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Sustainable Power: A Review of Recent Advancements in PVDF-Based Textiles for Energy Harvesting Applications

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Abstract

Recent advancements in the development and utilization of Polyvinylidene fluoride (PVDF)-based textiles for energy harvesting have shown promising potential in various applications. PVDF-based textiles have shown versatility and efficiency in converting ambient energy into viable electrical power sources, with applications in medical and health monitoring, sports and fitness, transportation, military and defence, structural health monitoring, industrial automation, environmental sensing, and soft robotics. Key design considerations such as electrode placement, structural integrity, and flexibility optimize the performance and durability of these textile energy harvesters. The article also highlights challenges and limitations associated with these materials and outlines potential future directions, such as wearable electronics, Internet of Things (IoT), biomedical applications, hybrid energy harvesting systems, and advanced materials and nanostructures. Overall, PVDF-based textiles are a sustainable and efficient solution for energy harvesting, with far-reaching implications for various industries and applications.

Keywords: Energy Harvesting;Renewable Energy;Smart Textiles; Piezoelectricity; PVDF; Nanogenerators

1. Introduction

Energy harvesting technologies play a crucial role in powering electronic devices, IoT sensors, and various electronic applications in both consumer and industrial sectors [1].These technologies harness ambient energy sources like mechanical vibrations, solar radiation, and thermal gradients to generate electricity, reducing reliance on conventional batteries and extending the operational lifetime of electronic devices [2].

Techniques like piezoelectricity, photovoltaics, thermoelectricity, and electromagnetic induction, as shown in, convert mechanical vibrations into electrical energy, contributing to self-sufficient and environmentally friendly energy solutions [3]. The integration of energy harvesting techniques and smart textiles is poised to revolutionize sustainability and technology, enabling fabrics to generate power for our interconnected world[4]. Polyvinylidene fluoride (PVDF)-based textiles have emerged as promising candidates for energy harvesting applications, offering flexibility, lightweight, and compatibility with textile fabrication processes like weaving, knitting, and coating [5, 6].

This review article provides a comprehensive overview of recent investigations and advancements in using PVDF-based textile energy harvesters in various application domains. Specifically, the following points will be discussed: fabrication techniques, design considerations, performance evaluation methods, applications, recent investigations, challenges, and future directions of PVDF-based textile energy harvesters. By synthesizing the latest research findings and developments in this field, this article seeks to highlight the potential of PVDF-based textiles as efficient and sustainable materials for harvesting energy from the surrounding environment.

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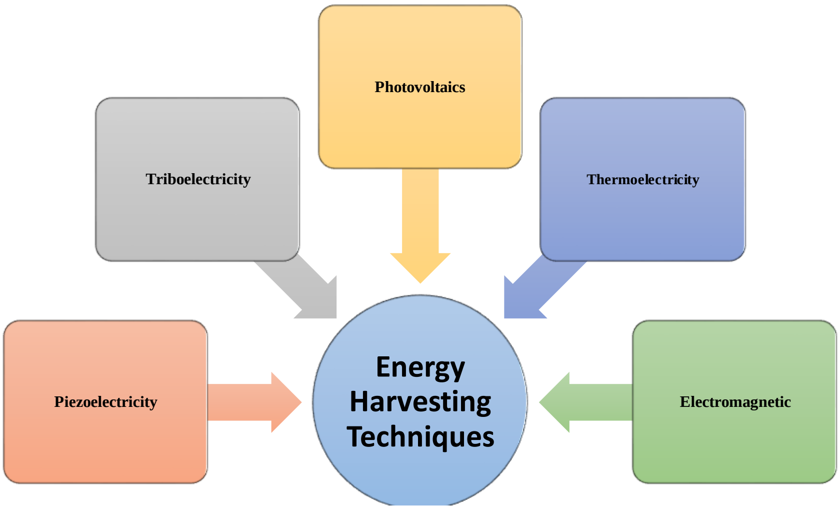

Fig. 1 Techniques of Energy Harvesting

1.1 Piezoelectric Textiles: Fundamentals and Properties

Piezoelectric textiles utilize the piezoelectric properties of materials like Polyvinylidene Fluoride (PVDF) and PZT to convert mechanical energy into electrical power [7]. Discovered by the Curie brothers in 1880, this technology captures ambient vibration energy from infrastructure, machinery, and the natural environment [8]. By integrating piezoelectric flexible polymers into textiles and garments, biomechanical energy from the human body can be converted into usable electricity through movement and activity [9]. Piezoelectric materials are used in various fields, including medical, military, environmental, and commercial sectors, for applications such as infrared detectors, radiometers, laser detectors, energy-sensitive equipment, photoconductive or photovoltaic detectors, pollution monitoring, and gas analysis [3].

1.2 Basic Principle of piezoelectricity

Piezoelectric materials are specialized crystalline types with non-centrosymmetric charge centers[10]. When mechanical influences like pressure, impact, vibration, stretching, or stress are applied, they transform into forces acting on subunits and ions, causing relative shifts in the locations of oppositely charged atoms within non-centrosymmetric unit cells [11]. This can result in a net polarization of positive and negative charges on the material's surface, generating an electric field and causing voltage differences between electrodes, as shown in **Fig. 2.**[12]. The piezoelectric effect is a reversible phenomenon, causing charged ions to move and leading to physical deformation [13]. Piezoelectric materials have various subset features, including ferroelectricity, pyroelectricity, and triboelectricity [14].

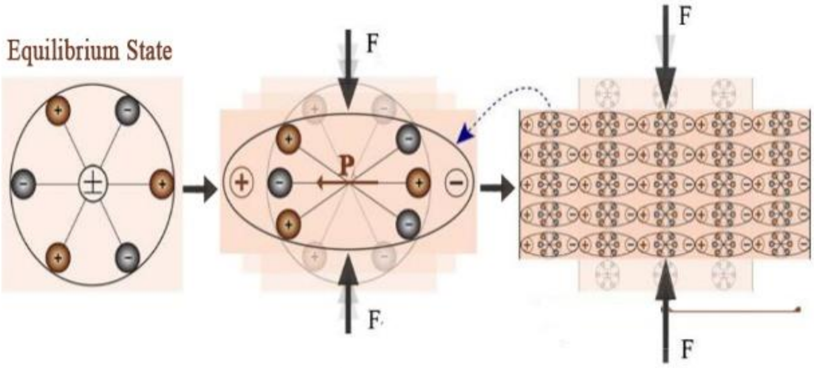

Fig. 2 A schematic illustration shows the transformation of the crystal lattice of piezo material from equilibrium state to polarization state (P) after applying mechanical force (F) [12]

1.3 Classification of Piezoelectric Materials

Piezoelectric materials are categorized, as shown in **Table 1** into naturally crystalline, synthetically crystalline ceramics(inorganic), and polymeric (organic) subgroups [15-17].

Table 1 Classifications of Piezoelectric Materials

Natural Piezoelectric Materials	Synthetic Piezoelectric Ceramics	Synthetic piezoelectric Polymerics
Quartz, Rochelle salt, berlinite, cane sugar, topaz, tourmaline, wood, silk, enamel, dentin, tendon, and bone provide electromechanical coupling. [17]	Lead zirconate titanate (PZT), Zinc oxide(ZnO), Barium titanate($BaTiO_3$), Lead titanate ($PbTiO_3$), [8] Lithium niobate ($LiNbO_3$), Lithium tantalite ($LiTaO_3$), Sodium tungstate(Na_2WO_3), Lead lanthanum, Zirconate titanate (PLZT), [18] Potassium niobate ($KNbO_3$),$Ba_2NaNb_5O_5$ and $Pb_2KNb_5O_{15}$[19]	PVDF and its co-polymers like: Polyvinylidene fluoride co-tetrafluoroethylene (PVDF-TrFE),Polyvinylidene fluoride-co-hexafluoropropylene (PVDF-HFP),Polyvinylidene fluoride-co-chlorotrifluoroethylene (PVDF-CTFE), Polyvinylidene fluoride-co-tetrafluoroethylene (PVDF-TFE),),[3], [20]

1.3.1 Polyvinylidene Fluoride (PVDF)

Polyvinylidene fluoride (PVDF), also known as PVF2, is a specialized polymeric material with unique properties due to its strong bond between carbon and fluorine atoms and the fluorine shielding of the carbon backbone[5]. Invented in 1948 by Ford and Hanfordand, PVDF was used for packaging films and protective coatings [21]. PVDF is now marketed under various brand names including Kynar® from Arkema, KF® from Kureha, Solef®, and Hylar® from Solvay [5].

1.3.1.1 Manufacturing of PVDF Polymer

PVDF is a polymer produced through an aqueous free-radical emulsion and suspension polymerization using vinylidene fluoride (VDF) as a monomer, as shown in **Fig. 3**. [22]. The process involves combining VDF with water and surfactants, heating to 50-80°Cfor approximately 50-100 minutes and agitating mechanically to generate free radicals. The resulting powder is pelletized and molded into various shapes, with common yields exceeding 85% conversion [23].

Fig. 3 Polymerization of 1,1-difluoroethylene.[22]

1.3.1.2 Overview of PVDF Properties

PVDF is a promising piezoelectric material for textiles, offering mechanical compliance, chemical resistance[24], UV radiation and hydrolysis resistance, wear resistance, physiological inertness, thermal stability, compatibility with fiber and fabric manufacturing processes, and applications like sensors and fuel cells [3].

1.3.1.2.1 Crystalline Structural Properties

Polyvinylidene fluoride (PVDF) is a linear, semicrystalline, and thermoplastic homopolymer in the fluoropolymer family. The simple linear chemical structure (CH2–CF2) of PVDF allows for greater flexibility due to its lack of side chains or pendant groups, allowing carbon-carbon bonds to rotate freely and removing restrictions on intermolecular interactions), as shown in **Fig. 4**[5, 25].

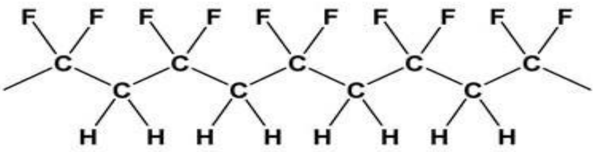

Fig. 4 The Molecular structure of PVDF polymer[5]

The degree of crystallinity ranges from 35-70%, which is crucial for its applications in piezoelectric materials. Crystalline regions generate electric charges, while amorphous regions enhance the material's flexibility and mechanical properties [26, 27]. Crystalline regions are responsible for pyro-, piezo-, and ferroelectric properties, with the β-phase and γ-phase being most interesting for piezoelectricity [28]. Amorphous regions lack a regular structure, are disordered with random chain orientation, contain weaker intermolecular forces, facilitate crystallite motions, and prevent a coherent net-sum polarization vector. These regions contribute to the material's flexibility and processability, often found between the crystalline domains [24, 29].

1.3.1.2.1.1 Crystalline Polymorphs of PVDF

PVDF, a piezoelectric material, has distinct crystalline polymorphs (phases) influencing its properties. The primary phases are α (alpha), β (beta), γ (gamma), δ (delta), and ε (epsilon), each contributing uniquely to the material's structural and functional attributes.[28] The most investigated and used crystalline phases in recent scientific research are α, β, and γ, as shown in **Fig. 5**[5, 30].

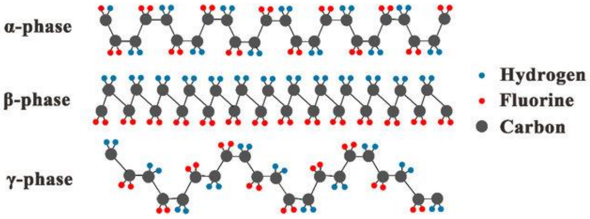

Fig. 5 The structures of the most investigated and used crystalline PVDF phases in recent scientific research [30]

α-Phase:
The α-phase is the most common crystalline form at room temperature, obtained from melt crystallization. It features monoclinic unit cells and a centrosymmetric crystal lattice, making it non-piezoelectric. Chains have TGTG' conformations, preventing effective dipole alignment and inhibiting crystallization and phase packing [31]. The molecular arrangement in the α-phase is a random coil configuration, limiting its application in piezoelectric devices [3].

β-Phase:
The β-phase is crucial for piezoelectric behaviour due to its high dipole moment and electroactive features. It is essential in the all-trans (TTT) planar zigzag conformation of chains, generating an electric charge in response to mechanical stress [32]. PVDF's unique β-phase properties make it versatile in various applications, including actuators, biosensors, energy harvesting materials, audio devices, transducers, and non-volatile memories [24]. The β-phase can be enhanced by various scientific methods and processing techniques such as mechanical stretching, electric field poling solvent casting nucleating agents, and blending with copolymers and polymers.
Mechanical stretching, which involves applying mechanical stress to PVDF films, is an established method [33]. Electric field poling aligns molecular dipoles along the direction of the electric field, favouring the formation of the piezoelectrically active β-phase [34]. Solvent casting involves dissolving PVDF in a solvent, casting it into a film, and evaporating the solvent [33]. Nucleating agents like nanoparticles can aid in the formation of the β-phase by acting as catalysts [35]. Blending with copolymers and polymers can alter crystallization kinetics and promote the formation of the β-phase, with the choice of copolymer and blending ratio adjusted to optimize piezoelectric properties. Examples of blending methods include PVDF-TrFE, P(VDF-TrFE-CTFE)[36], PMMA poly (methyl methacrylate)-PVDF, Polyethylene terephthalate (PET)-PVDF[37], carbon-based materials [38], metal oxides, and graphene [39].

γ-Phase:
The γ-phase, characterized by a combination of polar and non-polar regions, occurs at high temperatures and is characterized by a TTTGTTTG' sequence with alternating trans and gauche bonds, which inhibits effective crystallization and reduces potential polarity and ferroelectric properties compared to the β-phase [33, 40].

δ-Phase:
The δ-phase, characterized by defects and less ordered structure, is formed by polarizing α-phase crystals at high electric fields, resulting in a mirror-like α-phase with orthorhombic structure. Its complex crystal structure, moderate polarization, and piezo/pyro/ferroelectric properties can be formed through special processing conditions [25].

ε-Phase:
The ε-phase, a recently discovered phase in PVDF, exhibits an all-trans (TTT) planar zigzag conformation similar to the β phase, with a ferroelectric nature lower than the β phase [28].

1.3.1.2.2 Electroactive Properties

Polyvinylidene fluoride (PVDF) is a unique material with unique electroactive properties, particularly in its piezoelectric phases. It generates an electric charge in response to mechanical stress or deformation, with the β-phase being crucial for piezoelectricity with an average coefficient (d_{33}) of 24-34 (pC/N) [41]. The piezoelectric coefficient is influenced by stretch ratio, temperature, crystallinity, and poling conditions. The piezoelectric coefficient of PVDF is calculated using the equation of (d33=dq/dF), where the accumulated electric charge is dq, and the applied mechanical force is dF [42]. PVDF exhibits ferroelectric behaviour with spontaneous, reversible electric polarization under an applied electric field [43]. It also exhibits pyroelectric behaviour, especially for the β phase, generating a charge in response to changes in temperature [24]. PVDF's strong triboelectric properties make it useful for energy harvesting and electrostatic sensing [44].Its high dielectric constant (ε), which ranges from 10 to 12, is crucial for storing electrical energy in an electric field, making it ideal for applications like capacitors and sensors [45]. PVDF is a highly effective electrical insulator with a volume resistivity of 1-2 X 10^{14} Ω.cm [46]. Its molecular properties, including strong localized bonding, large band gaps, and packing configurations, enhance its electrical resistance. Its high dielectric strength, low conductivity, and low dielectric loss tangent make it suitable for various dielectric and cabling applications [8]. At a specific temperature (Tc), PVDF undergoes the curie transition, transforming it into a non-polar paraelectric state. The Curie temperature is around 140-160°C [13].

1.3.1.2.3 Mechanical Properties

PVDF is a high-strength material with a tensile strength of 36-56 MPa, flexural strength of 70-120 MPa, and a moderate Young's modulus (~1.5 to 2 GPa). [47] Its flexural strength is crucial for structural integrity and deformation responsiveness. PVDF's elongation at break varies from 20-50%, with shrinkage affecting flexibility and resilience. Its hardness ranges from 65-80 Shore D, contributing to durability and wear resistance.[46] Its compressive strength is typically 80-100 MPa, and its low creep ensures deformation resistance under sustained load. [48]

1.3.1.2.4 Physical Properties

PVDF's physical properties are influenced by its architectural structure, ranging from translucent to opaque white [49]. Its density varies between 1.68 g/cm3 for amorphous PVDF, 1.75–1.78 g/cm3 for crystalline regions, and 1.97 g/cm3 for β crystalline form[33,50]. Its molecular weight ranges from 50,000 to 500,000 g/mol and melt viscosity from 100 to 50,000 Pa.s at 200ºC. PVDF has a low penetration value and poor permeability in gases and liquids compared to other fluoropolymers [5] ornatural fibers[51]. Its exceptional UV and high energy radiation resistance makes it a preferred material for demanding applications [3].

1.3.1.2.5 Thermal Properties

PVDF, a thermoplastic material with a crystal structure, is crucial for smart textiles [52] and industrial processes due to its melting point (160-170°C), mold temperature (40-100°C) [5], glass transition temperature (Tg) (-32 40°C) [52] , and thermal conductivity (0.165-0.185 W/m.K), which influences its use in various industries. PVDF has excellent properties for sensors, actuators, and biomedical devices due to its thermal stability [53].

1.3.1.2.6 Chemical Properties

PVDF, a semi-crystalline material, is renowned for its chemical inertness and resistance to various chemicals, making it suitable for corrosion-resistant coatings on chemical process equipment and architecture panels [54]. It is soluble in polar solvents like esters, DMAc, acetone, and DMF, and resistant to mineral and organic acids, and aliphatic and aromatic hydrocarbons[55]. However, PVDF can be sensitive to environmental conditions during processing, such as higher temperatures, up-normal UV radiation, and exposure to strong alkalis. These factors can potentially lead to degradation over time, affecting adversely its piezoelectric properties and forming smaller fluorinated molecules, which could pose environmental and health risks [56].

1.3.1.2.7 Biological and Environmental Properties

PVDF, a recyclable thermoplastic polymer, is safe for various applications due to its high resistance to chemicals, UV radiation, and extreme temperatures [57]. It is biocompatible, non-toxic in the normal conditions of processing, and doesn't support microbial growth, making it ideal for medical applications like implants and drug delivery systems. Its biocompatibility and non-toxic nature make it a valuable material [3].

1.4 Fabrication Techniques for PVDF-based Textiles:

PVDF polymers are processed into fibers [58], composites [59], coatings, and woven membranes [1] to obtain PVDF-based textiles using different fabrication techniques melt casting [60],solution casting [61], spin coating [62], film casting [63]and weaving [64]and knitting [32]. In the recent 5 years, various advancements have been investigated using different fabrication techniques of PVDF for energy harvesting.

1.4.1 Melt Casting

Melt casting is a process where PVDF polymer is heated above its 230°C melting point, transferred into moulds, and cooled to create a desired shape, used in various fabrication techniques like compression moulding, injection moulding, extrusion, hot embossing, film extrusion, melt spinning, melt blowing, and 3D printing [57, 62].Many studies have been investigated recently for fabricating PVDF polymers using the melt casting technique.

Melt extrusion and leaching techniques were used by Zhu et al. to fabricate a piezoelectric generator (PEG) based on micro ribbon structured polyvinylidene fluoride (PVDF), resulting in excellent piezoelectric output (3.1 V, 25 nA), high sensitivity (0.092 V/N), short response time (70 ms), and long-term stability. These characteristics make this PEG work as a self-powered sensor in sportive wearables with high performance low-cost, facile, continuous, and eco-friendly [65].

Mokhtari et al. have created energy generators and sensors from nanostructured piezoelectric nanocomposite fibers using knitting, braiding, and weaving techniques. Through a melt-spinning process, they developed hybrid piezoelectric PVDF fiber with and without barium titanate (BT) nanoparticles. The hybrid PVDF fiber with BT nanoparticles with 98% of the electroactive β-phase generated a maximum output open circuit voltage of 4 V and a power density of 87 µW cm^{-2} during cyclic compression. They have demonstrated a knee sleeve prototype based on a PVDF/BT wearable device for monitoring real-time precise healthcare. This process is also scalable for industrial strain sensing and energy harvesting smart textiles, allowing for various sensing responses like hydraulic and pneumatic pressure sensors with tuneable sensitivity [32].

1.4.2 Solution Casting

Solution casting involves dissolving a polymer in a solvent like DMF, DMSO, [23] DMAC, or NMP, [66] and depositing it on a non-adherent substrate to create porous polymer membranes. PVDF solubility depends on the solvent's molecular weight, temperature, and polarity. Processing techniques include electrospinning and solution blow-spinning[27].Electrospinning offers precise fiber control but requires complex high-voltage equipment and environmental sensitivity [67], while solution blow spinning is simpler, cost-effective, and easier to scale up for high production, but may produce less uniform fibers [27].

Wang et al. developed piezoelectric film pressure sensors made of aligned PVDF-TrFE/MXene composite nanofibers were fabricated via electrospinning, resulting in significantly improved piezoelectric response compared to pure PVDF-TrFE films. The composite films can generate a peak-to-peak output voltage of 1.58 V under sinusoidal force, three times more than pure PVDF-TrFE fibrous membrane. These flexible and lightweight film sensors can be applied on skin or fabric to monitor the daily activities of the human body and harvest mechanical energy once attached to the keyboards and other daily-used devices. The PVDF-TrFE/MXene composite system is capable of sensing humidity, which can be prepared as humidity-responsive pressure sensors after appropriate modification. In addition, it has great potential in self-powered multi-response electronic skin [68].

Wu et al. proposed a study on piezoelectric yarns made from cesium lead halide perovskite decorated PVDF nanofibers. The yarn was assembled using a one-step electrospinning process, with the nanofibers directly and coaxially deposited on the stainless-steel yarn by a customized collector, as shown in **Fig. 6** . The CsPbI2Br decorated PVDF nanofibers showed higher piezoelectric performance. The PENG yarn, with HI_0.45 nanofibers and annealed at 150 °C for 10 min, demonstrated the best output voltage (8.4 V) and current (1.92 μA). The piezoelectric yarns can be twisted, bent, knotted, braided, and woven while electrical signals can be generated After 3 months of fabrication, the PENG yarns maintained their performance during 19,200 cycles of mechanical stresses, showing excellent stability and durability, making them promise for harvesting mechanical energy from body movement and assembling into flexible electronic textiles, especially for fitness monitoring [69].

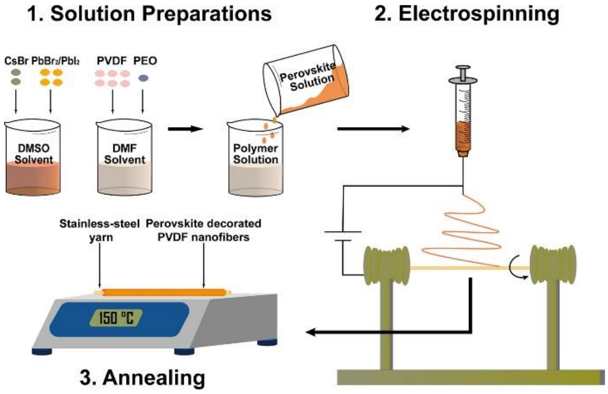

Fig. 6 A schematic of preparation steps for perovskite decorated PVDF nanofibers on the stainless-steel yarn.[69]

Dai et al. proposed a piezoelectric sensing fabric using core-spun Cu/P(VDF-TrFE) nanofibrous yarns. These yarns were fabricated by P(VDF-TrFE) as a piezoelectric material and Cu wire as an inner electrode layer through a one-step conjugate electrospinning process. The fabric demonstrated good flexibility, breathability, mechanical stability, and sensing capability. It could generate a current of 38 nA and a voltage of 2.7 V under 15 N pressure, allowing human motion monitoring and wireless transmission to smartphones. This study may provide a simple and promising approach to designing a smart textile for human motion monitoring [9].

PVDF piezoelectric yarn sensor was proposed by Kang et al. based on electrospinning and 2D braiding technology and is used for real-time online damage monitoring in advanced 3D textile composites. This sensor, embedded into 3D orthogonal composites, generates 1V voltage and sustains long-term cycles at 4Hz. The sensor's potential in damage monitoring as a piezoelectric sensor in composites is demonstrated. [59]

A waterproof and breathable triboelectric nanogenerator (WB-TENG) was designed by Lan et al. to monitor plant health in real-time, capable of harvesting typical environmental energy from wind and raindrops, enabling high agricultural yield. The WB-TENG is made of poly (vinylidene fluoride-co-hexafluoropropylene) nanofibers embedded with fluorinated carbon nanotubes (F-CNT) microspheres which was realized by simultaneous electrospinning and electro-spraying, respectively. It has a high output power density of 330.6 μW cm-2, breathability, and hydrophobicity, and can self-attach to plant leaves without compromising plant physiological activities. This technology shows potential for self-powered agriculture systems. [70]

A coaxial electrospinning technique has been used by S. Wang et al. to fabricate silk fibroin/poly (vinylidene difluoride) piezoelectric nanofibers (NFs) with excellent flexibility, as shown in **Fig. 7**. The strong interaction between SF and PVDF promotes β-phase nucleation, enhancing output performance. The SF/PVDF NFs achieved an output of 16.5 V with 290 nA current, over 6-fold higher than pure PVDF NFs. The composite NFs demonstrated excellent stability over 2000 cycles without performance decline. The composite NFs can detect mechanical stimulation from joint bending, making them potential for self-powered sensors and smart car control achieving its application in the human-machine interaction [71].

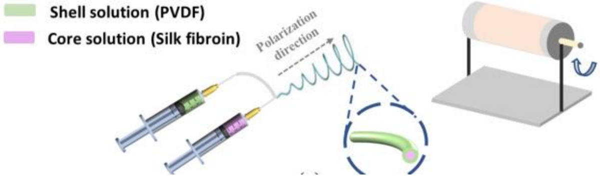

Fig. 7 A schematic illustration of the coaxial electrospinning process[71]

The study of Busolo et al. presented a durable and washable triboelectric yarn for smart textile applications, featuring a carbon nanotube (CNT) yarn as the conductive core and an electrospun poly (vinylidene fluoride) (PVDF) fiber coating, as shown in **Fig. 8**.

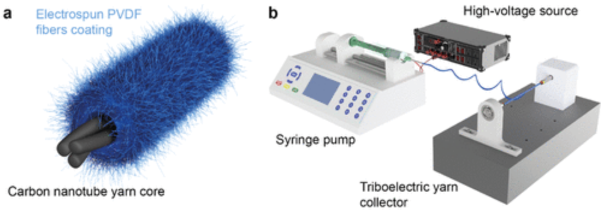

Fig. 8 Fabrication and characterization of the triboelectric yarn. (a) A schematic of the triboelectric yarn core-shell structure. (b) A schematic of the fabrication setup for the triboelectric yarn based on an electrospinning machine with a custom-made rotation.[27]

The yarn maintained and increased its power output by 33% after 200,000 fatigue cycles, achieving a peak power density of 20.7 μW/cm^2. It demonstrated excellent wear resistance and retained its power output after 10 washing cycles. The triboelectric yarn produced an open-circuit voltage of 2.6 V and a short-circuit current of 465 nA under simulated heel strike conditions, with a maximum root-mean-square power output of 96 nW at 400 MΩ resistance after 200,000 fatigue cycles. The high fatigue resistance, wear resistance, and washing durability demonstrated by this triboelectric yarn make it a promising candidate for integration into wearable robotic systems that require reliable energy harvesting and sensing capabilities under repeated mechanical stresses. [72]

The study of Atif et al. using computational fluid dynamics (CFD) and a k-ε turbulence model investigated the characteristics of high-speed air expelled from a solution blow spinning (SBS) nozzle for fiber production, as shown **Fig. 9** . The nozzle was designed to produce polyvinylidene fluoride (PVDF) fibers at air pressures between 1 and 5 bar. The resulting submicron fibers were analyzed using a scanning electron microscope (SEM). Results indicated that higher air pressure (4 bar) was more suitable for producing thin PVDF fibers, but fiber diameter increased at 5 bar [27].

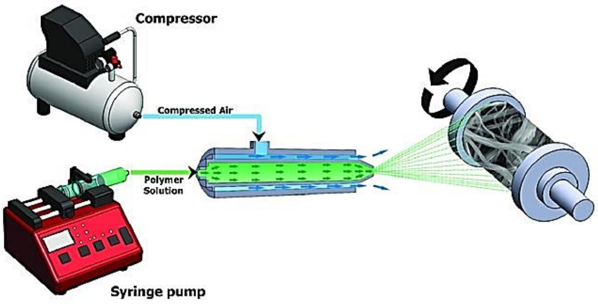

Fig. 9 A schematic diagram of conventional SBS set-up.[73]

A new piezoelectric membrane made from PVDF/TPU nanofibers was developed by Lee et al. using the SBS process. The membranes showed a high piezoelectric response and sensitivity under various applied forces, with the highest values of 3.7 V and 1.8 N. V^{-1} under 2 N and 2 Hz applied forces. This was due to the high miscibility of the polymer blend and optimal processing conditions of SBS, resulting in small nanofiber diameters and defect-free morphology. The optimal TPU content was found at 5wt.%, exhibiting the best piezoelectric characteristics. This innovative elastic-piezo nanofibrous membrane has potential applications in energy-harvesting devices and wearable electronics [73].

Another study by Omran et al examined the mechanical and piezoelectric properties of PVDF nanofibers produced through solution blow spinning. A piezo harvesting system is proposed, enabling power generation from piezoelectric sensors to energize a low-power DC load. The system uses a full-bridge rectifier and a boost converter to regulate the boosted DC voltage. Simulation and experimental tests show that the nanofibers can achieve a tensile strength of 12.6 MPa and a voltage of around 2.5 V, making them suitable for energy harvesting and footstep generation [55].

The study of Kulkarni & Kumari explored the use of Polyvinylidene fluoride (PVDF) as a reinforcement for piezoelectric nanogenerators (PENGs) in mechanical energy harvesting and low power electronics using a solvent casting approach followed by electrode poling process. By adding varying concentrations of reduced graphene oxide (rGO), the PVDF-BTO composite energy harvesting performance was improved. The optimal rGO content was found to enhance mechanical properties, with the piezoelectric output voltage from 0.98 V for pure PVDF to 4.1 V for PVDF-BTO-rGO when rGO content is 1.25 wt% for finger tapping condition [74].

A series of PVA/PPA-PEI: PVDF TENGs were fabricated by Chen et al. using a low-cost solution-casting method. The positive triboelectric layer showed excellent flame retardancy after doping a polyelectrolyte with nitrogen and phosphorus elements. The PVA/10 wt% PVA-PEI: PVDF TENG generated the optimum triboelectric performance, with a maximum open-circuit voltage of 28.8 ± 0.4 V, short-circuit current of 62.3 ± 5.4 μA, and power of 228.8 μW. This study provides a promising way to modify traditional TENGs with enhanced electrical performance and good flame retardancy [60].

Gariya et al. have developed a soft pneumatic actuator with a piezoelectric effect (SPA-P) using a PVDF/CNF/IL flexible membrane using a solution casting technique. The actuator body is made of Ecoflex-OO50 hyperelastic material, and the CPNC membrane is created using IL to disperse CNFs into the PVDF matrix. The SPA-P shows a noticeable bending of 5° at 18 kPa and creates a maximum bending of 134° at 29 kPa of pneumatic pressure. The SPA-P generates fluctuating electric voltage ranging from 73.5 mV to 257 mV, which can be used for automatic control and step-up into volts using the LTC3108 circuit. This actuator can be also used as a robotic gripper and wearable medical device with automatic feedback control [61].

1.4.3 Spin Coating

Spin coating is a method for converting PVDF into thin film coatings for devices, using centrifugal forces and solvent drying [75]. It involves depositing PVDF in a volatile solvent onto a substrate, rotating it at high speeds, and evaporating, offering ease of use and flexibility, as shown in **Fig. 10**[76].

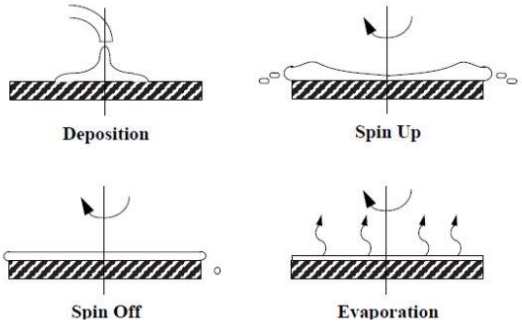

Fig. 10 Spin Coating process for PVDF polymers[76]

The spin coating method was used by Islam et al. to create a composite film, a piezoelectric nanogenerator (PNG), using PVDF and ZnO nanoparticles as the matrix. The composite film enhanced the open-circuit voltage to 4.2 V, compared to 1.2 V for pure PVDF samples. The spin coating method achieved non-brittle outcomes and piezoelectric characteristics, making it suitable for wearable self-powered devices like water strider robot systems [75].

A flexible piezoelectric sensor (FPS) was proposed by Huang et al. to be used in intelligent robots, human-machine interaction, and health measurement systems. Carbon quantum dots (CQDs) were used to improve the performance of polyvinylidene fluoride-hexafluoropropylene (PVDF-HFP/CQDs) piezoelectric film prepared using spin coating. This film has increased β phase content by 14.4%, resulting in better sensitivity (36.6 mV/g), linearity (R2 > 99 %), and mechanical stability. Potential applications include anti-touch alarm systems, finger-bending detection, voice recognition, and vibration monitoring [77].

A high-performance wearable electricity generation approach was developed by Jin et al. through manipulating the relative permittivity of a triboelectric nanogenerator (TENG) using an AC@PVDF composite film. The film was prepared by a solution method with PVDF raw materials, a compatible active carbon (AC) particle, and N, N-dimethylformamide (DMF)then coating into a film. Compared with the pure PVDF, the 0.8% AC@PVDF film based TENG obtained an enhancement in voltage, current, and power by 2.5, 3.5, and 9.8 times, respectively. AC particles offer enhanced interfacial polarization, enhancing static charge storage and electrical output performance. AC@PVDF thin-film-based wearable TEGs power electronic watches and serve as active body motion sensors, making it a sustainable energy solution for on-body electronics [63].

A flexible, sensitive capacitive pressure sensor made by Gao and Chen using nylon textile and PVDF dielectric film made by spin-coating technique has high sensitivity (33.5 kPa^{-1}), low detection limit (0.84 Pa), and a quick response time of 27 ms. This pressure sensor showed excellent reliability under 100,000 working cycles of continuous operation. It can monitor breath, pulse, and elbow movement in basketball and can be also used as a touch sensor to judge the hardness of the object, working as an IoT sensor node [1].

1.4.4 Weaving and Knitting

PVDF-based textiles, produced through weaving, offer mechanical strength, durability, and mechanical integrity [64],while knitted PVDF-based textiles offer excellent flexibility and stretchability, making both of them suitable for wearable electronics and smart textiles [78].

The study of Kim et al. introduced piezoelectric pressure sensors made from woven fabrics using polyvinylidene fluoride (PVDF) weft and polyethylene terephthalate (PET) warp yarns, with different weave structures 1/1 (plain), 2/2, and 3/3 weft rib patterns, demonstrating their sensitivity and stability. The sensor with a 2/2 weft rib pattern had a 245% higher sensitivity of 83 mV N^{-1}, and its detection performance was evaluated with various input sources and human motions such as pressing, bending, twisting, and crumpling. The large all-fabric pressure sensor also demonstrated highly sensitive and stable sensing performance during sport practice [64].

Hasan et al. innovated the fabrication of Ti3C2Tx MXene-embedded polyvinylidene fluoride (PVDF) nanocomposite triboelectric fiber using a thermal drawing process. This triboelectric nanogenerator (TENG) has shown a 53% and 58% improvement in output open circuit voltage and short circuit current compared to pristine PVDF fiber. The fiber's performance is enhanced due to the synergistic interaction between MXene surface termination groups and polar PVDF polymer. The fiber's flexibility allows for large-area weaving of fabric TENG devices, with a power density of 40.8 mW m^{-2} and stable performance over 12000 cycles. The fabric also has energy harvesting capabilities by operating a digital clock a calculator and a self-powered sensor for human activities and walking pattern monitoring [79].

1.5 Application Domains of PVDF-Based Textile for Energy Harvesters:

PVDF-based textile energy harvesters offer a wide range of potential applications across various domains due to their flexibility, lightweight nature, and ability to generate electricity from mechanical vibrations [1, 25, 52] like human body movements (e.g. walking, hand movement, arm bending, and grasping) [65, 77], automotive [44], machine vibrations [81], and environmental sources (e.g. wind, water, rain, solar energy) [70]. Furthermore, PVDF-based textile has the potential to significantly contribute to the development of the Internet of Things (IoT), connecting numerous electronic devices within a cloud, thereby revolutionizing the daily lives of many people soon [13, 79, 80]. The number of studies investigating PVDF-based textiles for energy harvesting has exhibited a notable upward trend over the past 10 years, as shown in **Fig. 11**[84]. Several state-of-the-art approaches have been developed to harvest energy from PVDF-based textiles in various fields as shown in **Fig. 12** such as medical and health monitoring, sports and fitness monitoring, transportation and automotive, military and defence, structural and health monitoring, industrial monitoring and automation, environmental sensing and monitoring, and soft robotics and wearable skeletons.

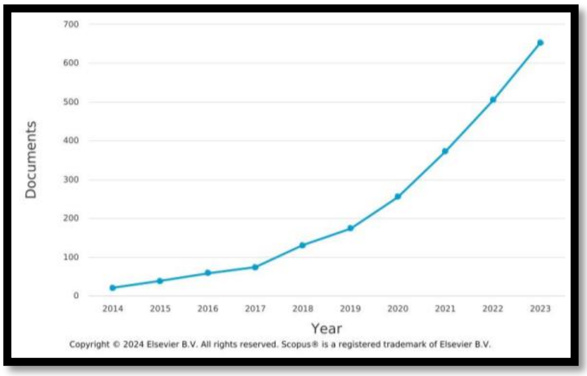

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Fig. 11 Representative graph illustrating the investigation of PVDF-based textiles for energy harvesting from 2014 to 2023, based on data extracted from Scopus (2024).[84]

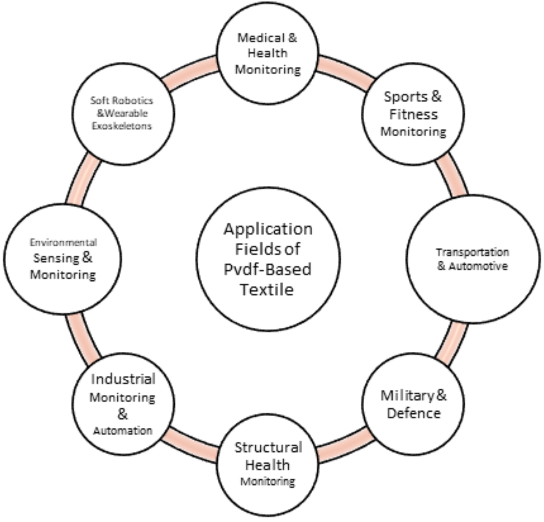

Fig. 12 Application Fields of PVDF-Based Textile for Energy Harvesting

1.5.1 Medical and Health Monitoring

The medical sector is embracing wearable and implantable devices for monitoring vital signs and patient activity [85]. However, these devices rely on finite battery sources, increasing costs and discomfort [86]. PVDF-based textile energy harvesters offer unique advantages for medical and health monitoring applications like heart beat rate, respiration rate [39, 48, 82], disease diagnosis, and smart E-skin applications [67]. PVDF, a biocompatible and flexible material, can be seamlessly integrated into wearable garments and textiles for wearable sensors[11, 32, 84]. Its versatile energy harvesting modes (e.g. using the mechanical movement of the human body), lightweight design, and scalable manufacturing make it attractive for healthcare systems [88]. This paves the way for improved patient comfort, reduced healthcare costs, and more effective monitoring and treatment strategies [13].

1.5.2 Sports and Fitness

Sports and fitness monitoring is becoming increasingly data-driven, allowing coaches to understand and improve athletes' health, strengthen fitness, and plan targeted training [89]. PVDF nanofiber mats can be embedded into athletic clothing or equipment to monitor movements, gait, and vibrations during training or competitions [66, 87]. The collected data can be used for performance analysis, injury prevention, and form correction, providing valuable insights for athletes and coaches [61, 88]. The lightweight and breathable nature of the nanofiber mats ensures comfort and minimal interference with athletic activities [89, 90].

1.5.3 Transportation and Automotives

PVDF nanofiber mats can be used in automotive applications to harvest vibration energy from vehicle movements and road conditions [44], powering sensors and electronics for self-powered monitoring systems, enhancing energy conversion efficiency and durability [91, 92].

1.5.4 Military and Defence

PVDF-based textile energy harvesters are increasingly being used in military and defence applications to power various electronic systems and devices [9, 93, 94]. These energy harvesters offer a sustainable and self-powered solution, reducing reliance on traditional batteries and addressing logistics and weight limitations [45, 95]. They are particularly useful for powering wearable electronics, health monitoring systems [99], and structural health monitoring of military vehicles and equipment [45, 97, 98].

1.5.5 Structural Health Monitoring (SHM)

PVDF-based textile energy harvesters can be incorporated into structural materials to monitor the health and integrity of civil infrastructure [102], aerospace components [103], and mechanical systems [101,102]. By harvesting energy from structural vibrations [67, 91], these harvesters can power sensors for detecting cracks, deformations, and fatigue, thus enabling early warning systems for maintenance and repair [56, 103].

1.5.6 Industrial Monitoring and Automation

PVDF textile energy harvesters are considered a promising solution for industrial monitoring and automation [32]. They can be integrated into machinery components to harvest energy from vibrations, enabling real-time data collection and monitoring [78, 91, 101]. These harvesters can also be used for predictive maintenance which enhances machine learning (ML) applications, allowing for proactive maintenance and reduced downtime [107]. They can also power IoT sensor nodes, enabling real-time monitoring and decision-making [78, 104]. PVDF textile harvesters are flexible and conformable, making them suitable for integration into various industrial components, enabling comprehensive monitoring and data collection [108].

1.5.7 Environmental sensing and monitoring

PVDF nanofiber mats can be integrated into architectural membranes, bridges tents, or sails to harvest energy from environmental vibrations [70],sounds [106-108],lights [42,109], humidity [113]..etc powering environmental sensors for monitoring weather, air quality, seismic activity, and ecological parameters [42]. Their lightweight and outdoor durability make them ideal for long-term environmental monitoring applications [113].

1.5.8 Soft robotics and wearable exoskeletons

PVDF textile energy harvesters are a promising solution for powering soft robotic systems and wearable exoskeletons [72, 111]. These harvesters can be integrated into flexible structures to harvest energy from natural movements and deformations, allowing self-powered and sustainable operation [12, 112] They. can also act as highly sensitive vibration and deformation sensors, detecting subtle movements or interactions between the robotic system and the environment or human user based on artificial intelligence [113, 114]. They can also be integrated into wearable exoskeleton suits, harvesting energy from the wearer's movements and actions, and reducing reliance on external power sources [69, 115, 116].

1.6 Challenges and Future Directions:

Based on a comprehensive literature review and the current state of the art in using PVDF-based textiles for energy harvesting, this review identifies key challenges and future directions for utilizing PVDF in various energy harvesting applications as follows:

1.6.1 Limitations and Challenges

PVDF-based textiles face several limitations and challenges in several energy harvesting applications as follows:

1.6.1.1 Output Power Density:

PVDF-based textiles generally have a lower power density than traditional piezoelectric materials like ceramics. The output power may be insufficient for powering certain electronics or devices, limiting their application scope.

1.6.1.2 Mechanical Durability:

Due to repeated deformation cycles, PVDF textiles can experience mechanical degradation and fatigue over time. This can lead to a decrease in piezoelectric performance and a shorter operational lifespan. The flexible nature of PVDF textiles can cause creep and relaxation, which may affect the long-term stability of the piezoelectric properties. Proper encapsulation and reinforcement techniques are crucial to enhance the mechanical robustness of PVDF textiles, but these may add complexity and potentially compromise flexibility.

1.6.1.3 Environmental Factors:

PVDF is a stable polymer to common conditions like sunlight, water, and most chemicals at room temperature. However, it may be sensitive to higher temperature radiations during processing or waste disposal by burning, potentially causing breakdown and fluorinated molecules release, posing environmental and health risks. Developing better ways to recycle PVDF wastes, instead of disposal by burning, is efficient and clean.

1.6.1.4 Integration and Packaging:

Integrating PVDF textiles into rigid and compact systems or products can be challenging due to their flexible and porous nature. Proper electrical interconnections and shielding are necessary to minimize signal losses and electromagnetic interference. Proper encapsulation and packaging techniques are required to protect the material and ensure reliable operation.

1.6.1.5 Scalability and Manufacturing:

The manufacturing processes for PVDF-based textiles may not be as well-established (e.g. Solution Blow Spinning process) or cost-effective (e.g., Electrospinning process) as traditional piezoelectric materials. Achieving consistent quality and properties across large-scale production can be challenging, particularly for complex textile structures or patterns. Specialized equipment and facilities may be required, increasing the overall cost, and limiting accessibility.

1.6.1.6 Optimization and Design:

Optimizing the piezoelectric properties of PVDF textiles requires careful consideration of factors such as fiber orientation, weaving patterns, electrode configurations, and poling processes. Achieving efficient energy conversion and maximizing power output often requires extensive modelling, simulations, and experimental iterations. Designing efficient energy harvesting systems with PVDF textiles involves integrating the textile structure with appropriate mechanical amplification mechanisms, power conditioning circuits, and energy storage components.

1.6.1.7 Application-specific Challenges:

Different domains may present unique challenges which may require additional engineering efforts or material modifications. In wearable and biomedical applications, PVDF textiles must address challenges such as biocompatibility, breathability, and comfort considerations. In structural health monitoring or aerospace applications, PVDF textiles may need to withstand harsh environments, extreme temperatures, or high vibration levels. In consumer electronics or Internet of Things (IoT) applications, the power requirements, form factors, and cost constraints may limit the use of PVDF textiles.

1.6.2 Future Directions

Despite these challenges, PVDF-based textile energy harvesters offer a versatile and sustainable solution for powering various electronic systems in various domains which reveals promising directions for energy harvesting. These directions will depend on continued research and development efforts to overcome the related challenges to material optimization, fabrication techniques, system integration, and application-specific engineering solutions. Herein, are some potential future directions for these energy harvesters:

1.6.2.1 Wearable Electronics and the Internet of Things (IoT):

PVDF-based textiles, despite its stiffness and lack of breathability challenges, can be improved by employing strategies like solution casting, plasma treatment, and blending with hydrophilic polymers like polyethylene glycol (PEG). These methods enhance air circulation, breathability, hydrophilicity, and moisture management in PVDF-based wearable textiles. PVDF-based textile energy harvesters can enable self-powered wearable devices, such as health monitoring systems, fitness trackers, and smart clothing. These textiles can harvest energy from human body movements or ambient vibrations, providing a sustainable power source for IoT devices and sensors.

1.6.2.2 Structural Health Monitoring:

Integrating PVDF textile sensors into structures like buildings, bridges, and aerospace components can enable continuous monitoring of structural integrity and early detection of damage or fatigue. The flexibility and conformability of PVDF textiles make them suitable for embedding into various structural components.

1.6.2.3 Energy-Harvesting Floors and Pavements:

PVDF textile energy harvesters can be integrated into flooring systems, pavements, or sidewalks to harvest energy from foot traffic or vehicular movements. This energy can be used to power lighting, sensors, or other infrastructure in smart cities or buildings.

1.6.2.4 Biomedical Applications:

PVDF textiles can be used for energy harvesting in biomedical devices, such as implantable sensors or wearable health monitoring systems, powered by body movements or muscle contractions. Their flexibility and potential biocompatibility make them attractive for such applications.

1.6.2.5 Hybrid Energy Harvesting Systems:

Combining PVDF textiles with other energy harvesting technologies, such as solar cells or thermoelectric generators, can create hybrid systems that leverage multiple energy sources for improved efficiency and reliability.

1.6.2.6 Smart Textiles and Interactive Clothing:

PVDF-based textiles can enable interactive and responsive clothing by incorporating energy-harvesting capabilities and integrating them with sensors, actuators, and displays. This can lead to innovative applications in the fashion, sports, and entertainment industries.

1.6.2.7 Environmental Monitoring and Remote Sensing:

PVDF textile energy harvesters can power wireless sensor networks for environmental monitoring, such as tracking air or water quality, detecting soil moisture, or monitoring wildlife movements. Their flexibility and potential for large-area deployment make them suitable for such applications.

1.6.2.8 Advanced Materials and Nanostructures:

Research efforts are underway to explore advanced PVDF-based materials and nanostructures, such as PVDF nanofibers, composites, or hybrid materials, to enhance the piezoelectric properties and energy harvesting performance.

1.6.2.9 Scalable and Cost-Effective Manufacturing:

Ongoing research into improving manufacturing techniques, such as roll-to-roll processing or additive manufacturing, can potentially enable large-scale production of PVDF-based textiles at lower costs, making them more accessible for various applications.

1.6.2.10 Integration with Energy Storage and Power Management:

Developing efficient energy storage solutions and power management systems specifically designed for PVDF textile energy harvesters can improve their overall effectiveness and enable broader applications.

Conclusion

The development of PVDF-based textiles for energy harvesting applications is a promising field due to the growing demand for sustainable and self-powered electronic systems. This review article provides an overview of recent advancements in this field, highlighting the unique properties of PVDF and its suitability for textile-based energy harvesting applications. The article discusses various fabrication techniques, such as melt casting, solution casting, spin coating, film casting, weaving, and knitting, and emphasizes the importance of optimizing factors like electrode placement, structural integrity, and flexibility for efficient energy conversion and long-term durability. PVDF-based textiles have shown potential in various applications, including medical and health monitoring, sports and fitness, transportation, military and defence, structural health monitoring, industrial automation, environmental sensing, and soft robotics. These advancements have led to the development of self-powered wearable devices, sustainable infrastructure monitoring systems, and innovative energy harvesting solutions across various sectors. However, the review acknowledges challenges and limitations associated with these materials, such as output power density, mechanical durability, environmental sensitivity, integration and packaging challenges, scalability and manufacturing concerns, and application-specific hurdles. To unlock the full potential of PVDF-based textiles for energy harvesting, future directions include wearable electronics, IoT applications, structural health monitoring systems, energy-harvesting floors and pavements, biomedical applications, hybrid energy harvesting systems, smart textiles and interactive clothing, environmental monitoring, and remote sensing, advanced materials and nanostructures, scalable and cost-effective manufacturing techniques, and efficient energy storage and power management solutions.

Declaration of Conflicts of Interest

The Authors declare that there is no conflict of interest.

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