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Some Studies on Flexible Polymer-Based Energy Harvesting Systems

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Abstract *– The increasing demand for lightweight, flexible, wearable, and self-powered electronic systems has stimulated extensive research on polymer-based energy-harvesting materials. Conventional inorganic piezoelectric ceramics exhibit high electromechanical performance but are generally rigid, brittle and unsuitable for conformal or wearable applications. Flexible electroactive polymers, particularly poly(vinylidene fluoride) (PVDF) and poly(vinylidene fluoride-co-trifluoroethylene) [P(VDF-TrFE)], provide an attractive alternative because of their flexibility, low density, chemical stability, processability and inherent piezoelectric properties. Kawai (1969), [1], established the fundamental piezoelectric behavior of PVDF, initiating extensive research into electroactive polymeric materials. Subsequent developments have focused on increasing the electroactive β-phase, controlling molecular orientation, introducing nanofillers, engineering interfaces and designing hierarchical device structures.*

This paper presents a focused study of flexible polymer-based energy harvesting systems, emphasising piezoelectric, triboelectric and hybrid mechanisms. It discusses the influence of polymer phase structure, fabrication technique, nanofiller incorporation, ceramic–polymer interfaces, and device architecture. Representative systems based on ZnO/PVDF, graphene/PVDF, KNN/PVDF, $BaTiO_3$/PVDF, $BaTiO_3$/P(VDF-TrFE) and related composites demonstrate the potential of polymer-based materials for mechanical-energy conversion. Recent approaches involving electrospinning, surface engineering, interfacial modification, nanostructuring and hybrid piezoelectric–triboelectric operation are also examined. Finally, the major challenges related to output reproducibility, standardization, long-term stability, energy-storage integration and practical scalability are identified.

Keywords- *PVDF, P(VDF-TrFE), flexible energy harvesting, piezoelectric nanogenerator, triboelectric nanogenerator, polymer nanocomposite, KNN, $BaTiO_3$, wearable electronics.*

INTRODUCTION

The rapid development of wearable electronics, wireless sensors, biomedical devices, Internet-of-Things systems, and portable electronics has created a need for small, sustainable power sources. Conventional batteries provide high energy density but require periodic charging or replacement and can limit the mechanical flexibility of wearable systems. Consequently, mechanical energy harvesting has emerged as an important approach for powering low-energy electronic devices. Yang *et al.* (2018), [2], emphasized that piezoelectric energy harvesting can provide compact energy-conversion systems for applications including wearable devices, biomedical electronics and structural monitoring.

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Piezoelectric, triboelectric, or hybrid mechanisms can convert mechanical energy from human movement, vibration, pressure, bending, stretching, and environmental motion into electrical energy. Polymer-based materials are particularly attractive because they can withstand repeated deformation without the brittleness normally associated with ceramic piezoelectric materials. Lu *et al.* (2020), [3], reviewed the development of PVDF-based flexible nanogenerators and identified nanofiller incorporation, structural design and fabrication optimization as major routes for improving energy-harvesting performance.

Among electroactive polymers, PVDF has attracted exceptional attention because it combines flexibility with ferroelectric, piezoelectric and pyroelectric behavior. Its molecular structure permits several crystalline phases, among which the β-phase possesses a strong net dipole moment and is particularly important for piezoelectric applications. Kawai (1969), [1], demonstrated the piezoelectric nature of PVDF. Salimi and Yousefi (2003), [4], subsequently demonstrated the relationship between stretching and β-phase formation.

The development of copolymers has further expanded the performance of polymer-based harvesters. P(VDF-TrFE) exhibits a higher tendency toward electroactive crystalline structures and can provide strong piezoelectric response without requiring the same degree of mechanical stretching used for conventional PVDF. Pi *et al.* (2014), [5], demonstrated flexible energy harvesting using P(VDF-TrFE) thin films. Cho *et al.* (2015), [6], further demonstrated that surface morphology can influence the energy-harvesting performance of the polymer.

More recent studies have moved beyond neat polymers toward polymer nanocomposites. Ceramic nanoparticles, nanowires, carbonaceous fillers and two-dimensional materials can modify the polymer crystalline phase, dielectric properties, interfacial polarization, mechanical modulus and stress distribution. Sukumaran *et al.* (2021), [7], highlighted the importance of materials engineering, structural design and fabrication methods in developing flexible PVDF devices. An overview of. Flexible polymer energy harvesting is presented in Fig. 1.

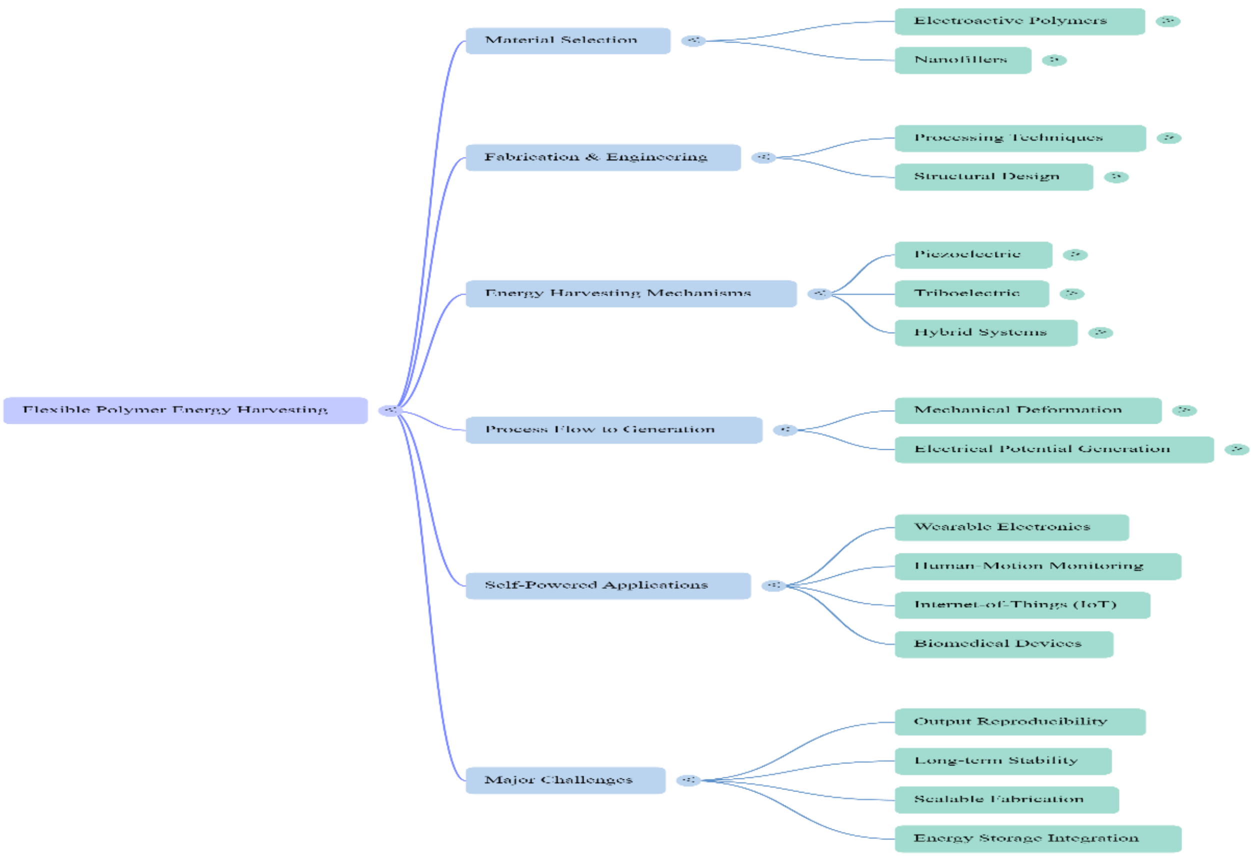

Fig. 1- Flexible polymer energy harvesting: an overview

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WORKING PRINCIPLES OF FLEXIBLE POLYMER-BASED ENERGY HARVESTING

Piezoelectric energy harvesting

The direct piezoelectric effect describes the generation of electrical charge when a piezoelectric material is mechanically deformed. In a simplified form, the generated charge is related to the applied mechanical stress through the piezoelectric coefficient:

$$D_i = d_{ij}T_j + \varepsilon_{ij}^T E_j$$

where D_i is the electric displacement, d_{ij} is the piezoelectric coefficient, T_j is mechanical stress, ε_{ij}^T is the permittivity at constant stress and E_j is the electric field.

For flexible polymer harvesters, the deformation may occur through compression, tension, bending, stretching or vibration. Metallic electrodes positioned on one or both sides of the polymer film can collect the generated charge. The electrical response is commonly characterised through open-circuit voltage, short-circuit current, power density and energy conversion behaviour.

The piezoelectric response of PVDF is strongly associated with molecular conformation. PVDF contains $–CH_2–CF_2–$ repeating units, and the electroactive β-phase produces a favorable arrangement of molecular dipoles. Processing methods such as mechanical stretching, electrical poling, annealing, electrospinning and nanofiller incorporation can influence the phase composition.

Triboelectric energy harvesting

Triboelectric nanogenerators (TENGs) convert mechanical energy into electrical energy through contact electrification and electrostatic induction. Wang (2013), [8], established the broader framework for triboelectric nanogenerators. Yoon, Ryu and Kim (2018), [9], reviewed fluoropolymer-based TENGs and discussed material, structural and circuit-level approaches for improving performance. PVDF is particularly attractive for triboelectric systems because it combines strong electronegativity with mechanical flexibility. Mi *et al.* (2018), [10], demonstrated a PVDF-nanofiber-based flexible TENG producing 106.2 V and a power density of 13.3 W m^{-2} under the reported test conditions.

Hybrid energy harvesting

Hybrid devices combine two or more conversion mechanisms, most commonly piezoelectric and triboelectric effects. Singh and Khare (2018), [11], demonstrated a hybrid system in which ZnO-modified PVDF contributed to both piezoelectric and triboelectric behavior. The reported maximum instantaneous power density was approximately 24.5 μW cm^{-2} without additional surface treatment or electrical poling.

Hybridisation provides an opportunity to exploit different mechanical stimuli and broaden the operating range of an energy harvester. However, output voltage alone should not be used to compare different harvesting systems because voltage, current and power depend strongly on device dimensions, loading conditions, frequency, external resistance and measurement configuration.

PVDF AND P(VDF-TRFE) AS FLEXIBLE PIEZOELECTRIC MATERIALS

PVDF

PVDF is a semicrystalline fluoropolymer consisting of repeating vinylidene fluoride units. It exhibits α, β, γ and other crystalline forms. Among these, the β-phase is particularly important for piezoelectric applications because the molecular dipoles are arranged in a manner that produces a high net polarization.

Kawai (1969), Salimi and Yousefi (2003), [4], showed how stretching affects the crystalline phase. These studies established two fundamental principles for PVDF-based harvesters: electroactive-phase development and molecular orientation. Processing parameters therefore strongly influence PVDF device performance. Mechanical stretching, high-voltage poling, thermal treatment, solvent choice, electrospinning, and nanofiller incorporation can modify crystallinity and phase composition. Ahbab *et al.* (2025) [12] summarised the relationship between PVDF fabrication, phase transitions, material properties and piezoelectric applications.

P(VDF-TrFE)

The copolymer P(VDF-TrFE) is formed by incorporating trifluoroethylene into PVDF. The copolymer generally exhibits enhanced ferroelectric and piezoelectric characteristics and can be processed into flexible films and fibers. Pi *et al.* (2014), [5], demonstrated the use of P(VDF-TrFE) in flexible piezoelectric nanogenerators. Surface modification can further improve mechanical

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deformation and charge generation. Cho *et al.* (2015), [6], showed that morphology engineering can improve energy-harvesting behavior. P(VDF-TrFE) is therefore particularly suitable for flexible devices requiring repeated deformation, high sensitivity and relatively strong piezoelectric response. Fig. 2 shows the PVDF and PVDF-TrFE comparative study.

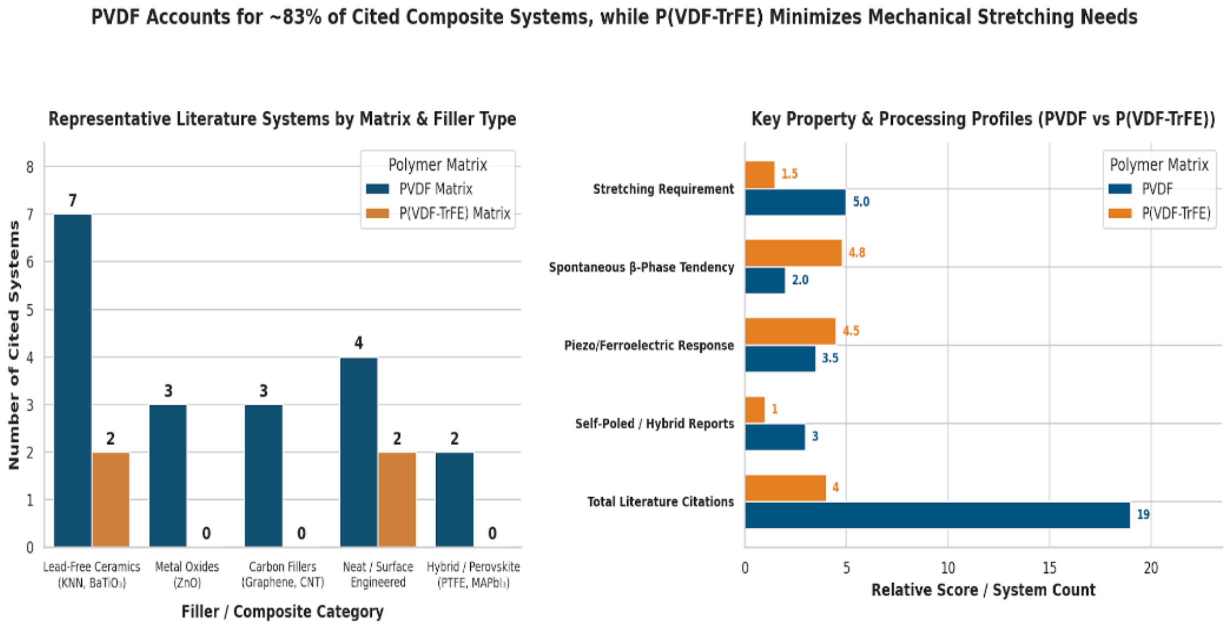

Figure 2: PVDF and PVDF-TrFE comparative study

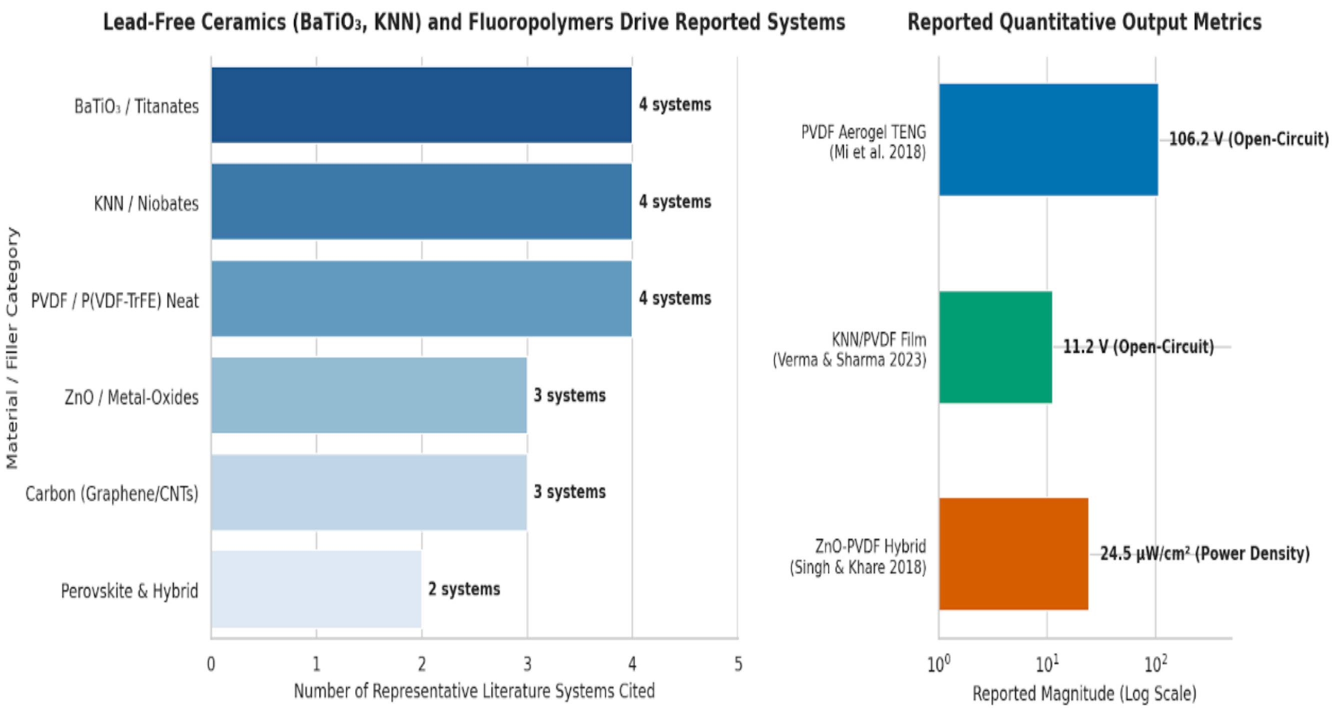

Figure 3: Polymer-ceramics composite: an overview of energy harvesting output.

POLYMER NANOCOMPOSITES FOR ENHANCED ENERGY HARVESTING

Although neat PVDF and P(VDF-TrFE) possess useful piezoelectric properties, their relatively modest piezoelectric coefficients compared with ceramic materials have encouraged the development of polymer nanocomposites. The incorporation of a suitable filler can increase dielectric permittivity, interfacial polarisation, mechanical stress transfer and electroactive-phase formation; an overview is presented in Figure **3**.

Mishra *et al.* (2019), [13], discussed the role of polymer–filler interactions, filler morphology and processing in polymer composite energy harvesters.

Carbon-based fillers

Graphene and related carbon nanomaterials have been investigated for their electrical conductivity, high aspect ratio, and ability to interact with the polymer matrix. Abolhasani, Shirvanimoghaddam and Naebe (2017), [14], reported that a small graphene concentration could significantly increase the β-phase fraction and open-circuit voltage of electrospun PVDF nanofibers. Park *et al.* (2017), [15], further demonstrated that electrode configuration and graphene incorporation can influence the energy-harvesting efficiency. Researchers have also investigated carbon nanotubes as electroactive, phase-promoting fillers. Kabir *et al.* (2017), [16], investigated the formation of β-phase PVDF in CNT-containing composites.

ZnO/PVDF composites

ZnO is an attractive filler because it is piezoelectric, chemically stable and relatively inexpensive. Choi *et al.* (2017), [17], investigated the mechanical and electrical behavior of PVDF-ZnO structures. Thakur *et al.* (2018), [18], demonstrated a self-poled ZnO/PVDF device with enhanced electroactive-phase content and high durability. ZnO incorporation can simultaneously influence the local electric field, β-phase nucleation, and stress distribution.

Singh and Khare (2018), [11], demonstrated that ZnO/PVDF can also be integrated with PTFE to exploit both piezoelectric and triboelectric mechanisms.

LEAD-FREE CERAMIC–POLYMER COMPOSITES

Lead-free piezoelectric ceramics are particularly attractive for flexible polymer composites because they can provide higher piezoelectric response than the polymer matrix while avoiding lead-containing ceramic systems. Important candidates include KNN, $BaTiO_3$, ZnO, Bi-based ceramics and related alkaline niobates.

KNN/PVDF composites

Potassium sodium niobate, $K_{0.5}Na_{0.5}NbO_3$ (KNN), is one of the most widely investigated lead-free piezoelectric ceramics. Its incorporation into PVDF can increase dielectric and piezoelectric response while maintaining flexibility. Kang *et al.* (2015), [19], demonstrated NKN nanoparticle-embedded P(VDF-TrFE) nanofibers for flexible energy harvesting. Bairagi and Ali (2020), [20], investigated the effect of KNN nanorod concentration on flexible PVDF devices. Their results demonstrated the importance of optimising filler concentration rather than simply maximising ceramic loading. Bairagi and Ali (2020), [21], further demonstrated the effect of surface modification of KNN on composite performance. Verma and Sharma (2023) [22] reported a maximum open-circuit voltage of 11.2 V and short-circuit current of 0.3 µA for the optimised KNN/PVDF device. The study also demonstrated harvesting from elbow and finger-joint motion.

These results demonstrate that the polymer–ceramic interface and filler concentration are critical parameters. Excessive ceramic loading can increase stiffness, produce particle agglomeration and reduce the flexibility required for wearable applications.

$BaTiO_3$/PVDF and $BaTiO_3$/P(VDF-TrFE)

$BaTiO_3$ is another important lead-free ferroelectric ceramic. Zhao *et al.* (2015), [23], demonstrated high-output $BaTiO_3$/PVDF nanocomposite generators using oriented ceramic nanoparticles. Shi *et al.* (2021), [24], demonstrated that an interfacial PMMA layer around $BaTiO_3$ nanowires could improve dispersion and interfacial stress transfer. The study emphasised that composite performance is not determined solely by the intrinsic properties of the filler; the polymer–ceramic interface is equally important. Kim *et al.* (2023), [25], demonstrated a scalable approach for flexible $BaTiO_3$/PVDF composite fabrication and reported both energy-harvesting and energy-storage functionality. Fu *et al.* (2018) [26] further showed that one-dimensional ceramic structures can improve stress transfer and durability.

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FABRICATION AND STRUCTURAL ENGINEERING

The performance of flexible polymer energy harvesters depends strongly on fabrication. Conventional solution casting provides a simple route for preparing films but may produce randomly oriented polymer chains and filler particles. Electrospinning provides high surface area, nanofiber formation and partial molecular orientation, making it particularly useful for wearable energy harvesters.

Mirjalali *et al.* (2023), [27], highlighted the advantages of electrospun polymer nanofibers, including flexibility, processability and enhanced piezoelectric performance. Structural engineering can include porous structures, aligned nanofibers, multilayer configurations, surface microstructures and patterned electrodes. Such architectures increase the effective mechanical deformation and can improve charge generation without necessarily increasing the active material volume. Interface engineering is another important strategy. In ceramic–polymer composites, differences in dielectric properties and elastic modulus can produce localized electric fields and stress concentrations. Proper surface modification of ceramic fillers can improve dispersion, reduce agglomeration and promote stronger polymer–ceramic interactions.

The overall energy-harvesting performance can therefore be viewed as the combined effect of:

polymer phase structure → filler characteristics → interface → morphology → mechanical deformation → charge generation → electrode collection.

This multiscale relationship is particularly important for lead-free ceramic–polymer systems.

APPLICATIONS OF FLEXIBLE POLYMER ENERGY HARVESTERS

Flexible polymer energy harvesters have been investigated for wearable electronics, human-motion monitoring, self-powered sensors, biomedical systems and low-power electronics. Human motion provides mechanical energy through walking, finger movement, joint bending, body vibration, and pressure. PVDF-based devices are attractive for such applications because their mechanical flexibility allows them to conform to curved surfaces. Ghosh and Mandal (2018), [28], demonstrated the use of aligned polymer nanofibers for wearable sensing and energy harvesting. Jella *et al.* (2018), [29], investigated PVDF-based composite films for flexible energy harvesting. Although perovskite-containing systems can provide high electrical output, researchers must consider environmental stability and material toxicity when selecting materials for practical applications. Triboelectric systems offer another route for wearable applications. Mi *et al.* (2018), [10], demonstrated the use of porous structures and PVDF nanofibers to simultaneously obtain high electrical output and sensing capability.

CHALLENGES AND FUTURE PROSPECTS

Despite significant progress, flexible polymer energy harvesters still face several challenges.

Reported voltage and current values are often difficult to compare because experimental conditions vary considerably. Differences in device area, applied force, deformation frequency, acceleration, load resistance, electrode configuration and measurement circuitry can produce large variations in reported output.

Polymer nanocomposites frequently show an optimum filler concentration. Increasing ceramic content does not necessarily increase the final device output because particle agglomeration, increased stiffness, leakage current and reduced flexibility may occur.

The polymer–ceramic interface requires greater attention. Surface functionalization, coupling layers, core–shell structures and controlled interfacial chemistry can improve stress transfer and local polarization. The work of Shi *et al.* (2021), [24], illustrates the importance of interface engineering.

Long-term durability and environmental stability must be evaluated under realistic bending, stretching, humidity and temperature conditions. A device that produces a high instantaneous voltage but loses performance after repeated mechanical cycling may have limited practical value.

Finally, the harvested electrical energy generally needs rectification, voltage regulation and storage before it can operate an electronic load. Future systems are therefore expected to integrate the energy harvester with rectifiers, capacitors, batteries, power-management circuits and self-powered sensing units. Recent research is also moving toward multifunctional materials that combine energy harvesting with sensing, structural monitoring and energy storage. Ahbab *et al.* (2025) [12] emphasised continued development in PVDF processing, phase control, and composite approaches.

CONCLUSION

Flexible polymer-based energy harvesting has developed from the early demonstration of PVDF piezoelectricity into a broad field involving electroactive polymers, ceramic–polymer nanocomposites, electrospun fibers, triboelectric systems and multifunctional hybrid devices. PVDF remains one of the most important polymer matrices because of its flexibility, chemical stability, processability and electroactive crystalline phases. P(VDF-TrFE) provides an additional route toward enhanced piezoelectric performance. The literature demonstrates that the electrical output of flexible polymer harvesters can be improved through β-phase enhancement, molecular orientation, nanofiller incorporation, ceramic alignment, surface modification, interface engineering and hierarchical structural design. Lead-free ceramic fillers such as KNN and $BaTiO_3$ are particularly promising because they can increase the electromechanical response while retaining the flexibility of the polymer matrix.

However, future progress should focus not only on maximizing instantaneous voltage but also on reproducible power output, mechanical durability, standardized testing, scalable fabrication and integration with power-management circuits. In particular, controlled polymer–ceramic interfaces and optimized filler concentrations are expected to play a central role in developing flexible, environmentally acceptable and practically useful energy-harvesting systems.

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