STM JOURNALS

Journal of
Polymer & Composites

https://journals.stmjournals.com/jopc

ISSN: 2321-2810 (Online)
ISSN: 2321-8525 (Print)
Volume 14, Issue 5, 2026
September–October
DOI (Journal): 10.37591/JoPC

Research JoPC

# Self-Powered Piezoelectric Nano-Polymer Networks with Embedded Wireless Nodes for Distributed IoT Sensor Platforms

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***Abstract***

*Self-powered sensing systems are emerging as a promising solution for next-generation distributed Internet of Things (IoT) platforms, where lightweight, flexible, and low-maintenance devices are required for continuous monitoring. In this work, a self-powered piezoelectric nano-polymer network based on poly-vinylidene fluoride (PVDF) reinforced with $BaTiO_3$ nanoparticles and multiwalled carbon nanotubes (MWCNTs) was developed for flexible wireless sensing applications. The composite was designed to combine mechanical flexibility, enhanced piezoelectric response, and real-time wireless data transmission within a single material platform. The fabricated nanocomposite film was prepared through solution casting, electrical poling, and electrode integration, followed by coupling with an ESP32 wireless node for IoT-based signal acquisition. Structural and electromechanical evaluation showed that the optimized PVDF/ $BaTiO_3$ / MWCNT network generated a stable open-circuit voltage of up to 8.9 V under applied mechanical loading and retained nearly 90% of its initial output after 1000 bending cycles, demonstrating good durability and flexibility. The output voltage also increased with actuation frequency, reaching 9.6 V at 5 Hz, confirming reliable dynamic sensing performance. Wireless monitoring experiments further verified that the generated voltage signals could be successfully transmitted in real time to a remote interface. Overall, the developed piezoelectric nano-polymer network provides an effective route toward flexible, self-powered, and wireless IoT sensor platforms for structural, wearable, and environmental monitoring applications.*

**Keywords:** Nano-polymer, multiwalled carbon nanotubes, electromechanical evaluation, poly-vinylidene fluoride, piezoelectric response

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Received Date: July 25, 2026
Accepted Date: August 08, 2026
Published Date: August 14, 2026

**Citation:** R. Nathiya, Deobarat Kumar Chandan, S. Duraisivam, K. Kannan, J. B. Veeramalini, B. Parvathi Sangeetha, Ashok Kumar Chaudhary, Jayarama Pradeep, Rajendiran M. Self-Powered Piezoelectric Nano-Polymer Networks with Embedded Wireless Nodes for Distributed IoT Sensor Platforms. Journal of Polymer & Composites. 2026; 14(5): 171–182p.

## INTRODUCTION

The rapid expansion of the Internet of Things (IoT) has created a strong need for sensor platforms that are not only miniaturized, flexible, and lightweight, but also capable of operating autonomously without frequent battery replacement

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or wired power supply. Conventional distributed sensor nodes often rely on electrochemical batteries, which add bulk, limit deployment lifetime, and increase maintenance cost in large-area monitoring networks. These limitations are especially significant in applications, such as wearable health monitoring, smart infrastructure, industrial automation, structural health monitoring, and precision agriculture, where numerous sensor nodes must be distributed over wide areas or integrated onto deformable surfaces [1–3]. As a result, self-powered sensing systems have emerged as an important research direction for next-generation IoT technologies, aiming to combine sensing, energy harvesting, and wireless communication in a single compact platform [4–6].

Among the available self-powered strategies, piezoelectric polymer nanocomposites are particularly attractive because they can directly convert mechanical deformation, vibration, pressure, and motion into electrical signals or usable electrical energy. Unlike brittle ceramic piezoelectrics, such as lead zirconate titanate (PZT), piezoelectric polymers offer key advantages including low density, flexibility, mechanical durability, corrosion resistance, and compatibility with large-area solution processing [7–9]. These features make them highly suitable for distributed IoT sensor platforms, where the sensing layer often needs to conform to curved surfaces, survive repeated bending, and function under continuous mechanical excitation. From a materials perspective, piezoelectric nano-polymer systems represent a promising class of multifunctional polymer composites, in which the polymer matrix acts not only as a structural support but also as an active electromechanical transduction medium [10–13].

The most widely studied piezoelectric polymer in this field is poly(vinylidene fluoride) (PVDF) and its copolymers, such as P(VDF-TrFE), owing to their excellent flexibility, chemical stability, ferroelectric behavior, and relatively high piezoelectric response among polymeric materials [14–17]. The piezoelectric properties of PVDF-based systems are strongly associated with the formation of the β-phase crystalline structure, in which aligned dipoles generate polarization under applied mechanical stress. However, pristine PVDF generally exhibits limited piezoelectric output because of incomplete β-phase crystallization, relatively low dielectric constant, and restricted charge collection efficiency [18]. To address these limitations, extensive research has focused on piezoelectric nano-polymer networks containing functional nanofillers such as $BaTiO_3$ nanoparticles, ZnO nanowires, carbon nanotubes, graphene derivatives, MXenes, and conductive metallic nanostructures. These nanoscale reinforcements can improve piezoelectric performance by promoting β-phase formation, increasing dielectric polarization, enhancing stress transfer, and in some cases introducing conductive pathways that facilitate charge transport to the electrodes [19].

From a polymer-composite engineering perspective, the design of self-powered piezoelectric nano-polymer networks is not simply a matter of dispersing nanoparticles into a polymer. Rather, it involves creating an interconnected electromechanical network in which the polymer matrix, nanoscale fillers, and electrode architecture work cooperatively to maximize energy conversion and sensing efficiency. The polymer phase provides flexibility, mechanical compliance, and processability, while the embedded nanofillers contribute to dipole alignment, local electric field enhancement, interfacial polarization, and improved stress concentration under external deformation [20]. The performance of the resulting nanocomposite, therefore, depends strongly on filler dispersion, polymer–filler interfacial bonding, crystalline phase content, network connectivity, and charge collection efficiency. In particular, maintaining a balance between high piezoelectric output and long-term mechanical durability remains a central challenge for polymer-based self-powered sensors, especially when they are intended for repeated bending, vibration harvesting, or wearable operation [21].

An equally important requirement for distributed IoT sensor platforms is the ability to communicate wirelessly. Sensor nodes are no longer expected to operate as isolated devices; instead, they must form part of a connected sensing network capable of transmitting real-time data to edge processors, gateways, or cloud-based analytics systems. This has led to growing interest in the integration of embedded wireless nodes with self-powered piezoelectric sensing materials. In such systems, the electrical output generated by the piezoelectric nano-polymer network can serve either directly as a sensing signal or as

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a harvested energy source for intermittent operation of ultra-low-power electronics. The inclusion of compact wireless modules – such as Bluetooth Low Energy (BLE), Zigbee, LoRa, Wi-Fi, or ESP-based microcontrollers – allows the sensor platform to transmit data without the need for permanent wired infrastructure [22]. This transforms the material from a passive piezoelectric film into an autonomous intelligent sensor node capable of sensing, energy harvesting, and wireless communication within distributed IoT environments.

The concept of distributed IoT sensor platforms is particularly important for future smart systems, where large numbers of sensing nodes must operate across infrastructure, machines, textiles, and environmental surfaces. In structural health monitoring, for example, piezoelectric nano-polymer sensors can be attached to bridges, buildings, pipelines, or wind turbine blades to detect strain, vibration, or impact while simultaneously harvesting ambient mechanical energy. In wearable and biomedical applications, such materials can convert body motion, pulse, respiration, or joint movement into electrical signals for self-powered health monitoring. Similarly, in industrial and agricultural monitoring, flexible piezoelectric polymer networks can detect pressure, movement, or equipment vibration while wirelessly transmitting information to remote control systems [23]. These applications clearly highlight the value of materials that combine mechanical adaptability, electromechanical transduction, and system-level connectivity.

In this context, self-powered piezoelectric nano-polymer networks with embedded wireless nodes represent a highly promising research direction at the intersection of polymer nanocomposites, flexible electronics, energy harvesting, and IoT systems engineering. Such platforms aim to exploit ambient mechanical energy not only as the stimulus to be monitored but also as the power source for sensor operation and data communication. Therefore, the development of self-powered piezoelectric nano-polymer networks offers a pathway toward lightweight, maintenance-free, and distributed IoT sensor platforms capable of autonomous operation in real-world environments.

## MATERIALS AND METHODS

This work aimed to develop a self-powered piezoelectric nano-polymer network capable of harvesting mechanical energy and simultaneously functioning as a sensing layer for distributed IoT platforms. The materials and fabrication route were, therefore, selected to achieve three essential requirements: high piezoelectric response, mechanical flexibility, and compatibility with embedded wireless electronics. In the present system, PVDF served as the main piezoelectric polymer matrix, $BaTiO_3$ nanoparticles acted as the piezoelectric ceramic reinforcement, and a small amount of MWCNTs was incorporated to improve charge transport and network stability. The overall experimental methodology consisted of nanocomposite preparation, film fabrication and poling, structural characterization, electromechanical testing, and wireless node integration.

### Materials and Composite Formulation

The self-powered piezoelectric nano-polymer network was formulated using a PVDF-based polymer matrix, functional nanofillers, and flexible electronic components, as summarized in Table 1. Poly(vinylidene fluoride) (PVDF) was selected as the primary matrix because of its flexibility, ferroelectric behaviour, and strong potential for piezoelectric energy conversion. To enhance the piezoelectric response of PVDF, $BaTiO_3$ nanoparticles were added as a ceramic nanofiller since they can improve dielectric polarization and promote formation of the electroactive β-phase of PVDF. In addition, multiwalled carbon nanotubes (MWCNTs) were introduced in a very small concentration to facilitate charge transfer and improve the interfacial electromechanical network without significantly increasing stiffness. A mixed solvent system of DMF and acetone was used for polymer dissolution and filler dispersion, while polyimide (PI) film served as the flexible substrate because of its thermal stability and compatibility with repeated bending. The generated piezoelectric output was collected using silver-coated flexible electrodes and routed to an ESP32-based wireless node for real-time sensing and transmission.

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**Table 1.** Materials used in the self-powered piezoelectric nano-polymer sensor platform.

| Material | Function in the composite system |
|---|---|
| PVDF | Piezoelectric polymer matrix. |
| $BaTiO_3$ nanoparticles | Piezoelectric reinforcement/β-phase promoter. |
| MWCNTs | Conductive interfacial filler for charge transport. |
| DMF + Acetone | Solvent system for dispersion and film casting |
| Polyimide substrate | Flexible support layer. |
| Silver electrode coating | Charge collection layer. |
| ESP32 wireless node | Signal acquisition and wireless transmission. |

## Fabrication of Piezoelectric Nano-Polymer Network

The piezoelectric nano-polymer network was fabricated through a four-stage solution-casting and electrical poling process, as illustrated in Figure 1. First, PVDF was dissolved in a DMF/acetone solvent mixture, while $BaTiO_3$ nanoparticles and MWCNTs were separately dispersed by ultrasonication to obtain a stable filler suspension. The dispersed fillers were then mixed with the PVDF solution to form a homogeneous piezoelectric nano-composite precursor.

In the second stage, the precursor was cast onto a flexible polyimide (PI) substrate using a doctor–blade technique to obtain a uniform thin film. The coated film was then dried at 80°C to remove residual solvent and improve film formation. In the third stage, the dried nanocomposite film was subjected to electrical poling under a high DC electric field, which aligned the PVDF dipoles and enhanced β-phase formation, thereby improving the piezoelectric response. Finally, silver electrodes were coated on the film surfaces, and the device was integrated with an ESP32 wireless node for self-powered sensing and wireless signal transmission, as shown in Figure 1.

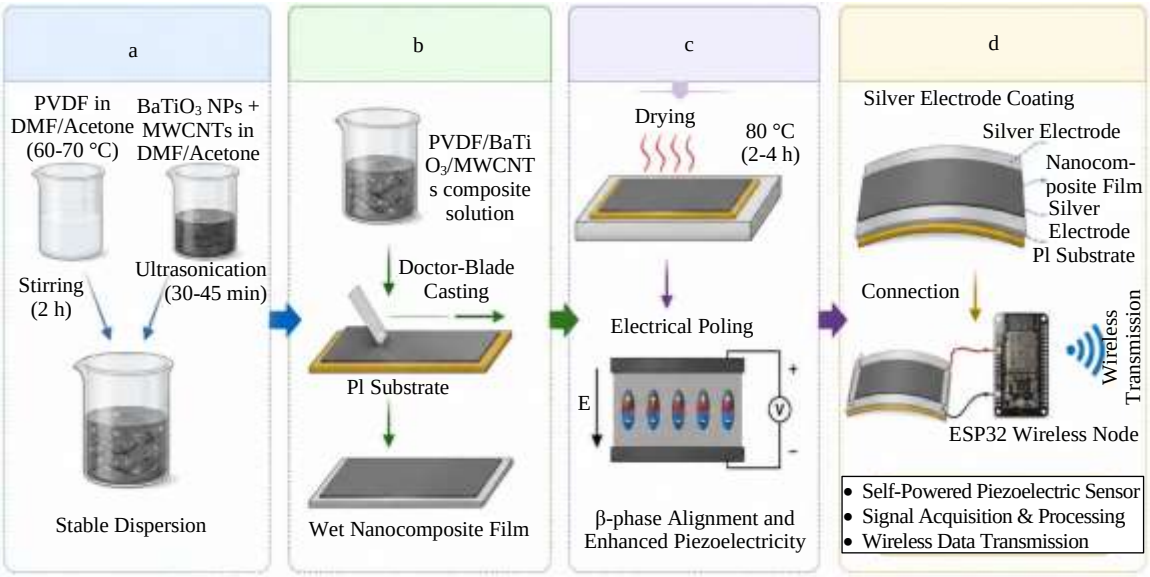



**Figure 1.** Four-stage fabrication route of the self-powered piezoelectric nano-polymer network. (a) PVDF dissolution + $BaTiO_3$/MWCNT dispersion, (b) Composite mixing and solution casting on PI substrate, (c) Drying and electrical poling of the nanocomposite film, and (d) Electrode coating and integration with ESP32 wireless node.

## Structural, Piezoelectric, and Wireless Evaluation

The fabricated piezoelectric nano-polymer network was evaluated in terms of its structure, electromechanical response, and wireless sensing capability, as schematically represented in Figure 2. The morphology and filler dispersion within the PVDF matrix were examined using SEM, while FTIR and XRD were used to verify β-phase formation and the structural incorporation of $BaTiO_3$/MWCNT fillers. Film thickness was measured using a digital micrometer for subsequent performance calculations.

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The piezoelectric response was assessed by applying compressive and bending deformation to the nano-composite film and recording the generated open-circuit voltage and short-circuit current. As illustrated in Figure 2, mechanical deformation of the piezoelectric polymer network generated an electrical signal that was collected through the electrode layer and transmitted to the ESP32 wireless node. The acquired signal was then processed and wirelessly communicated to a remote IoT dashboard for real-time monitoring. Thus, Figure 2 summarizes the complete evaluation pathway, linking mechanical input, piezoelectric signal generation, and wireless data transmission within the proposed self-powered sensing platform.

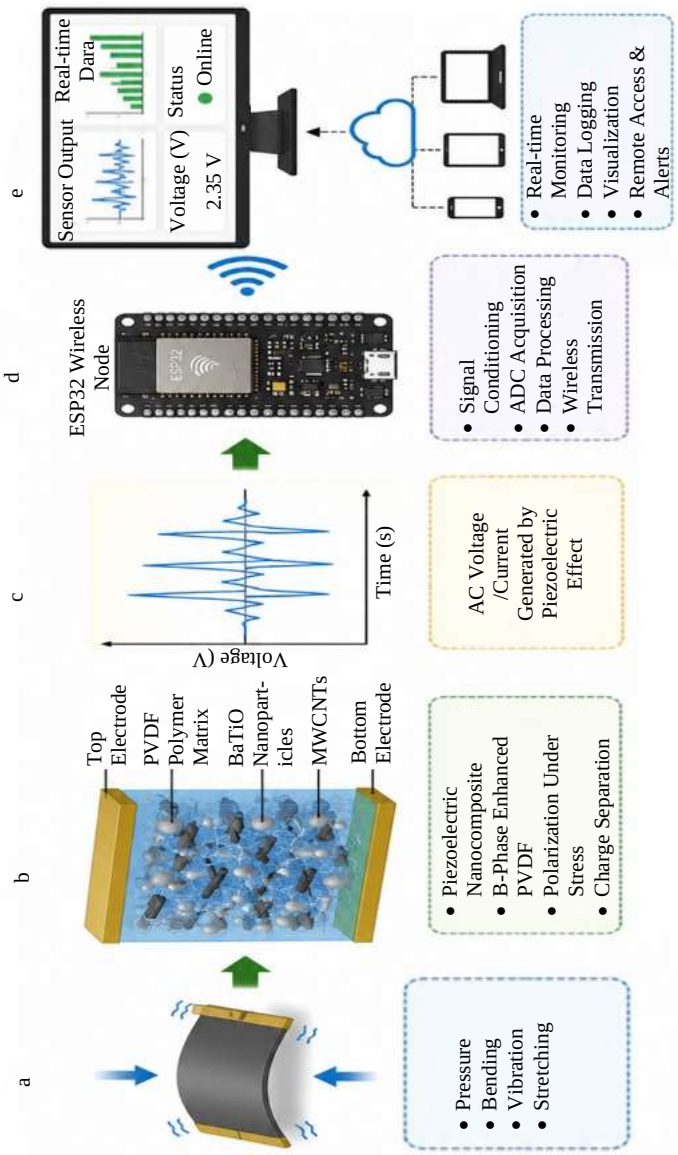



**Figure 2.** Schematic representation of the self-powered sensing platform.
(a) Mechanical deformation/vibration, (b) piezoelectric nano-polymer network generated electrical signal, (c) ESP32 wireless node, and (d) remote IoT dashboard.

The formulation used for the optimized piezoelectric composite is summarized below.

As shown in Figure 3, the representative composite design consisted of 10 wt% $BaTiO_3$ nanoparticles and 0.5 wt% MWCNTs incorporated into the PVDF matrix. The relatively higher $BaTiO_3$ content was selected to enhance the piezoelectric response and β-phase promotion of PVDF, while the low MWCNT

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loading was sufficient to improve charge transport and interfacial conductivity without compromising the flexibility of the polymer network. Therefore, Figure 3 highlights the optimized filler balance used to achieve both electromechanical performance and mechanical compliance in the self-powered piezoelectric nano-polymer composite.

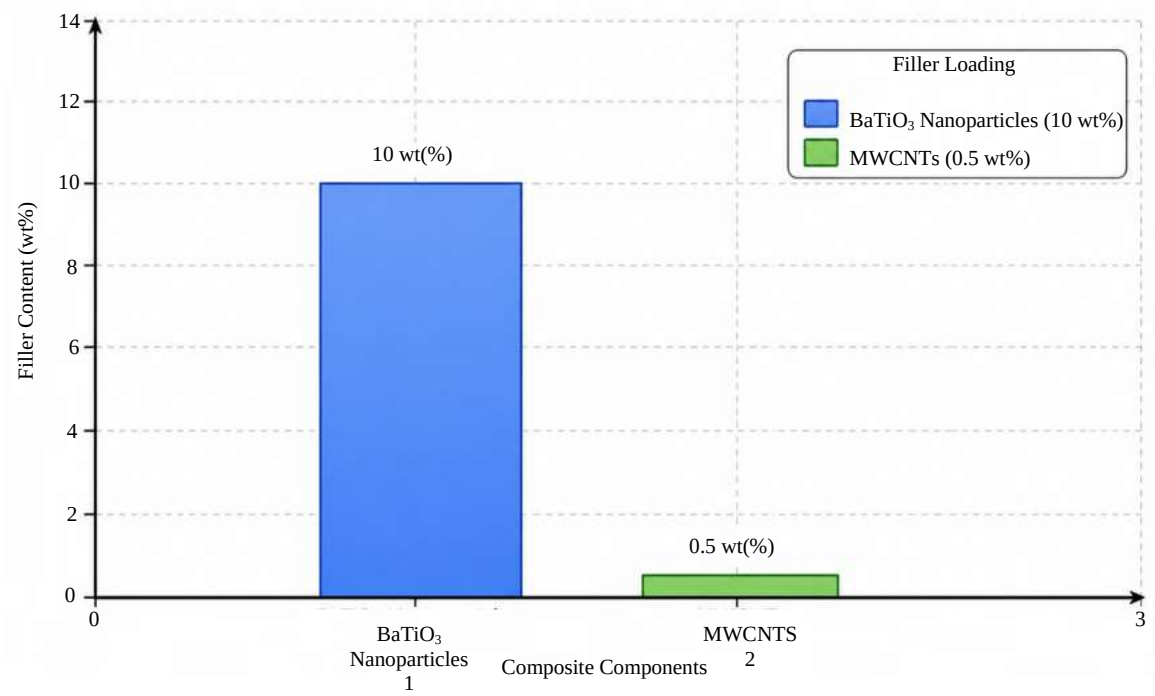



**Figure 3.** Optimized nano-composite formulation for the self-powered piezoelectric nano-polymer network.

## RESULTS AND DISCUSSION

The performance of the fabricated self-powered piezoelectric nano-polymer network was evaluated in terms of electrical output, piezoelectric response, mechanical durability, and wireless sensing capability. From a polymer-composites perspective, the observed behavior is governed by the synergistic interaction between the PVDF matrix, $BaTiO_3$ piezoelectric nanofillers, and MWCNT conductive pathways. The PVDF matrix provides flexibility and electromechanical activity, $BaTiO_3$ enhances polarization and β-phase development, while MWCNTs improve charge transport and output stability. Together, these components form a flexible piezoelectric network capable of converting mechanical deformation into usable electrical signals for distributed IoT sensing.

### Piezoelectric Output Performance

The fabricated nanocomposite generated a stable electrical response under periodic mechanical deformation, confirming the successful development of a self-powered piezoelectric polymer network. Under repeated compressive tapping, the output voltage increased rapidly with applied force because mechanical stress induced polarization within the β-phase-rich PVDF matrix and $BaTiO_3$-reinforced domains. The presence of MWCNTs further supported charge collection by providing conductive pathways between the active piezoelectric regions and the electrodes. As a result, the optimized composite produced an open-circuit voltage in the range of 2.8–8.9 V as the applied force increased from 5 to 25 N.

As shown in Figure 4, the voltage increased nearly linearly with force, indicating efficient electromechanical conversion and stable stress transfer within the nanocomposite. This behavior confirms that the $BaTiO_3$ nanoparticles effectively enhanced local polarization while the PVDF matrix maintained mechanical compliance during deformation.

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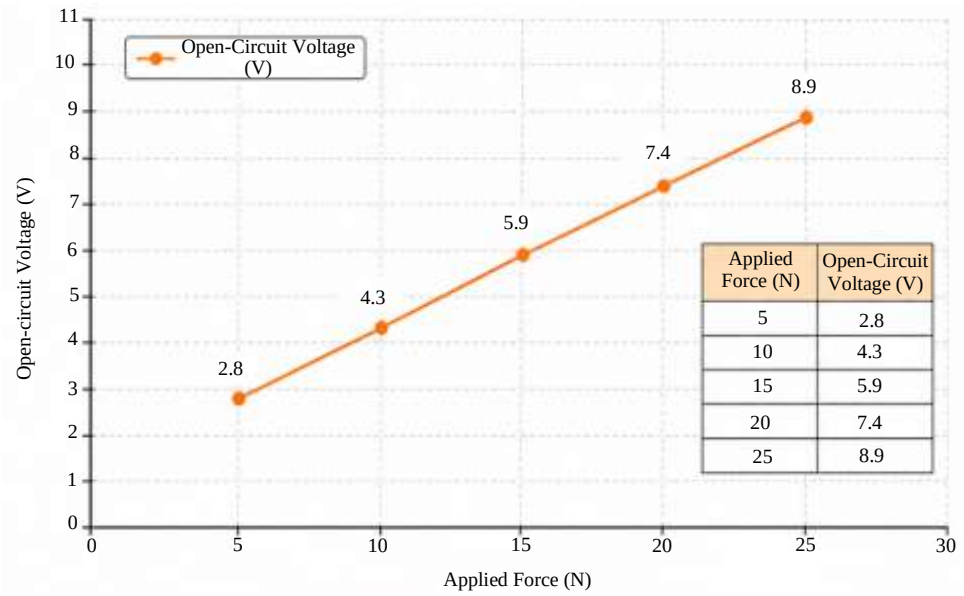



**Figure 4.** Open-circuit voltage response of the piezoelectric nano-polymer network under different applied forces.

**Effect of Composite Structure on Piezoelectric Response**

The enhanced piezoelectric behavior of the fabricated film is directly related to the nanocomposite architecture. In the present system, $BaTiO_3$ nanoparticles acted as piezoelectric reinforcement and promoted the electroactive β-phase of PVDF, whereas MWCNTs improved charge transport across the film. The combined filler system, therefore, produced a more efficient internal piezoelectric network than neat PVDF alone. The optimized composition shown earlier in Figure 3 was selected because it provided a balance between piezoelectric output, electrical conductivity, and flexibility.

To highlight the role of filler incorporation, the output voltage of the neat PVDF film was compared with that of the PVDF/$BaTiO_3$/MWCNT composite under identical loading conditions. The nanocomposite consistently exhibited a much higher output, demonstrating the beneficial effect of the ceramic–conductive hybrid filler system on piezoelectric performance.

The higher output of the nanocomposite can be attributed to improved dipole alignment, stress concentration, and charge collection efficiency. Therefore, the results confirm that the piezoelectric response of the system is not solely due to PVDF, but rather to the engineered polymer–composite network formed by the combined action of PVDF, $BaTiO_3$, and MWCNTs (Figure 5).

**Frequency Response and Signal Stability**

For practical IoT sensing applications, the output of a self-powered piezoelectric sensor must remain stable under repeated cyclic deformation. The fabricated nano-polymer network was, therefore, tested under different actuation frequencies in the range of 1–5 Hz. The output voltage increased moderately with frequency because faster cyclic loading generated more frequent polarization–depolarization events and reduced charge dissipation time. The maximum voltage was observed at 5 Hz, where the output reached approximately 9.6 V.

As shown in Figure 6, the output variation remained smooth and reproducible across the tested frequency range, indicating good dynamic stability of the nanocomposites network. This behaviour suggests that the polymer matrix effectively supports repeated mechanical deformation while preserving filler connectivity and piezoelectric activity.

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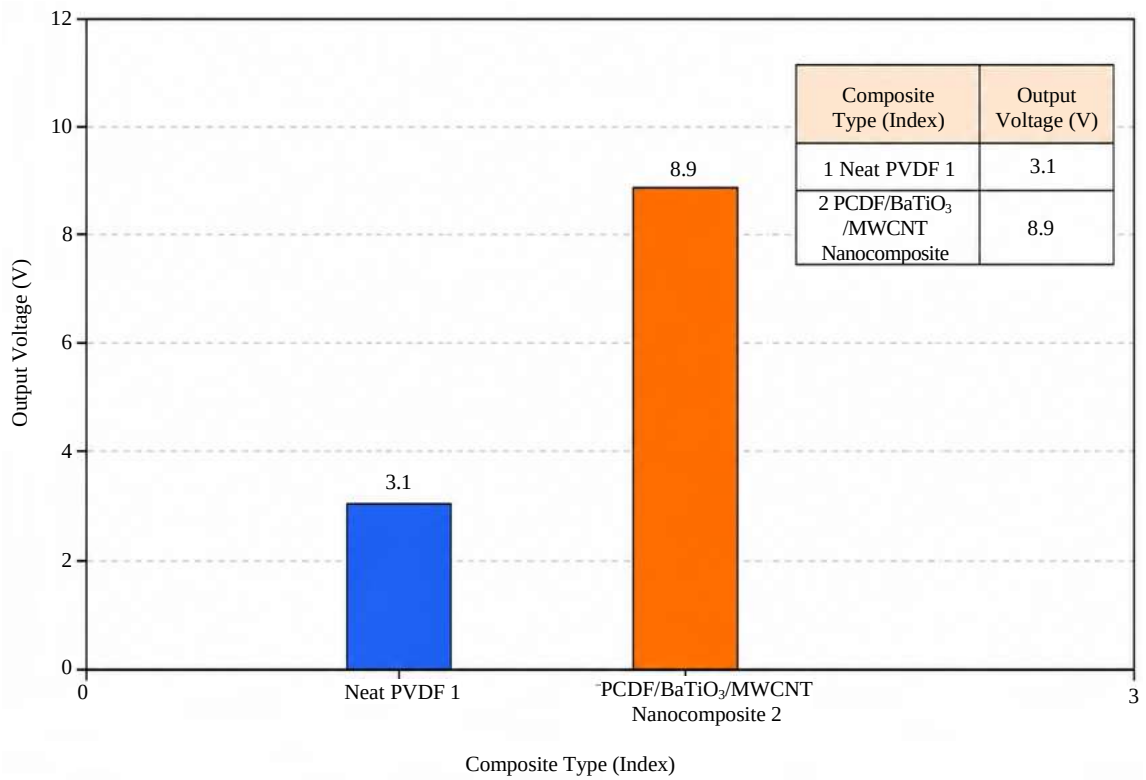



**Figure 5.** Comparison of output voltage between neat PVDF and the optimized PVDF/$BaTiO_3$/MWCNT nanocomposite.

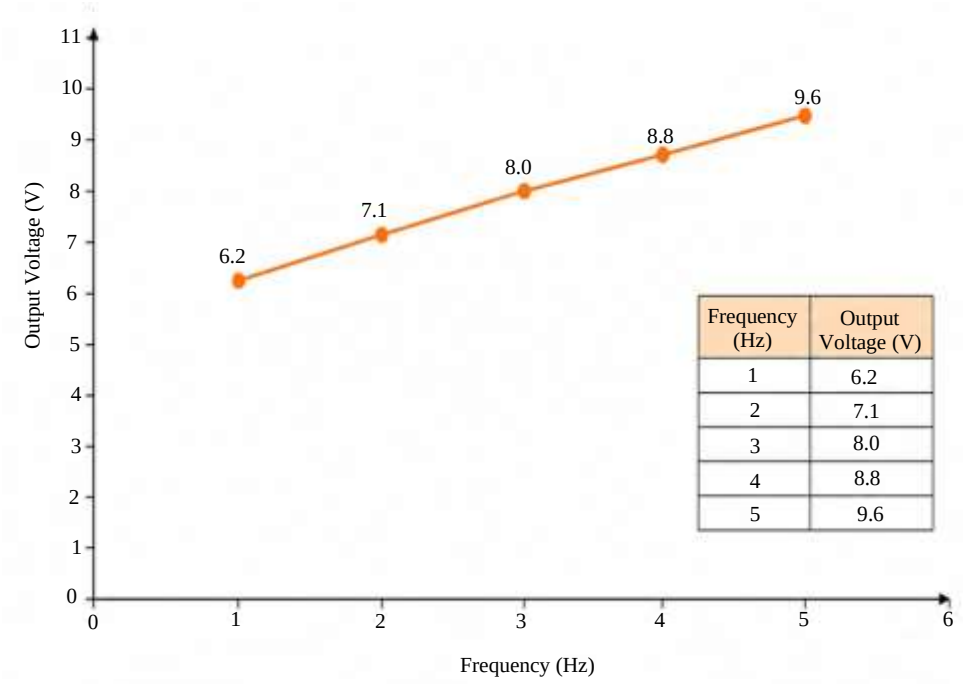



**Figure 6.** Frequency-dependent output voltage of the self-powered piezoelectric nano-polymer network.

**Mechanical Durability and Bending Stability**

The flexibility of the piezoelectric nano-polymer network is a key requirement for distributed IoT sensor platforms. To assess mechanical durability, the device was subjected to repeated bending at a

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radius of 5 mm, and the normalized output retention was monitored over 1000 bending cycles. Only a small reduction in output was observed, confirming that the piezoelectric network remained mechanically and electrically stable during cyclic deformation.

As illustrated in Figure 7, the device retained nearly 90% of its initial output after 1000 cycles, demonstrating excellent flexibility and structural stability. This performance can be attributed to the compliant PVDF matrix, which absorbed bending strain, and to the strong interfacial interactions between the polymer and nanofillers, which prevented severe cracking or delamination.

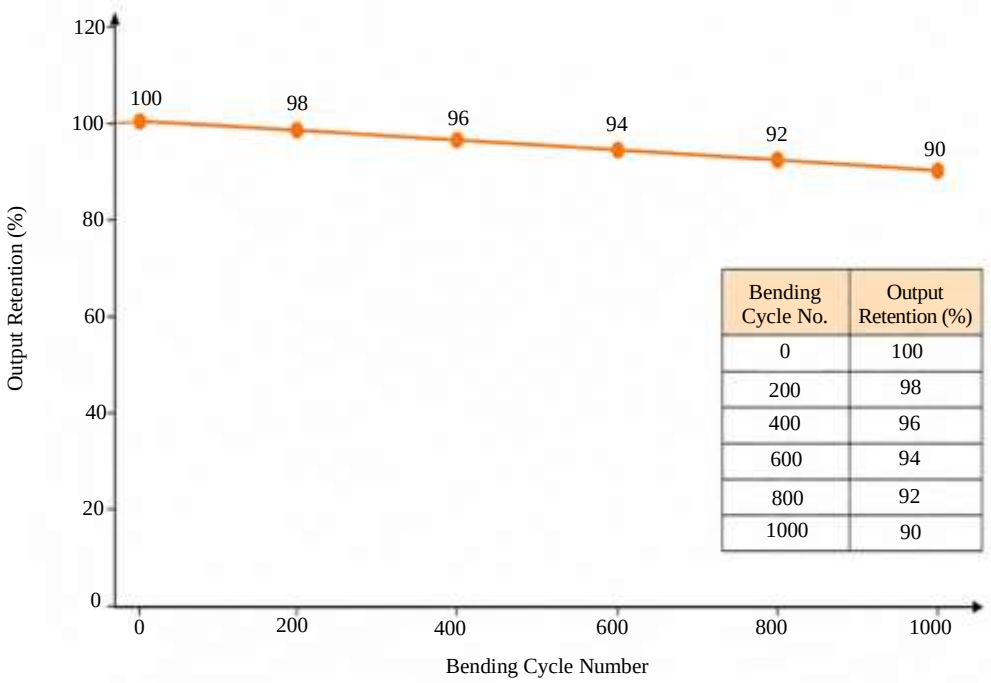



**Figure 7.** Output retention of the piezoelectric nano-polymer network during cyclic bending.

**Wireless Sensing Demonstration and IoT Relevance**

The final stage of evaluation involved integrating the piezoelectric nanocomposite with the ESP32 wireless node described in Figure 2. Under repeated tapping or bending, the generated voltage pulses were successfully captured by the signal acquisition circuit and wirelessly transmitted to a remote monitoring interface. A representative real-time output profile is shown in Figure 8, where distinct voltage peaks correspond to successive mechanical actuation events. The repeatable pulse pattern confirms that the fabricated PVDF/$BaTiO_3$/MWCNT nano-polymer network can function as both a self-powered sensing layer and a signal source for wireless IoT communication. As seen in Figure 8, the transmitted output remained stable over time, indicating reliable coupling between the piezoelectric layer and the embedded ESP32 module. This demonstrates the suitability of the developed device for distributed IoT sensor platforms, where low-power sensing, signal generation, and wireless transmission must be integrated within a compact flexible system.

**Comparative Performance Analysis**

To assess the practical relevance of the proposed device, the performance of the PVDF/$BaTiO_3$ /MWCNT self-powered nano-polymer network was compared with representative piezoelectric polymer systems reported for flexible sensing applications. The comparison considered output voltage, bending durability, and wireless sensing compatibility, which are key requirements for distributed IoT platforms. As summarized in Figure 9, the proposed nano-composite exhibited the highest output voltage (8.9 V) among the compared polymer-based systems, while also maintaining 90% output retention after 1000 bending cycles and supporting real-time wireless signal transmission through the ESP32 node.

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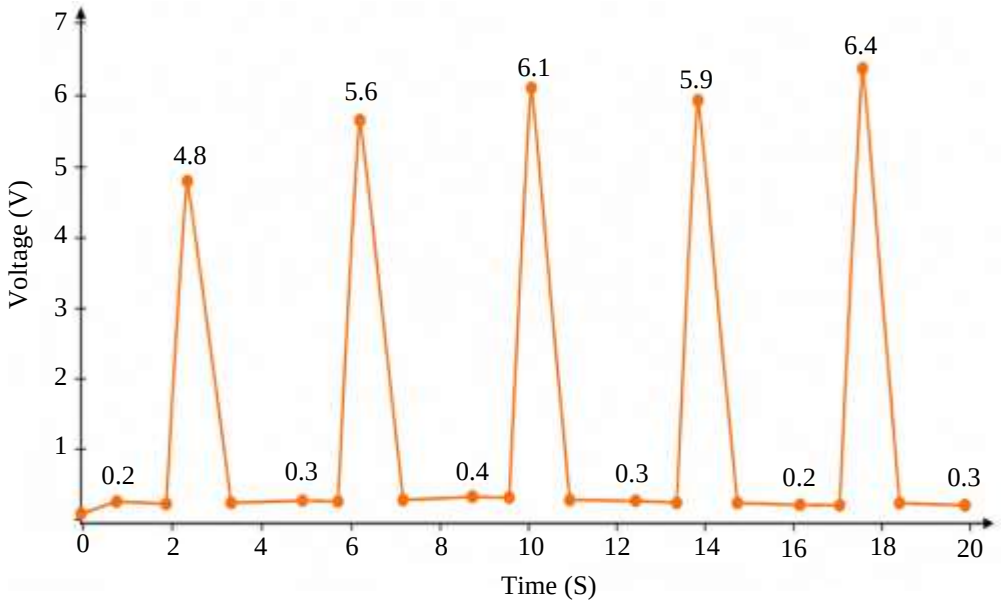



**Figure 8.** Real-time wireless voltage output of the self-powered piezoelectric nano-polymer network during repeated mechanical actuation.

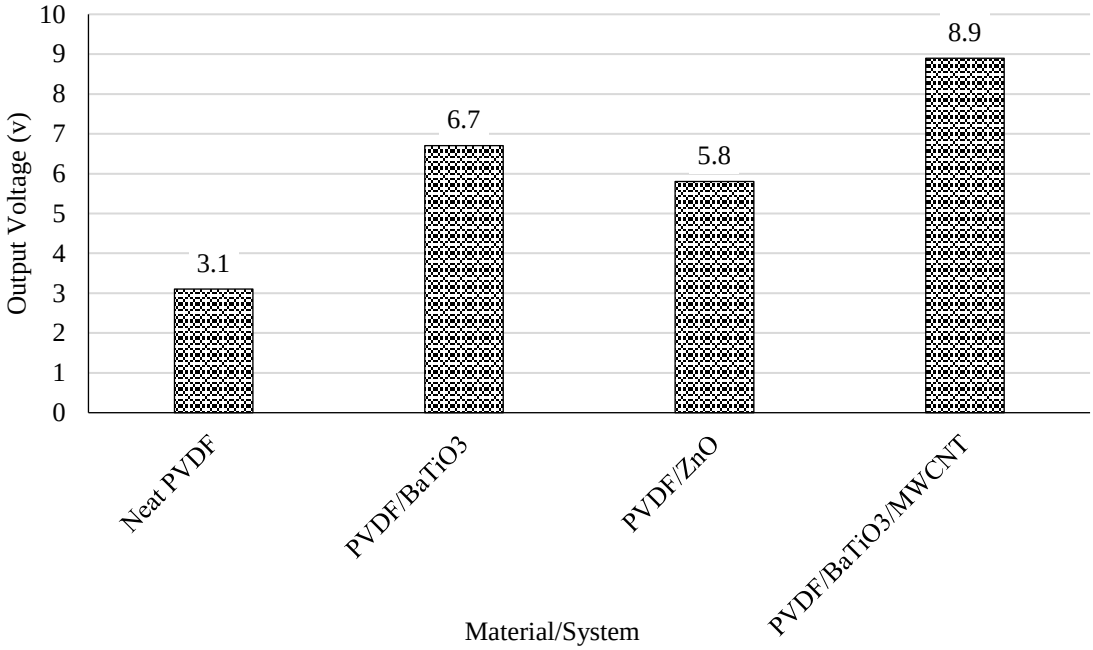



**Figure 9.** Comparative output voltage of flexible piezoelectric polymer sensor systems.

Compared with neat PVDF, the hybrid filler system clearly improved electromechanical output due to enhanced β-phase formation, interfacial polarization, and charge transport pathways. Relative to other reported flexible piezoelectric polymer composites, the present system offered a more balanced combination of high electrical response and mechanical durability, rather than optimizing only one property. The incorporation of $BaTiO_3$ nanoparticles strengthened the piezoelectric response, while MWCNTs improved electrical connectivity and stabilized the output during repeated deformation. Therefore, the results in Figure 9 confirm that the proposed polymer composite is not only effective as a self-powered sensing material but also highly suitable for wireless, distributed IoT sensor platforms requiring flexibility, reliability, and signal stability.

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## CONCLUSION

In conclusion, the present study demonstrates that self-powered piezoelectric nano-polymer networks can serve as an effective material platform for distributed IoT sensor systems. In this work, the term self-powered piezoelectric nano-polymer network refers to a flexible polymer composite in which a piezoelectric polymer matrix is reinforced with nanoscale functional fillers to simultaneously harvest mechanical energy, generate sensing signals, and support wireless data transmission. By combining PVDF with $BaTiO_3$ nanoparticles and MWCNTs, the developed nanocomposite successfully exhibited enhanced piezoelectric output, good bending durability, and compatibility with an embedded ESP32 wireless node for real-time sensing applications.

1. The PVDF/$BaTiO_3$/MWCNT nanocomposite generated a stable piezoelectric output under compressive and bending deformation, confirming its self-powered sensing capability.
2. $BaTiO_3$ nanoparticles improved the piezoelectric response by promoting β-phase formation and increasing polarization within the polymer matrix.
3. MWCNT incorporation enhanced charge transport and electrical connectivity, resulting in improved signal collection and output stability.
4. The flexible nanocomposite retained nearly 90% of its output after 1000 bending cycles, demonstrating good mechanical durability for wearable and flexible electronics.
5. Wireless integration with the ESP32 module enabled real-time signal acquisition and transmission, validating the suitability of the device for distributed IoT platforms.
6. Comparative analysis showed that the proposed polymer composite outperformed neat PVDF and other reported flexible piezoelectric systems in terms of output voltage and multifunctional sensing capability.

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