Table 2: FESEM-Based Microstructural Comparison of BCZT

|  |  |  |  |
| --- | --- | --- | --- |
| Parameter | Mureddu et al. [17] | Sharma et al. [16] | This Research |
| Grounding method | **Attrition milling** (1× and 2×) | **Ball milling for 6 hours** using zirconia balls | Manual grinding (4× and 5× cycles) |
| Grain Size (FESEM) | Not quantified; described as *fine*, dense grains | 2.9–3.5 μm (micron-sized grains) | 6.6 nm (4× ground) vs 6.1 nm (5× ground) |
| Grain Morphology | Densely packed, uniform microstructure | Large, faceted grains with clear boundaries | Granular, more uniform with 5× grinding |
| Microstructure Summary | Dense and homogeneous | Coarse-grained, typical of sintered bulk ceramics | Fine and homogenous (5× ground) |

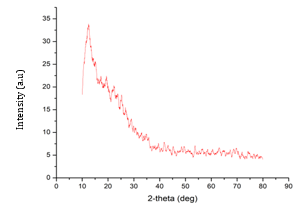
The structural characteristics of the BCZT–PDMS composite must be examined prior to testing to evaluate its suitability for further application. X-ray diffraction (XRD) analysis was conducted on composite samples with varying BCZT weight percentages. The XRD pattern of the BCZT–PDMS sample exhibits a broad and low-intensity peak, with a prominent diffraction peak observed at 11.34° (2θ). The full width at half maximum (FWHM) of this peak is 0.03°, which corresponds to a crystallite size of approximately 3013 nm, indicating a high degree of crystallinity and minimal lattice distortion. The narrow FWHM suggests well defined crystal domains, confirming the structural integrity of the ceramic component within the composite. Despite the presence of a crystalline peak from BCZT as shown in figure 7, the overall XRD pattern displays a broad, low intensity profile between 10° and 30° (2θ), characteristic of an amorphous or semicrystalline structure. This is attributed to the dominant PDMS material, which is inherently amorphous. Compared to pure BCZT powder, which exhibits sharp and intense diffraction peaks, the reduced peak intensity in the composite indicates that the BCZT particles are dispersed in a non-crystalline form within the PDMS matrix. This dispersion may suppress the crystalline contribution but can still enable uniform particle distribution. Such dispersion, even in the absence of sharp crystalline peaks, can enhance the piezoelectric response of the composite by ensuring consistent stress transfer under mechanical deformation.

Figure 7: X-Ray Diffraction of BCZT-PDMS

## Piezoelectric coefficient d33 measurement

The piezoelectric response is crucial for piezoelectric material to evaluate the material’s capability to generate electrical charge under mechanical stress. The trend graph of piezoelectric coefficient (d33) against the percentage of BCZT composite materials is shown in Figure 8. With an increase in the weight percentage of BCZT, the d33 values increase, resulting in higher efficiency in the conversion of mechanical energy into electrical charge. The maximum peak on the graph is observed at a BCZT concentration of 10%, which produced a value of 45 pC/N. As the theory the pure BCZT ceramics usually will has higher d33 compared to composited BCZT which can exceed 100pC/N due to it dense, crystalline structure, but it lacks in flexibility. In contrast flexible BCZT-PDMS composites typically achieve lower d33 values but offer mechanical compliance desirable for wearable and soft electronic applications [15]. The graph trend indicates that increasing the BCZT concentration could improve the piezoelectric response and its ability to generate electrical charge when mechanical stress is applied. It has been proved that the BCZT-PDMS composite exhibits great piezoelectric response. At lower concentrations of BCZT, the amount of active material is insufficient for exhibiting a significant piezoelectric effect. Meanwhile, at higher concentrations of BCZT in the thin film, there is a notable enhancement in the alignment of piezoelectric domains, leading to improved d33 values.



Figure 8: Piezoelectric Coefficient (d33)

## Testing and Experimental

The analysis of graph emphasizes the identification of peak values of output voltage and the output signal stability the force is set to 2 N, and the frequency is at 10 Hz. The voltage-time graph of the BCZT-PDMS thin film demonstrates periodic voltage spike when the nanogenerator is applies the mechanical excitation to the thin film under various BCZT weight percentage indicating the successful generation of electrical signals. The presence of the voltage spikes is showing piezoelectric properties which mean the BCZT-PDMS thin film is converting mechanical energy to into electrical energy. The consistency of the peaks shows the composite film is responsive to the applied mechanical stress (tapping) and showcasing its piezoelectric behaviour.

The variation on the peak voltage varies in different weight percentage of BCZT powder in the thin film. The higher peak indicates the stronger energy conversion of mechanical stress into electrical charges. At 1% weight percentage of BCZT, the output voltage is very minimal which approximately 2.5V due to low concentration of BCZT powder. As the weight percentage of BCZT increases at 3%, the output voltage slightly increases to approximately 4.5V. While, at 5%, the output voltage is 6 V, which is lower than at 10 %. The output reaches a peak of approximately 8 V at 10%, suggesting that this concentration provides the optimal balance between particle distribution and mechanical coupling within the composite As shown in Figure 8(d), when the BCZT content is increased to 10 wt%, the composite still maintains good flexibility and allows efficient stress transfer to the BCZT particles, resulting in the highest voltage output. In contrast, the lower BCZT concentration at 5 wt% may not provide enough interconnected piezoelectric regions to effectively convert mechanical stress into electrical energy. Consequently, the output voltage of the 5 wt% sample is approximately 25% lower than that of the 10 wt% sample.



Figure 9: Voltage output using solenoid tapping

Table 3: Summary of the Output Performance of Piezoelectric Nanogenerators Fabricated Using Various Piezoelectric Materials

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Study | Bczt content | **d₃₃ (pC/N)** | Voltage (v) | material |
| This work | 10 wt% | 45 | 8 | BCZT (solid-state, lab-synthesized), PDMS |
| Gao et al. | 8 vol% | 6 | 28.8 | BCZT (solid-state), PDMS (Sylgard 184) |
| Buatip et al.[7] | 15 wt% | Not reported | 13 | BCZT + MCNT, PDMS |
| Missaoui et al.[8] | 15wt% | Not reported | 13 | BCZT + MCNT,PDMS |

# Conclusion

In this study, BCZT (Ba₀.₈₅Ca₀.₁₅Ti₀.₉Zr₀.₁O₃) nanopowder was successfully synthesized via the solid-state reaction method, with variations in grounding cycles (1,2,3,4 and 5 times) to reduce crystal size. X-ray diffraction (XRD) and field emission scanning electron microscopy (FESEM) analyses confirmed that grounding the precursor materials five times resulted in enhanced crystallinity of the BCZT, with a well-defined cubic perovskite structure. To develop a flexible and eco-friendly piezoelectric energy harvester, the synthesized BCZT was embedded in a PDMS (polydimethylsiloxane) matrix at varying weight percentages (1%, 3%, 5%, and 10%). The structural analysis revealed that while pure BCZT retains its crystalline structure, the BCZT-PDMS composites exhibit an overall amorphous nature due to the polymer matrix dominance. The piezoelectric performance, evaluated by measuring the piezoelectric charge coefficient (d₃₃) and output voltage generation under a consistent mechanical stimulus with the setup of 2 N force and 10 Hz frequency via solenoid tapping. The results show that increasing BCZT content in the PDMS matrix enhances the d33​ value, reaching 45 pC/N at 10% BCZT loading, which falls within the reported optimal range of 5–60 pC/N for BCZT–PDMS composites. Notably, the 10 wt% BCZT-PDMS composites produced the highest output voltage of 8 V. Therefore, a 10 wt% BCZT loading in PDMS is identified as the optimal composition for achieving high piezoelectric output in flexible energy harvesting applications. This work highlights the potential of BCZT-PDMS composites as a promising candidate for self-powered, sustainable electronic devices. Although the BCZT-PDMS composite demonstrates potential efficiency, this research did not evaluate its long-term durability under repetitive stress or real-world conditions such as humidity or human movement, hence constraining its practical assessment. In order to improve multifunctionality and conduct durability tests to guarantee long-term reliability, future research should investigate more on filler and material. With its flexibility and biocompatibility, the composite holds strong potential for wearable health monitoring, smart footwear energy harvesting, and tactile sensing in human-machine interfaces.

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