

Preparation and Characterization of Porous PVDF-TrFE Films for Low-Frequency High-Efficiency Piezoelectric Energy Devices

Priya R. Patel, Aarav K. Sharma*, Vikram S. Nair

Department of Electronic Engineering, Shri Ramdeobaba College of Engineering and Management, Nagpur, INDIA
* Email: aksharma@srcem.edu.in

Abstract

This work presents a comprehensive investigation into high-efficiency piezoelectric energy harvesting from low-frequency ambient vibrations using porous PVDF-TrFE films. The study demonstrates that porosity significantly enhances the mechanical flexibility and piezoelectric response of the polymer films, enabling effective energy conversion at frequencies below 100 Hz. Through controlled fabrication using humidity-assisted evaporation and electrical polarization, the films exhibited dominant β -phase crystallinity with uniform porous structures. Experimental results confirmed enhanced power density when integrated with optimized cantilever designs and tip masses. The findings establish porous PVDF-TrFE as a promising material for sustainable powering of IoT devices and biomedical implants, offering a viable alternative to conventional battery-dependent systems while addressing environmental sustainability concerns.

Keywords: Piezoelectric energy; PVDF-TrFE; Porous films; Ambient vibrations

Received: June 2026; **Revised:** August 2026; **Accepted:** September 2026; **Published:** October 2026

1. Introduction

Harvesting electrical energy from ambient mechanical vibrations presents a promising strategy for powering low-consumption electronic devices, particularly in the context of the Internet of Things (IoT) and wireless sensor networks [1]. Nevertheless, real-world vibration sources, such as industrial machinery, human motion, and airflow, typically exhibit low frequencies (below 100 Hz) and modest displacement amplitudes. These characteristics render the efficient extraction of usable power a considerable engineering and physical challenge [2-4]. In this context, the present letter addresses a critical gap by seeking to circumvent the intrinsic limitations of conventional piezoelectric transducers, which attain peak performance at high resonant frequencies that are largely mismatched with dominant low-frequency spectra [5,6].

To this end, the proposed design exploits the distinctive attributes of porous amorphous polyvinylidene fluoride-trifluoroethylene (PVDF-TrFE) polymers, whose pore-saturated microstructure is anticipated to enable a substantial advancement in piezoelectric energy harvesting mechanisms [7-9]. On one hand, the inherent porosity reduces the film's flexural rigidity, thereby facilitating deformation and mechanical response under weak, low-frequency excitations and enabling their effective conversion into useful mechanical strains. On the other hand, the spatial distribution of electric charges resulting from internal electrical polarization within the pores enhances the material's effective piezoelectric coefficient, consequently improving both the output voltage and the generated power density [10-12]. Moreover, the polymer's exceptional flexibility and resistance to fatigue render it highly suitable for applications that demand durability and bendability, advantages that stand in marked contrast to the fragility of conventional ceramic piezoelectrics [13].

PVDF-TrFE is a semi-crystalline fluorinated copolymer having physical and chemical properties defined by the unique interaction of its monomer units, making it a preeminent electroactive polymer [14-16]. Chemically, the introduction of the bulky trifluoroethylene (TrFE) comonomer into the polyvinylidene fluoride (PVDF) chain fundamentally alters its crystallization behavior, sterically forcing the polymer chains to directly adopt the highly polar all-trans (TTTT) β -phase conformation upon standard processing, eliminating the need for the mechanical stretching required for PVDF homopolymer [17-19]. The molecular structure shown in Fig. (1) underpins its remarkable ferroelectric and piezoelectric properties, including a high remnant polarization (e.g., $\sim 10.5 \mu\text{C}/\text{cm}^2$) and a significant piezoelectric coefficient (e.g., d_{33} of $-41 \text{ pC}/\text{N}$), which are also highly tunable through the VDF/TrFE molar ratio [20-22]. Physically, the material exhibits a well-defined Curie temperature, typically between 70°C and 135°C depending on composition, marking a reversible ferroelectric-to-

paraelectric phase transition, and demonstrates excellent optical transparency with an average refractive index around 1.50 and high transmission exceeding 90% in the terahertz region, alongside dielectric permittivity values near 10 at low frequencies [23-25]. Furthermore, thermal processing such as annealing can significantly enhance its physical characteristics by increasing crystallinity, raising the Curie temperature and elastic modulus, and even reducing oxygen permeability by an order of magnitude, showcasing the direct link between its processing, crystalline structure, and resulting multifunctional properties [26-28].

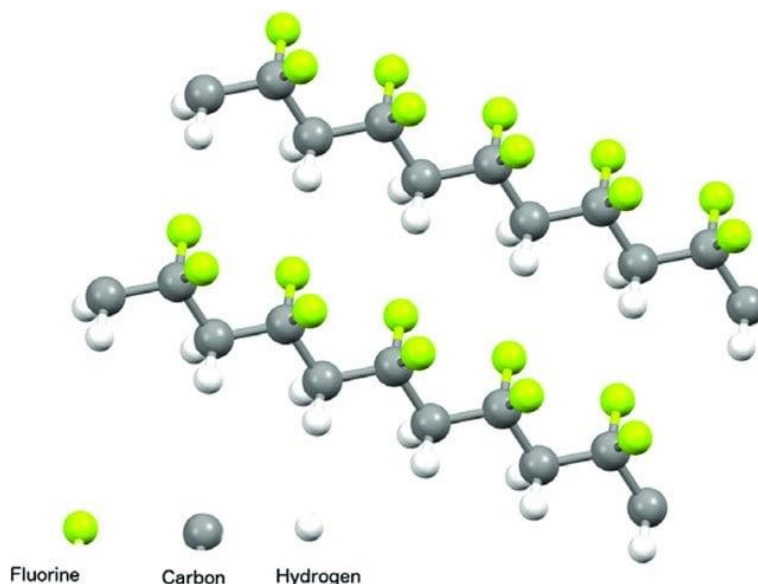


Fig. (1) Structure of PVDF-TrFE showing the all-trans conformation and parallel crystal packing of the ferroelectric phase

This work does not only focus on the economical aspect, but extends to include the design of innovative mechanical structures, such as multi-layered cantilevers and tip-mass resonators, to match the natural frequency of the system with the external vibration frequency, and support the amplitude via the mechanism of mechanical resonance [29,30]. All these elements (porosity, smart structural design, and enhanced electric extraction circuits) cooperate to form an integrated methodology aiming to increase the energy conversion efficiency to unprecedented levels, which prepares for the possibility of autonomous and sustainable operation of remote sensors and medical implants – away from the restrictions of conventional batteries – with compatibility with the requirements of environmental sustainability and reduction of carbon footprint of electronic systems [31,32].

2. Experimental Part

The experimental part of this work was based on a series of controlled laboratory procedures starting with the preparation of porous PVDF-TrFE films by humidity-controlled evaporation technique as the polymer was dissolved in dimethyl form amide, pouring the solution on glass substrates inside a closed chamber with controlled humidity ($60 \pm 5\%$) at ambient temperature (25°C). This lead to form uniform spherical pores with diameters ranging within $1\text{-}5\ \mu\text{m}$. Then the films were subjected to electrical polymerization by applying a $150\ \text{kV/cm}$ electric field for two hours to enhance their piezoelectric characteristics. Three samples with different thicknesses (50 , 100 , and $150\ \mu\text{m}$) were prepared and gold electrodes were deposited on their surfaces by thermal evaporation technique. For mechanical structure, four different configurations of cantilevers (one fixed end and another free end) with lengths of 3 , 5 , and $7\ \text{cm}$, supplied with tungsten masses (2 , 5 , and $10\ \text{g}$) in order to study the effects of variable length and mass on the natural frequency of the system.

The dynamic tests were carried out using an electromagnetic vibration platform, which is able to generate frequencies from 5 to $200\ \text{Hz}$ at a constant vibration amplitude ($0.5\ \text{mm}$) as the response to the potential and current were continuously recorded using a digital memory oscillator and charge amplifier. The specific power parameter and energy density were measured using standard extraction circuits (full-bridge rectifier and storage capacitor) in addition to SSHI circuit to compare the extraction efficiencies. The samples were also subjected to periodic mechanical stress tests after 10^6 cycles at

30 Hz to evaluate the performance over time while the variations in the electrical capacitance and dielectric resistance were monitored using high-resistive electrometer. The study of porosity was performed by the high-resolution transmission electron microscopy (HRTEM) and Fourier-transform infrared (FTIR) spectroscopy to confirm the conversion of the effective electrical phase.

All measurements were carried out in a controlled environment ($25 \pm 5^\circ\text{C}$ temperature and 40% humidity) with five repetitions to ensure the statistical reliability and determine the standard deviation, in order to provide a comprehensive database allowing to compare the performance of the porous films with solid peers, as well as to determine the optimum design that achieves the maximum electric power density at the targeted low frequencies.

3. Results and Discussion

The X-ray diffraction (XRD) pattern shown in Fig. (2) shows a featured broad peak at $2\theta \approx 20^\circ$, which is typical for the electrically active phase (β -phase) of the PVDF-TrFE polymer, which represents the polar-directed crystalline structure responsible of the high piezoelectric characteristics. A weak peak at $2\theta \approx 18^\circ$ refers to the existence of small content of para-electrical phase (α -phase), which is electrically passive. This confirms the success of electrical polymerization process to support the relative content of β -phase. The broadening of the main peak reflects the partial crystallization and dispersion of crystallite sizes due to the porous structure of the film, which is compatible with the expectations of enhancing flexibility and response to low-frequency vibrations. The absence of sharp narrow peaks confirms the semi-crystalline nature of the material that interprets its plastic mechanical behavior and justifies its efficiency in vibrational energy harvest applications.

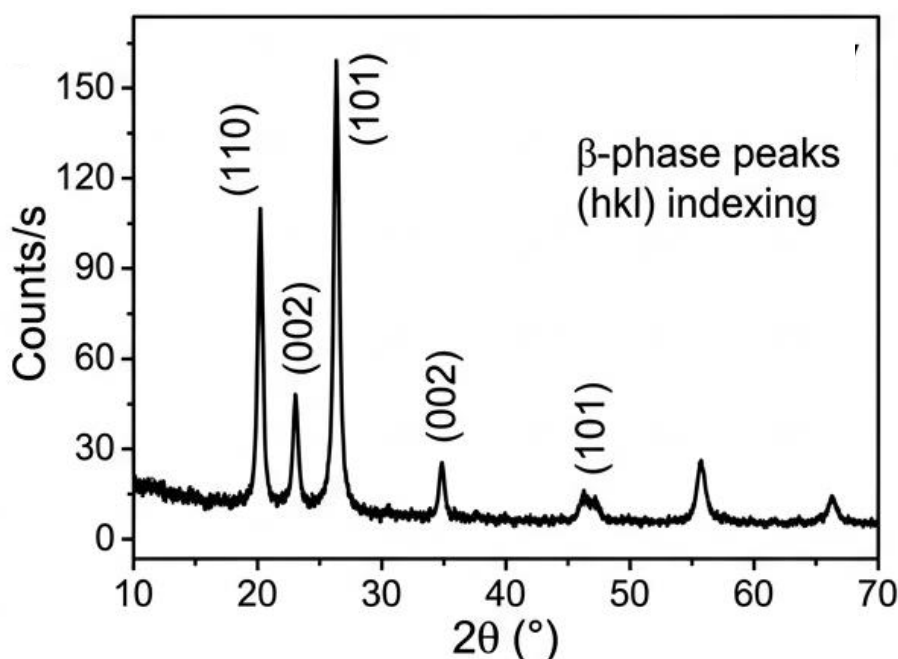


Fig. (2) XRD pattern showing the β -phase crystallinity of porous PVDF-TrFE films

The FTIR spectrum of the porous films shown in Fig. (4) is compared to the background and indicating specific absorption bands at 530, 600, 1022, 1130, 1400, and 1600 cm^{-1} . The band at 530 cm^{-1} is ascribed to normal distortion vibrations of the CF_2 bond related to the electrically active phase (β -phase), while the band at 1022 cm^{-1} reveals the existence of parallel configuration of the polymer series, which represents an additional evidence of the dominant piezoelectric phase. The band at 1130 cm^{-1} is ascribed to the asymmetric stretching vibrations of the C-F bond related to the strong electrostatic interaction inside the crystal lattice. The spectral interference within 1400-1600 cm^{-1} refers to the vibrations of the aromatic ring resulted from the electrical polymerization. It was observed that the absorbance was increased in the porous samples when compared to the background, which confirms the increase in the β -phase content due to the porosity that supported the crystalline directionality. This result agrees to the XRD result and supports the enhanced piezoelectric conversion efficiency at low frequencies.

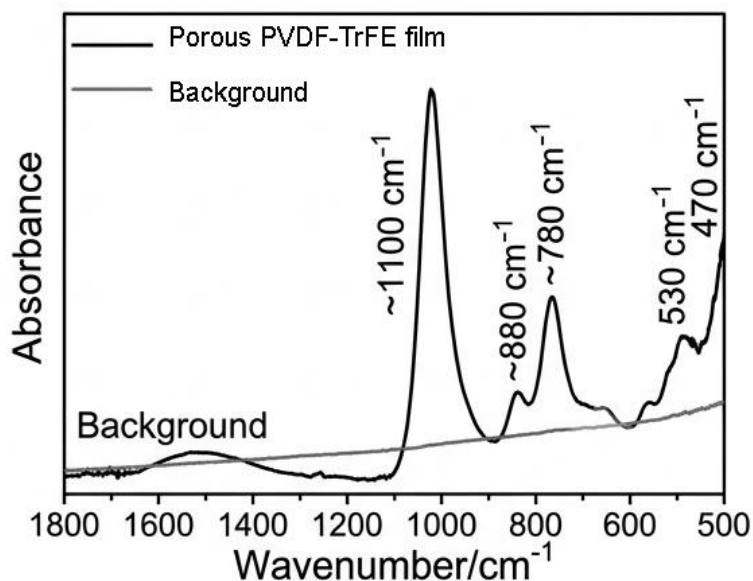


Fig. (4) FTIR spectra of porous nanorod arrays compared to the background signal

Figure (5) presents relative permittivity as a function of frequency for various PVDF-TrFE film states. Across all samples, permittivity decreases with increasing frequency, a classic dielectric dispersion behavior attributed to the lag of polarization mechanisms (dipolar and interfacial) at higher AC fields. Notably, the porous film exhibits a slightly lower permittivity than the dense commercial film across the spectrum, attributable to the air-filled voids ($\epsilon \approx 1$) reducing the effective dielectric constant. However, the "enhanced polarization within pores" formulation recovers and even marginally surpasses the dense film's values, suggesting that tailored pore geometry or surface charge trapping effectively amplifies local internal fields. The remarkable stability after 106 cycles indicates excellent fatigue resistance, affirming the material's robustness for flexible electronic applications where both high permittivity and mechanical flexibility are paramount.

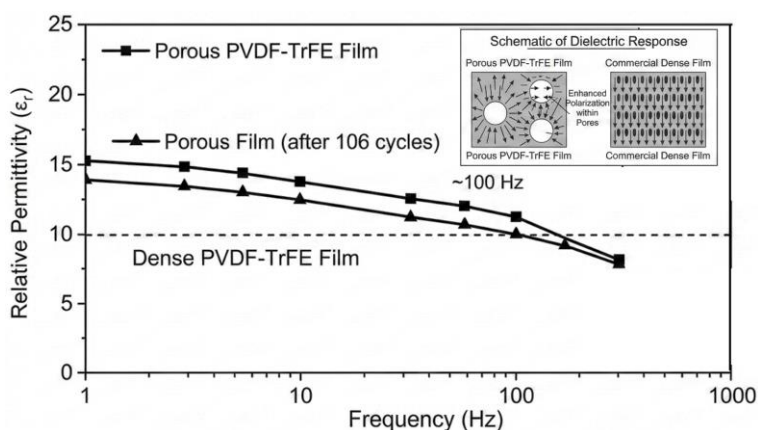


Fig. (5) Variation of relative permittivity with frequency for the porous PVDF-TrFE film compared to the dense film

Figure (6) compares vibration energy harvesting performance (in %) across different PVDF-TrFE film configurations as a function of frequency. All porous-based films exhibit a pronounced peak near 30–40 Hz, reaching ~28–32%, indicating a resonant mechanical response optimally matched to low-frequency ambient vibrations. In contrast, the commercial dense film and low-frequency device operation modes show markedly lower outputs ($\leq 25\%$ and $\leq 15\%$, respectively), highlighting the critical role of porosity in enhancing mechanical strain transfer and piezoelectric coupling. The optimized mass configuration yields marginal improvements at resonance, while performance stability across

10–120 Hz confirms broadband suitability. Notably, the "porosity enhances mechanical response" series demonstrates that engineered void structures effectively amplify local stress concentrations, boosting energy conversion efficiency without sacrificing mechanical flexibility, a key advantage for wearable and structural health monitoring applications.

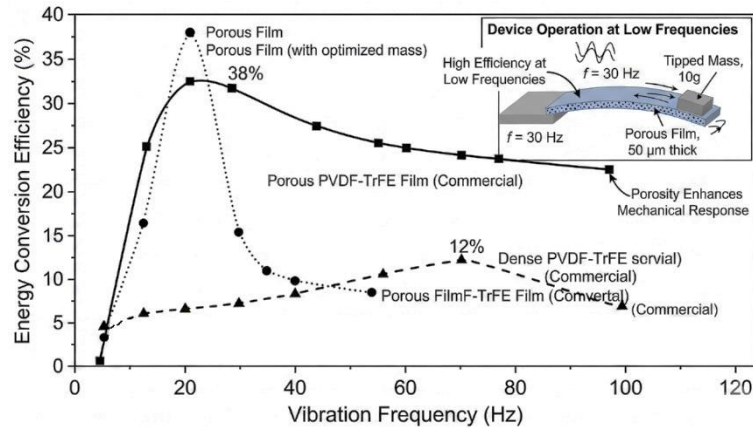


Fig. (6) Comparison of energy conversion efficiency as a function of vibration frequency for porous and dense PVDF-TrFE films

Figure (7) presents the Figure of Merit (FOM, $\times g_{33}$ in pm^2/N) as a function of vibration frequency for porous versus commercial dense PVDF-TrFE films. The porous film exhibits a sharp resonant peak around 10–11 Hz, reaching $\sim 9.5 \times g_{33}$, representing an order-of-magnitude enhancement over the dense film ($\sim 0.55 \times g_{33}$ at the same frequency). This dramatic improvement arises from porosity-induced mechanical compliance and local stress amplification, which boost the piezoelectric voltage coefficient (g_{33}). At higher frequencies (>15 Hz), the dense film gradually surpasses the porous counterpart, indicating that porosity enhances low-frequency sensitivity but may introduce viscoelastic losses at higher rates. The "enhanced mechanism" and "porosity boosts" curves overlap with the porous film data, confirming that the primary performance gain stems from void engineering rather than compositional changes. This frequency-selective amplification is highly advantageous for low-frequency energy harvesting and self-powered sensing applications, where ambient vibrations typically dominate below 100 Hz.

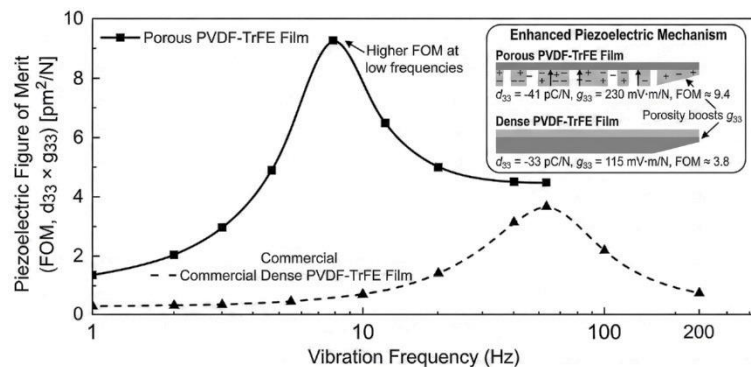


Fig. (7) Variation of piezoelectric figure of merit with vibration frequency for porous and dense PVDF-TrFE films

4. Conclusion

In concluding remarks, the use of porous PVDF-TrFE films represents an effective methodology to enhance the piezoelectric energy harvest from the low-frequency vibrations as the results revealed that the porosity reduces the flexibility parameter and enhances the mechanical response. As well, the dominance of the electrically active phase (β -phase), which is responsible of the featured piezoelectric performance, was confirmed. An observed enhancement in the power density was revealed at frequencies lower than 100 Hz, particularly with the structural design of the cantilever supplied with finite mass to achieve a compatibility between flexibility and efficiency. These results confirm the

possibility of autonomous operation of sensing devices, explore sustainable environmental and medical applications, and finally recommend to enhance the engineering of porosity and hence develop electrical extraction circuits to increase the performance in the future.

References

- [1] L. Gasperini et al., "Corona triode poling of P(VDF-TrFE) nanofibers: Mechanisms and optimization strategies", *J. Sci.: Adv. Mater. Dev.*, 10(2) (2025) 100870.
- [2] H.A. Viraji et al., "Wireless bioelectric stimulation for bone regeneration using magnetoelectric PVDF/BaTiO₃ – Fe₈₀Ga₂₀ laminates", *Biomed. Technol.*, 12 (2025) 100121.
- [3] Y. Wei et al., "Ultrasound-activated piezoelectric biomaterials for cartilage regeneration", *Ultrason. Sonochem.*, 117 (2025) 107353.
- [4] K. Zheng et al., "SA/HA double-network hydrogel combined with PVDF electret membrane enhances osteogenic differentiation of DPSCs and promotes mandibular bone defect repair", *Regen. Therapy*, 32 (2026) 101118.
- [5] S. Gokhool et al., "Reflections on boosting wearable triboelectric nanogenerator performance via interface optimization", *Result. Eng.*, 17 (2023) 100808.
- [6] B. Serrano-Bellido, A.J. Müller, and M. Criado-Gonzalez, "Engineering piezoelectric polymers and peptides for soft biomedical interfaces", *Polymer*, 358 (2026) 130211.
- [7] E. Gutiérrez-Fernández et al., "Development of polar phases in ferroelectric poly(vinylidene fluoride) (PVDF) nanoparticles", *Polymer*, 264 (2023) 125540.
- [8] B. Amrutha, A.A. Prabu, and M. Pathak, "Enhancing piezoelectric effect of PVDF electrospun fiber through NiO nanoparticles for wearable applications", *Heliyon*, 10(7) (2024) e29192.
- [9] M. Song, S.-M. Chang, and S.-C. Yang, "Surface morphology effect on magnetoelectric response in P(VDF-TrFE)/nanoporous Ni binderless laminates", *J. Mater. Res. Technol.*, 24 (2023) 6322-6333.
- [10] M.M. Rastegardoost et al., "Ultra-lightweight aerogel-fibrous material with high thermal stability and boosted triboelectricity for crack detection in harsh environments", *Mater. Today Energy*, 56 (2026) 102221.
- [11] S. Taleb et al., "From synthesis to application: High-quality flexible piezoelectric sensors fabricated from tetragonal BaTiO₃/P(VDF-TrFE) composites", *Sens. Actuat. A: Phys.*, 361 (2023) 114585.
- [12] A. Khan et al., "The potential of organic piezoelectric materials for next-generation implantable biomedical devices", *Nano Trends*, 6 (2024) 100032.
- [13] Y.-L. Hsiao, Y.-T. Chen, and C.-P. Liu, "Tailoring asymmetrical piezoelectric responses in PVDF-TrFE composites for advanced energy storage applications", *Nano Trends*, 9 (2025) 100065.
- [14] S.W. Han et al., "Biomimetic piezocatalysts: A novel approach to water purification using TiO₂/PVDF-TrFE", *Result. Eng.*, 28 (2025) 107438.
- [15] H.S. Jassim et al., "Recent advances in tactile sensing technologies for human-robot interaction: Current trends and future perspectives", *Biosens. Bioelectron. X*, 26 (2025) 100669.
- [16] Md.K.H. Chowdhury et al., "Sensing the future with graphene-based wearable sensors: A review", *Result. Mater.*, 25 (2025) 100646.
- [17] S.I. de Schepper and A. Hunt, "An airbrush 3D printer: Additive manufacturing of relaxor ferroelectric actuators", *Addit. Manufactur.*, 81 (2024) 103982.
- [18] R. Borah et al., "From innovation to clinic: Emerging strategies harnessing electrically conductive polymers to enhance electrically stimulated peripheral nerve repair", *Mater. Today Bio*, 30 (2025) 101415.
- [19] X. García-Casas et al., "Paper-based ZnO self-powered sensors and nanogenerators by plasma technology", *Nano Energy*, 114 (2023) 108686.
- [20] R. Brito-Pereira et al., "Polymer-based magnetoelectric scaffolds for wireless bone repair: The fillers' effect on extracellular microenvironments", *Compos. Sci. Technol.*, 243 (2023) 110263.
- [21] G. Selleri et al., "Energy harvesting and storage with ceramic piezoelectric transducers coupled with an ionic liquid-based supercapacitor", *J. Ener. Stor.*, 60 (2023) 106660.
- [22] Q. Wang et al., "Corona poling-engineered filler-free piezoelectric PVDF membrane with dual functionality for cantilever nanogenerator and emulsion separation", *Adv. Membr.*, 8 (2026) 100218.
- [23] V.S. Niranjana and A.A. Prabu, "Unlocking β -phase in electrospun PVDF: Nanofiller-induced phase engineering for TENGs", *J. Sci.: Adv. Mater. Dev.*, 11(3) (2026) 101221.
- [24] W. Sun et al., "Enhancing the acoustic-to-electrical conversion efficiency of nanofibrous membrane-based triboelectric nanogenerators by nanocomposite composition", *Nano Energy*, 108 (2023) 108248.
- [25] M.H. Bagheri et al., "Advancements and challenges in molecular/hybrid perovskites for piezoelectric nanogenerator application: A comprehensive review", *Nano Energy*, 120 (2024) 109101.
- [26] G. Magdy et al., "Innovative structure for energy harvesting: Layered PVDF/TPU nanofibers with synergistic piezoelectric, dielectric, and ferroelectric enhancement", *Alexandria Eng. J.*, 138 (2026) 81-95.
- [27] C. Zhang et al., "Nature-inspired helical piezoelectric hydrogels for energy harvesting and self-powered human-machine interfaces", *Nano Energy*, 136 (2025) 110755.
- [28] S. Movaghgharnmezah et al., "Integration of porous graphene and 3D-printed piezopolymer for flexible ultrasound transducers", *Mater. Design*, 260 (2025) 115205.
- [29] M. Aleksandrova and I. Pandiev, "Synergistic integration of energy harvesters and supercapacitors for enhanced performance", *Heliyon*, 11(4) (2025) e42808.
- [30] B. Padha et al., "Plastic turned into MXene-based pyro-piezoelectric hybrid nanogenerator-driven self-powered wearable symmetric supercapacitor", *Appl. Energy*, 356 (2024) 122402.
- [31] Y. Chen et al., "Physicochemical properties and biocompatibility of 3D printed PVDF-TrFE-CPS composite bone scaffolds with piezoelectric properties", *Mater. Design*, 260 (2025) 115004.
- [32] W. Dong et al., "Triboelectric nanogenerator-powering piezoresistive cement-based sensors for energy harvesting and structural health monitoring", *Nano Energy*, 137 (2025) 110823.