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Review of flexible energy harvesting for bioengineering in alignment with SDG

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ABSTRACT

To cater to the extensive body movements and deformations necessitated by biomedical equipment flexible piezoelectrics emerge as a promising solution for energy harvesting. This review research delves into the potential of Flexible Piezoelectric Materials (FPM) as a sustainable solution for clean and affordable energy, aligning with the United Nations' Sustainable Development Goals (SDGs). By systematically examining the secondary functions of stretchability, hybrid energy harvesting, and self-healing, the study aims to comprehensively understand these materials' mechanisms, strategies, and relationships between structural characteristics and properties. The research highlights the significance of designing piezoelectric materials that can conform to the curvilinear shape of the human body, enabling sustainable and efficient mechanical energy capture for various applications, such as biosensors and actuators. The study identifies critical areas for future investigation, including the commercialization of stretchable piezoelectric systems, prevention of unintended interference in hybrid energy harvesters, development of consistent wearability metrics, and enhancement of the elastic piezoelectric material, electrode circuit, and substrate for improved stretchability and comfort. In conclusion, this review research offers valuable insights into developing and implementing FPM as a promising and innovative approach to harnessing clean, affordable energy in line with the SDGs.

1. Introduction

Patient-centred healthcare has expanded beyond traditional hospital diagnoses in the context of an ageing global population. The Internet of Things (IoT) technology, with billions of intelligent devices, sensors, and actuators, provides a practical solution for real-time patient-centred monitoring and diagnosis, aligning with the United Nations' Sustainable Development Goals (SDGs) for good health and well-being [1–3]. However, power devices like batteries and supercapacitors require replacement or recharging, increasing costs and complicating long-term deployment in difficult-to-access areas [4–6]. Biomedical sensors and actuators using piezoelectrics offer a reliable, environmentally friendly, and low-maintenance alternative, harnessing mechanical energy from the human body [7].

Biomedical piezoelectrics possess desirable qualities such as high biocompatibility and sensitivity, making them suitable for energy harvesting. The global market for piezoelectric devices is projected to reach $27.5 billion by 2026, reflecting its significant and rapid growth [8]. Lightweight and flexible piezoelectric devices can conform to human joints and organs, enabling the collection of mechanical energy for use in biological sensors. As illustrated in Fig. 1, a typical flexible energy harvester comprises a piezoelectric thin film encased in a flexible substrate and connected to two probes on opposite surfaces [9,10]. These flexible piezoelectrics hold immense potential in the biomedical sector, as demonstrated by the extensive applications of these devices as energy generators or medical actuators.

Researchers are interested in developing technologies that generate electricity by capturing mechanical energy. These technologies can potentially convert biomechanical energy sources from the human body into usable power [11,12]. In the 1990 s, IBM pioneered the idea of natural movement-controlled computers, which has since spread throughout the tech industry. The human body generates approximately 0.3–1 W of energy through pulmonary function, heart rate, and blood flow, which can be harnessed for several decades as long as the person is alive. This energy could theoretically power implanted electronic devices, such as nanobots, electric pills, and sensors, supporting low-power, bio-implantable medical applications[12,13].

Pursuing Sustainable Development Goals (SDGs) demands innovative solutions, and materials play a pivotal role in achieving these objectives. When considering materials for clean and affordable energy

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solutions, such as Flexible Piezoelectric Materials (FPM), attention to structural and chemical properties is paramount. Structural properties encompass flexibility, durability, and adaptability [14–16]. FPM must conform to the curvilinear shape of the human body, making flexibility a fundamental requirement. These materials should withstand extensive deformations, as they will be subjected to various mechanical stresses and strains. Durability ensures a long operational lifespan, reducing the need for replacements and minimizing environmental impact.

Chemical properties are equally critical. Biocompatibility is imperative when FPM interacts with the human body. Materials must be non-toxic, non-inflammatory, and non-immunogenic to prevent adverse reactions. Environmental sustainability is achieved using eco-friendly materials with minimal carbon footprints throughout their lifecycle. Efficiency is also tied to chemical properties. Piezoelectric materials should exhibit high sensitivity to mechanical stress for optimal energy harvesting. This property directly influences the effectiveness of clean energy production[17,18]. Materials engineered for SDGs should strike a delicate balance between structural and chemical properties. They must be flexible yet robust, biocompatible, and efficient in energy conversion. Only by adhering to these stringent requirements can materials contribute meaningfully to sustainable development goals, providing clean and affordable energy solutions while safeguarding human and environmental well-being.

This review summarises the latest research on biocompatible and well-designed bio-implantable energy harvesters, addressing the challenges and future directions in materials science and engineering. Choosing between lead-based and lead-free piezoelectric ceramics for biomedical applications is a critical issue, as it directly relates to different periods of biological conditions studied. The findings of this research could contribute to the development of improved piezoelectric medical devices. The materials enabling bio-implantable and flexible piezoelectric energy harvesters are discussed, focusing on ceramic piezoelectric energy harvesters, which have garnered more interest than their polymer counterparts. The review also explores the biocompatibility and bioimplant ability of flexible piezoelectric device substrates, emphasising their importance in achieving sustainable healthcare solutions in line with the UN SDGs.

2. Fundamentals and mechanisms of piezoelectricity in sustainable development goals

The term "piezoelectricity" originates from the Greek word "piezo," meaning "to press," and refers to the process of generating electricity by applying pressure [19,20]. Various crystals, such as tourmaline, quartz, and topaz, can develop surface charges in response to mechanical stress [21,22]. In 1881, a thermodynamic prediction was made that electricity could induce mechanical strain, which was later confirmed experimentally. Since then, there has been significant progress in understanding piezoelectricity's fundamentals and practical applications, contributing to the United Nations' Sustainable Development Goals (SDGs) for affordable and clean energy [23–25].

This section discusses piezoelectric devices unique to inorganic piezoelectric materials, which, like hydroxyapatite, exhibit a non-centrosymmetric crystal structure or another form of symmetry breaking [26,27]. A crystal's piezoelectric voltage can be measured if the crystal undergoes net polarisation due to mechanical stimulation. As illustrated in Fig. 2, applying mechanical strain induces a distortion in the crystal structure of PZT, resulting in a shift in the ion balance. A dipole moment is produced in crystals when the equilibrium of ions within a single crystal unit changes. When neighbouring dipoles align, a domain with polarisation is formed. Polarisation paths within a crystal are subjectively determined [27–29].

Inorganic piezoelectric materials must be poled at high temperatures under a strong electric field to control polarisation in the direction of the poling electric field, as depicted in Fig. 2. This process is necessary for the crystal to generate net polarisation when subjected to mechanical stress, as shown in Fig. 2(a). Consequently, piezoelectric charges can form on the surface of inorganic piezoelectric materials by applying sufficient mechanical stress to the crystal, resulting in the crystal acquiring net polarisation [30–32]. The reverse piezoelectric effect refers to the phenomenon where external electric fields produce mechanical deformation in piezoelectric materials. Researchers and engineers can develop clean and sustainable energy sources by harnessing piezoelectricity, contributing to the global pursuit of SDGs. Piezoelectric materials can be utilised in various applications, such as energy harvesting from biomechanical sources, sensors, and actuators,

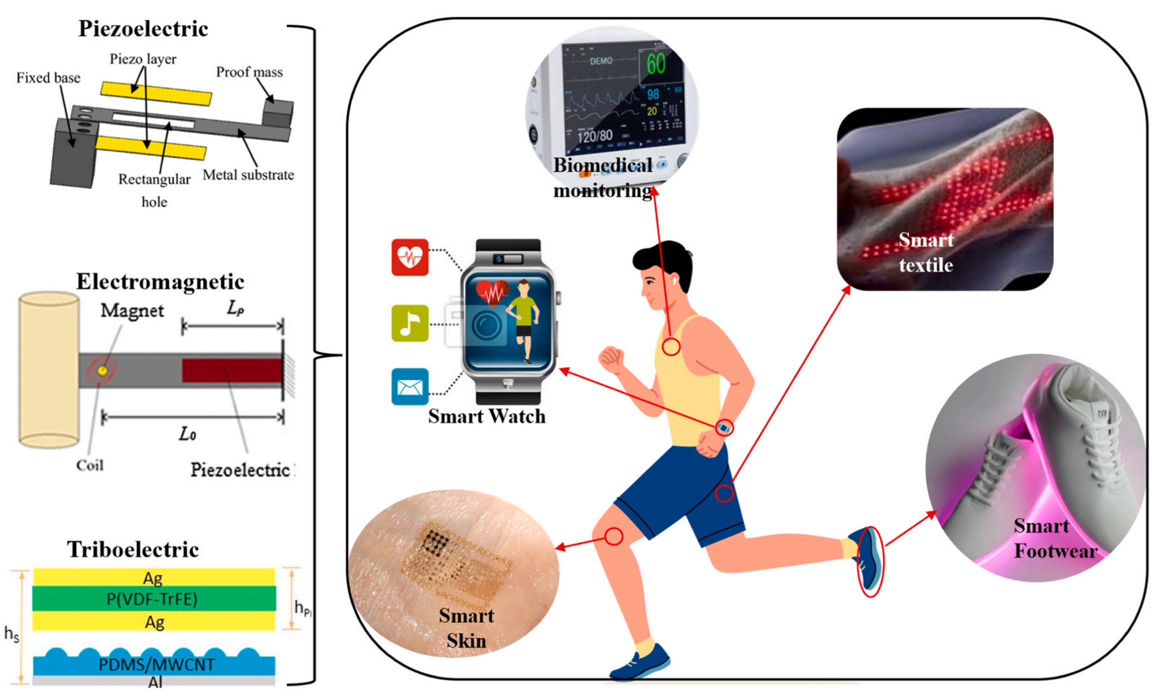

Fig. 1. Human-powered energy harvesting for intelligent electronics Recent advances and future challenges.

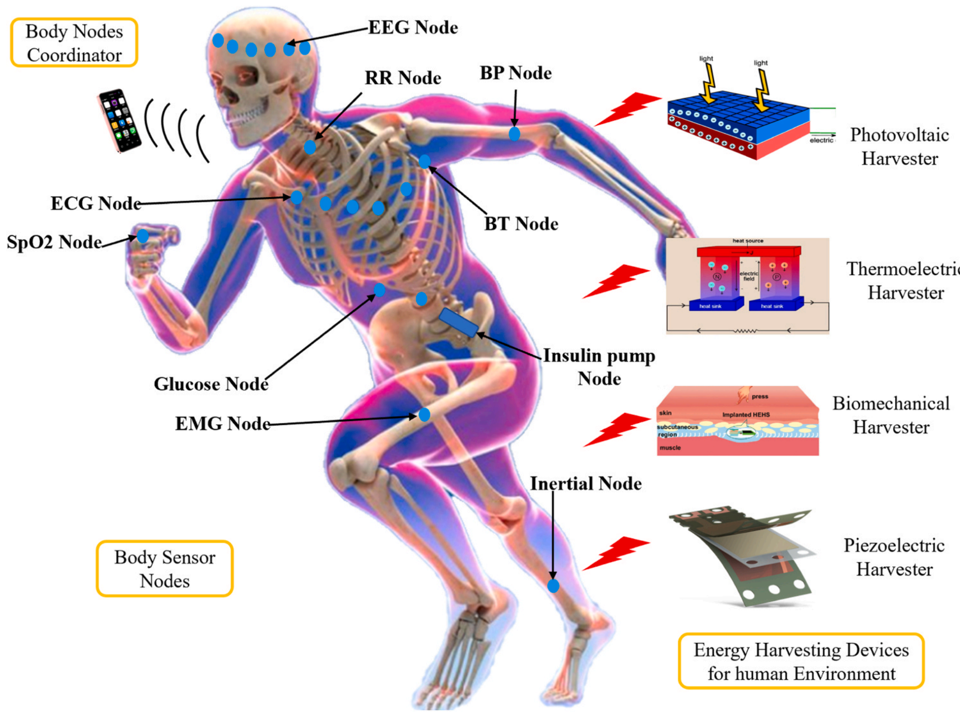

Fig. 2. Incorporate PZT and PVDF piezoelectric materials into the beer cellar to study the fundamentals and mechanics of Stretch crack crowd energy harvesting from human body heat.

supporting good health and well-being goals, affordable and clean energy, and responsible consumption and production.

The piezoelectricity of organic piezoelectric materials can be explained by the mechanical or electrical induction of a molecule's dipole reorientation, contributing to the United Nations' Sustainable Development Goals (SDGs) through sustainable energy solutions. Fig. 3 (b) illustrates the piezoelectricity mechanism of PVDF. This arises due to the differing electronegativities of carbon-fluorine and carbon-hydrogen atoms. PVDF molecular dipoles are generated randomly, with charges ranging from highly negative to very positive [33,34].

PVDF has antiparallel molecular dipoles in its natural state, resulting in a near-zero dipole and nonpolar material. High electrical fields and stretching can create polarised PVDF, where the molecular dipoles are predominantly parallel. By exploiting the piezoelectric properties of organic materials like PVDF, researchers can develop clean and sustainable energy sources that align with the global pursuit of SDGs. Organic piezoelectric materials can contribute to various applications, such as energy harvesting, sensors, and actuators, which support good health and well-being goals, affordable and clean energy, and responsible consumption and production. Developing and utilising organic piezoelectric materials help drive innovation towards a more sustainable future, in line with the United Nations' objectives for global progress.

2.1. Stretchability and its role in achieving SDG

Flexible piezoelectric applications may face challenges such as user discomfort, loose interfacial contact, poor wrinkle resistance, puckering, and breakage due to the rounded and pliable nature of human limbs, joints, and organs. Stretchable piezoelectrics can conform to curved and soft surfaces, addressing these issues and aligning with the United Nations' Sustainable Development Goals (SDGs) for promoting innovation and sustainable technologies [35,36]. By improving device design and reducing gadget size, stretchability can increase piezoelectric material

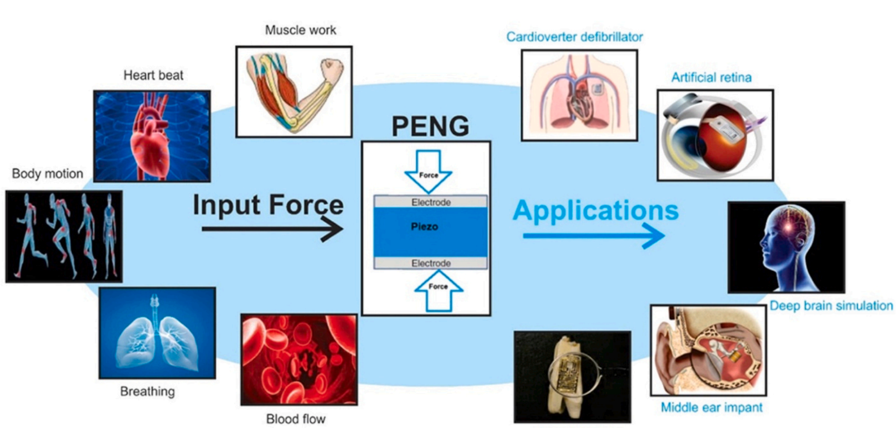

Fig. 3. To make rigid piezoelectric array devices more flexible, a combination of nano/micro-structure design, morphological design, elastic piezoelectric or non-piezoelectric matrix[200].

production and sensitivity, enhancing the potential for clean and sustainable energy solutions.

Stretchable piezoelectrics can be developed using various methods, including nano/micro-structure design, morphological design, elastic piezoelectric or non-piezoelectric matrices, and stretchy interconnections and substrates for rigid piezoelectric array devices [36,37]. These advancements help minimise gadget size and improve the design while increasing the allowable strain and enhancing piezoelectric material performance. A combination of these approaches can be employed to make rigid piezoelectric array devices more flexible [37,38]. By harnessing the potential of stretchable piezoelectrics, researchers can contribute to the global pursuit of SDGs, such as good health and well-being, affordable and clean energy, and responsible consumption and production. Developing and utilising stretchable piezoelectric materials promotes sustainable innovation and drives progress towards a more environmentally responsible future.

2.2. Energy harvesting for bioengineering for SDG

The United Nations has established 17 Sustainable Development Goals (SDGs) to address pressing global challenges and improve the well-being of people and the planet by 2030. Energy harvesters can contribute to these goals, particularly piezoelectric ones used in bioengineering applications. No Poverty (SDG 1): Piezoelectric energy harvesters can power medical devices and sensors in remote or underserved areas, enabling better healthcare access and diagnostics ultimately alleviating poverty-related health issues. Zero Hunger (SDG 2) is Energy harvesters that can be employed in precision agriculture and food quality monitoring systems, improving crop yields and reducing food wastage, contributing to food security. Good Health and Well-being (SDG 3) is a piezoelectric device that can power wearable health monitors, prosthetic limbs, and drug delivery systems, enhancing healthcare delivery and patient outcomes and reducing health disparities[38–40].

Quality Education (SDG 4) is energy harvesters that can help power electronic educational resources and devices, making quality education accessible, even in off-grid areas. Gender Equality (SDG 5) gives accessible healthcare powered by energy harvesters that can reduce maternal mortality rates and improve women's overall health, contributing to gender equality. Clean Water and Sanitation (SDG 6) give energy harvesting sensors that can monitor water quality in real-time, helping to ensure safe drinking water and sanitation systems. Affordable and Clean Energy (SDG 7) is piezoelectric energy harvesters themselves promote clean energy generation. In bioengineering, they can power medical devices without the need for disposable batteries, reducing energy costs and environmental impact. Decent Work and Economic Growth (SDG 8) is the development and manufacturing of piezoelectric energy harvesters to create job opportunities, and their implementation in healthcare devices can lead to cost savings in the long term[40–42].

Industry, Innovation, and Infrastructure (SDG 9) is the innovation in energy harvesting technology, including piezoelectric devices, contributes to sustainable infrastructure development and drives economic growth. Reduced Inequalities (SDG 10) is energy harvesting technology that ensures that even resource-constrained regions have access to vital medical services, reducing inequalities in healthcare access. Sustainable Cities and Communities (SDG 11) of energy harvesters can power smart city infrastructure, including environmental monitoring systems and healthcare facilities, contributing to sustainable urban development. Responsible Consumption and Production (SDG 12) of Energy harvesters can extend the lifespan of medical devices, reducing electronic waste and promoting responsible consumption.

Climate Action (SDG 13) is reducing the need for disposable batteries, and piezoelectric energy harvesters help mitigate electronic waste and promote sustainable energy use—life Below Water (SDG 14) and 15. Life on Land (SDG 15) energy harvesters can monitor environmental parameters, contributing to conserving marine and terrestrial ecosystems[42–44]. Peace, Justice, and Strong Institutions (SDG 16) access to healthcare through energy-harvested medical devices can promote peace and social justice. Partnerships for the Goals (SDG 17) are Collaborative efforts among governments, research institutions, and industry stakeholders that are essential for advancing energy harvesting technology and its applications in bioengineering. Piezoelectric energy harvesters play a significant role in achieving multiple SDGs by providing clean, sustainable energy for critical applications in healthcare, agriculture, education, and environmental monitoring, ultimately contributing to a more equitable and sustainable world.

Polyvinylidene fluoride (PVDF) is indeed known for its five crystalline polymorphs, with the α, β, γ, δ, and ε phases. While both α and ε phases are non-piezoelectric, it's essential to identify these phases and discuss their specific utility in any review related to PVDF. The β phase is the most used in piezoelectric applications. It exhibits piezoelectric solid properties, making it a crucial component in various sensors and actuators. Its high electroactive response and mechanical flexibility make it ideal for harvesting mechanical energy in pressure sensors and energy harvesters. The γ phase of certain materials, such as polyvinylidene fluoride (PVDF), is indeed considered a ferroelectric phase. However, it possesses some piezoelectric properties, although generally weaker than the β phase [41–44]. It can influence the material's overall properties, such as dielectric behaviour and thermal stability. The δ phase has a complex crystal structure and is often closely aligned with the β phase. The properties γ can be fine-tuned to achieve desired characteristics [44,45]. Still, it is generally weaker than the β phase, primarily due to a gauche bond occurring in every fourth repeating unit [45,46]. Researchers and engineers can make informed decisions when designing piezoelectric devices or materials by identifying these PVDF phases and their specific utilities. The emphasis on the β phase's piezoelectric properties highlights its significance in harnessing mechanical energy for various applications while acknowledging the presence of other phases like γ and δ to help optimise PVDF materials for specific performance requirements in non-piezoelectric applications or composite materials.

3. Design morphology in SDG

Stretchable morphologies, such as textiles, filamentary serpentines (FS), and kirigami, have been developed, contributing to the United Nations' Sustainable Development Goals (SDGs) through innovative and sustainable technologies. Fig. 4(a) displays an example of a stretchable fabric made from piezoelectric PVDF filaments. To construct this structure, row threads of PVDF and column threads of silicon tubes can be stitched together. When tensile stresses are applied to the PVDF threads in a stiff configuration, the threads' alternatingly patterned elastic polyester patches contract [45–47] Piezoelectric voltages are generated as the row and line strips, woven together and separated by flexible empty tubes, are repeatedly extended and retracted.

The fabric's stretchability and contraction modify the distance and capacitance between its row and column threads, transforming it into a touch sensor and enhancing its piezoelectric output. A helical structure improves the elasticity of the piezoelectric thread or strap. Fig. 4 illustrates a helical structure that winds a PVDF strap and a fabric band around an elastic core in opposite directions, enabling the system to expand by up to 158% without damage. When the helical piezoelectric harvester is integrated into clothing, it generates 3.9 V and 4.4 V during push-ups and squats, respectively [45,46]. To prevent electrical shorting when the fabric becomes wet, cotton threads can be employed as an insulating spacer between electrodes in stretchable textiles, or a core-shell structure can be utilised to thoroughly protect and separate the inner electrode from the outer electrode made of conductive yarn [47–49]. By developing and implementing such innovative design morphologies, researchers contribute to SDGs such as good health and well-being, affordable and clean energy, and responsible consumption and production, driving progress towards a more sustainable future.

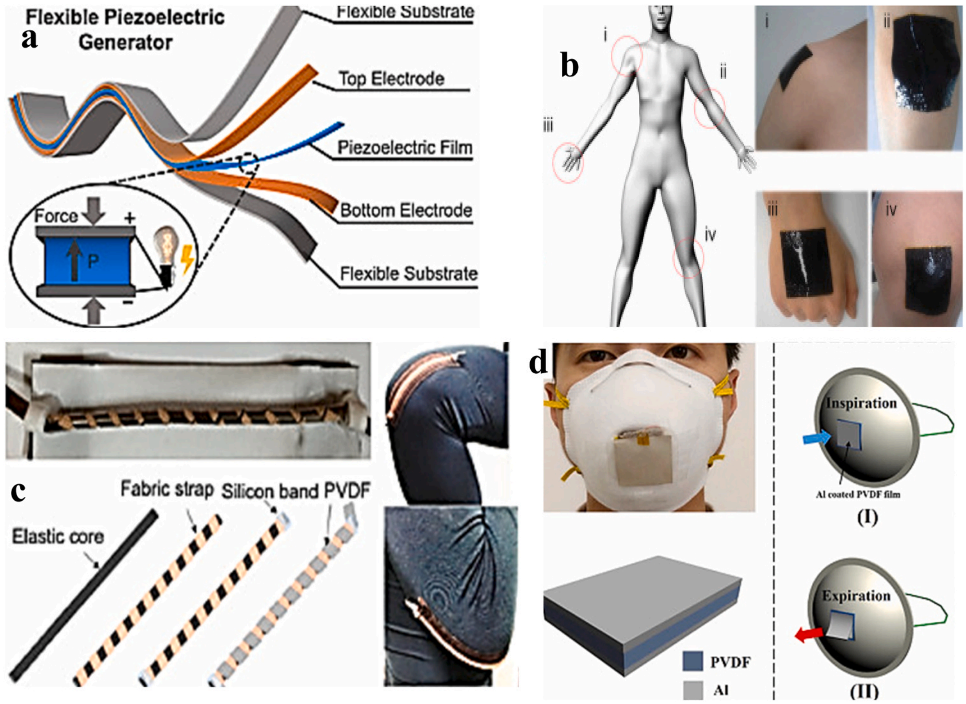

Fig. 4. (a) This diagram depicts a typical piezoelectric device architecture (b) showing piezoelectric or pyroelectric voltage outputs when stretched or subjected to heat gradients, and therefore being HSNG-compatible with a wide range of human body parts (c) Stretchy flexible piezoelectric helical strap morphology design using stretchable morphologies (d) Schematics and pictures show the 30 mm PVDF sheet coated with 60 nm Al and attached to the respirator as a wearable breathing device that runs a PyNG [199–201].

3.1. Incorporating SDG into stretchable piezoelectric designs

Filamentary serpentine (FS)-structured PVDF was cut into a mechanical pattern and adhered to Au electrodes to complete the fabrication. The FS e-tattoo easily conforms to the irregularities of human skin due to its exceptional flexibility [41,50,51]. However, the FS structure reduces stress at the expense of piezoelectric output and sensitivity. Compared to PVDF ribbons stretched in a straight line, the output after stress relief is only 3.6% lower than 0.40 mV per microstrain [47,52,53]. Kirigami structures, enabled by out-of-plane deformations across 2D flat sheets and complex 3D geometries, allow for stretchability and minimal output degradation during stress relaxation [41,54]. These structures are prevalent in lithium-ion batteries, cellular metamaterials, and solar tracking systems, contributing to the Sustainable Development Goals (SDGs) on clean energy and sustainable industrial development [55,56]. In 2018, it was demonstrated that kirigami PVDF films could withstand 18% strain without breaking, although their piezoelectric output was only 132 mV compared to 160 mV for uncut PVDF films under 1% strain [57–59].

Properly designing kirigami components, such as the number and placement of cuts, can prevent stress from building up in the corners of cuts, increasing piezoelectric outputs and the ability to stretch. According to finite element analysis models, the standard continuous electrode connection may diminish piezoelectric outcomes due to charge cancellation from opposing electrode stresses. A segmented electrode connection was proposed to address this issue, placing electrodes only where the strain is highest [44,60,61]. As a result, the output voltage of the kirigami-structured sensor increased from 1.63 to 2.6 V when subjected to 10% tensile strain. Optimising kirigami cut shapes can enhance piezoelectric mode performance.

The 3–3 method for pressing energy harvesting is the simplest and most prevalent. However, it is ineffective in simple kirigami structures due to planes during stretching. The ability to rotate other parts during stretching at the joint point contributes to the high flexibility of the joint [45,62,63]. As a result, the T-joint-cut kirigami-structured sensor demonstrated a remarkable 300% strain at a 6 V open-current voltage. Table 1 summarises various flexible piezoelectrics manufacturing methods, piezoelectricity, and stretchability. By focusing on developing stretchable piezoelectric designs, researchers contribute to the SDGs by promoting innovations that can advance healthcare, clean energy, and sustainable industrial development. (Fig. 5).

4. Sustainable hybrid energy harvesting

Flexible piezoelectric devices that can bend and provide power are crucial for sustainable applications in challenging environments. Integrating piezoelectric power-generating equipment with other renewable energy sources can contribute to Sustainable Development Goals (SDGs), specifically those related to clean and affordable energy [80, 81]. Fig. 6 illustrates how flexible piezoelectric devices can be combined with various energy harvesters to ensure a continuous power supply.

Thermoelectrics based on pyroelectric, photovoltaic, and triboelectric materials can generate electricity from solar, thermal, and friction-related mechanical energy [82–84]. By harnessing these diverse sources, hybrid energy harvesting systems can promote sustainable energy production and help reduce reliance on non-renewable energy resources. This section explores the mechanics and architectures of hybrid energy harvesting using flexible piezoelectric generators in conjunction with other energy harvesting technologies [85–87]. Developing and implementing these sustainable hybrid energy harvesting systems will contribute to the global effort to achieve the SDGs, particularly in clean energy and sustainable industrial development.

4.1. Sustainable mechanical energy harvesting

Piezoelectric materials can capture the energy generated by everyday mechanical actions such as pressing, bending, stretching, and twisting, contributing to sustainable energy solutions. Triboelectricity can also collect mechanical energy when two dissimilar materials are rubbed together [72,88,89]. Triboelectric materials offer several

Table 1
A summary of how stretchy flexible piezoelectric is manufactured, how they function, and how well they can be stretched.

Manufacturing	Material	Piezoelectricity	stretch
Micro-structure design -Transfer printing PZT ribbons onto prestrained PDMS substrates and circulating strain for buckled PZT	PZT on PDMS substrate	The current density of 2.5 μA mm^{-2} under the periodic strain of 8%	8%[64,65]
Transfer printing, buckling of PZT and PI layers, and compressive buckling of complex 3D microstructures	PZT and PI layers PVDF	8.1 V with 5 PZT layers, 790 mV	~2.8%[66,67]
Poled nanofibers were electrohydrodynamically printed on pre-stretched PET substrates, while straight PDVF nanofibers were mechano-electrospun on PDMS substrates.	PVDF on PDMS substrate and PET substrate	1.2 nA and 40 mV with 120 PVDF fibres under 30% strain and 4 nA and voltage of 150 mV with 50 fibres at 2.3 Hz.	100–110% [68,69]
Electrohydrodynamic printing with a helix configuration produced deformed and fractal PVDF fibres. Electrohydrodynamic helical printing of PVDF nanofibers with self-similarity	PVDF with a liquid metal electrode on a PDMS substrate	The average maximum current of 20 nA ~8 nA with 120% strain under bi-direction stretching	200–300% [31,70]
Core-shell P(VDF-TrFE) nanofibres electrospun yarns are twisted into ribbons and then overtwist into coils.	P(VDF-TrFE), Ag-coated nylon yarn, CNT sheets	2.6 V and 15 nA for a single 10 mm fibre squeezed laterally under 160 kPa, 50 W cm^{-3} output density 20 mV	740% [71,72]
Morphology design-sewing PVDF fastens and knits with elastic tubes, melt-rolling nanofibers, twisting and coiling them into a spiral structure.	Piezoelectric PVDF-rGO-BT fibres on a PET substrate	1.3 V and a power density of 3 Wkg^{-1}, 51 V and a power of 850 W when stretched laterally.	100% 6 mm for a 9 × 9 cm^2 device[73,74]
The PVDF strap and the fabric band wind like a helix around the elastic centre. weaving together various materials such as copper wires, cotton threads, and other materials	PVDF straps $BaTiO_3$-PVC threads	20 V at the knee, 1.9 V, and 24 nA at the bending elbow	158% Arm bending [67,72]
Cut-and-paste manufacturing forms a serpentine filament network by band-weaving PVDF thread with a core-shell structure and separated electrodes.	PVDF thread tattoo on Tegaderm substrate	2.2 V with a Tegaderm substrate, 3.5 V with 0.25% axial strain, up to 8 V when wet, and 2.74 V without a substrate.	112.9% [75,76]
Mechanical cutting for modelling, photolithography, design, transfer printing for device cutting, and a scalpel for centre and edge cutting.	PLA-SWCNT composite film PVDF on Kapton substrate	A densely spaced, centre-cutting pattern has a voltage of 299 mV at 5% strain and a current of 4 nA at 1% strain.	30% [77,78]
PVDF film direct-write 3D printing with FEA-guided intersegment electrode design and pattern.	PVDF film on a PET substrate, BaTiO3–P (VDF-TrFE) composite with silver electrode	T-joint-cut kirigami structures have 1.63 V under 10% strain, 6 V under 60 N compression force, and 5 Hz.	300% [46,79]

advantages over piezoelectric materials, including a broader range of materials and working modes, such as contact separation, sliding, single-electrode, and freestanding [67,90].

The synergistic integration of hybrid generators produces outputs higher than the linear sum of the triboelectric and piezoelectric processes, enabling continuous energy production and supporting the Sustainable Development Goals (SDGs) related to clean and affordable energy. Triboelectric action creates opposing charges on the surface, which migrate away from the contact separation surface after electrostatic induction [70,91,92]. The electrostatic properties of two materials induce externally produced triboelectric currents [69,93,94]. Piezoelectric sources provide triboelectric voltage and charges, simplifying the implementation of triboelectric energy generators by substituting the triboelectric layer (TEG) [27,95]. Tribo-piezoelectric hybrid energy generators, as shown in Fig. 7(b), contribute to sustainable energy production. When contact is broken, the electron source and acceptor function in place of a TEG's positively and negatively charged components. As the hybrid is pressed, the piezoelectric energy generator (PEG) transmits voltage and current from electrodes 1–2. The TEG contact interface displays the real-time expenses of energising the contact. Electrodes 1 and 2 accumulate electrostatic charges when the TEG's contact surfaces are stretched or scraped [96–98]. Triboelectric current can flow from electrode 1 to electrode 2 when the electrodes are electrically connected from the outside, promoting the development of sustainable mechanical energy harvesting systems.

4.2. Applications of aortic piezoelectric energy harvesting

Wrapping the aorta with a piezoelectric film to convert the mechanical energy of its expansion and retraction into electrical energy is an innovative concept with potential applications in energy harvesting and medical devices. Here are some considerations for such an approach. Energy Harvesting Mechanism is Piezoelectric materials generate electricity when subjected to mechanical stress or deformation. The aorta's expansion and retraction during the cardiac cycle could generate mechanical energy that a piezoelectric film may harness. Materials used in direct contact with the aorta must be biocompatible to prevent adverse reactions, inflammation, or clot formation [90–92]. The piezoelectric film and any associated components should be carefully chosen to ensure they are safe for implantation. The piezoelectric film must be mechanically robust to withstand the continuous pulsatile motion of the aorta over time. It should not degrade or become damaged due to the mechanical stresses it experiences.

The efficiency of energy conversion from mechanical to electrical energy is crucial. The design should optimise this efficiency to ensure sufficient electrical power is generated for the intended applications. Energy Storage and Management of harvested electrical energy may vary in intensity and timing depending on the cardiac cycle. Adequate energy storage and management systems may be required to store and regulate the energy for consistent use by medical devices or other applications. Real-Time Monitoring and Device Integration is electrical energy generated that could power real-time monitoring sensors or therapeutic devices. The integration of these components should be seamless and provide accurate data collection for clinical applications [92–94].

Ensuring the safety and reliability of the piezoelectric film is critical. Continuous operation within the dynamic aortic environment requires rigorous testing to guarantee performance and longevity. Any medical device, including an energy-harvesting system wrapped around the aorta, must undergo extensive safety testing and regulatory approvals before clinical use. Compliance with medical device standards is essential. The device should be designed for long-term use and minimal degradation over time. This is especially important considering the aorta's critical role in the circulatory system. Developing minimally invasive surgical techniques for wrapping the aorta with the piezoelectric film could reduce the risks associated with invasive procedures.

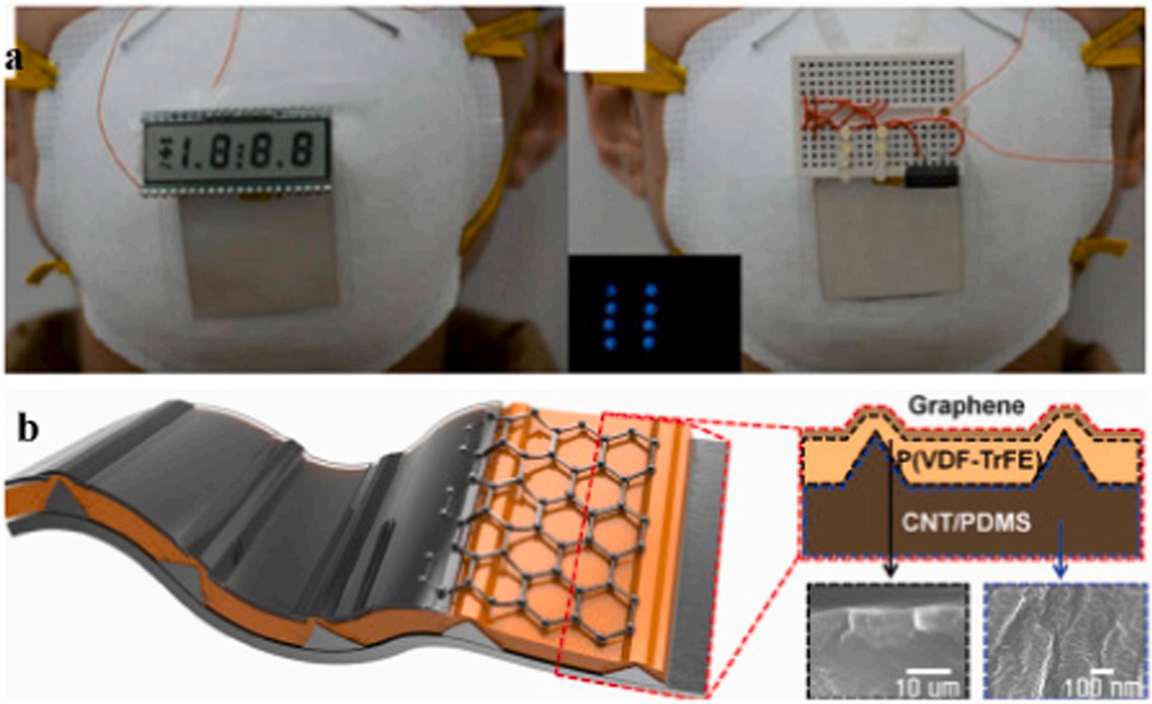

Fig. 5. (a) PyNG was an LCD with eight LEDs that ran on breath power. An accurate voltmeter measured the voltage and current at varying temperatures. (b Micropatterned polyvinylidene fluoride (PVDF)/tetrafluoroethylene (TrFE), polydimethylsiloxane (PDMS)/carbon nanotubes (CNTs), graphene nanosheets (GNS), and graphene nanotubes (GNTs) hybrid nanogenerators (HSNGs) [200–202].

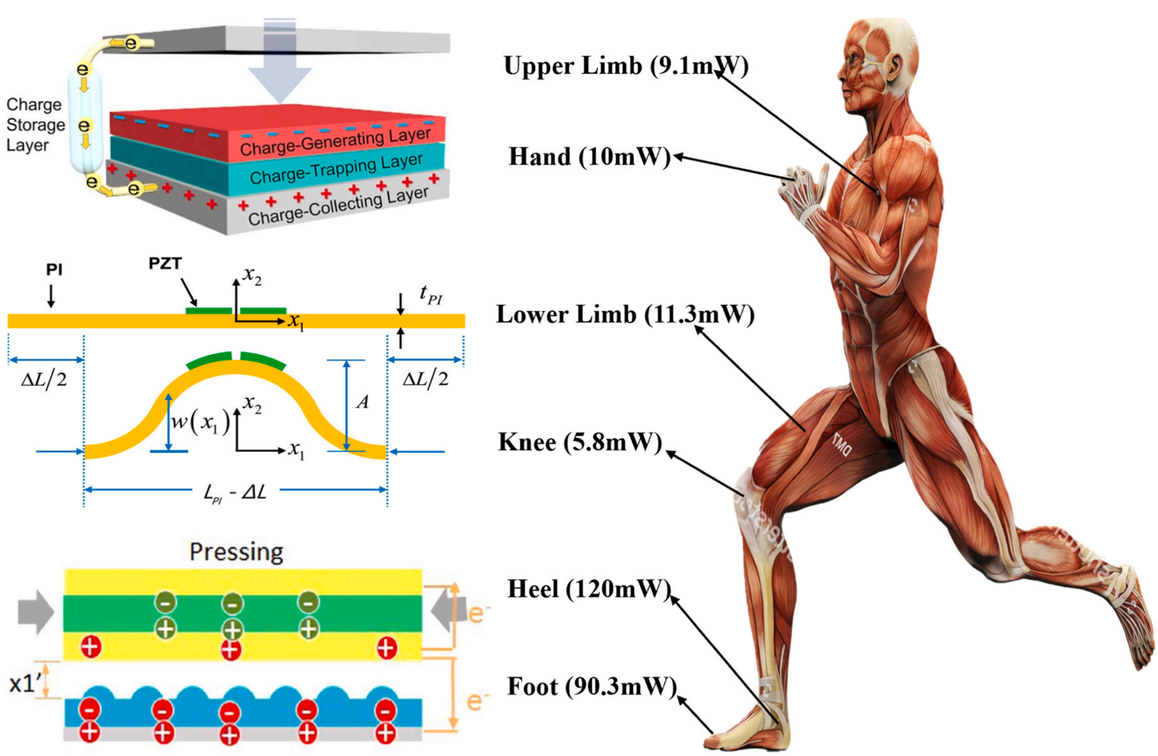

Fig. 6. Human body piezoelectric energy Three synergistic processes and architectures that merge flexible piezoelectric and triboelectric energy producers [201–203].

Ethical considerations regarding patient consent, privacy, and the potential for device misuse or hacking should be addressed. The concept of wrapping the aorta with a piezoelectric film to convert mechanical energy into electrical energy is innovative and promising [93–95]. However, it involves complex engineering and medical challenges, including biocompatibility, efficiency, safety, regulatory approval, and long-term durability. Collaboration between cardiology, materials science, and medical device engineering experts would be essential in developing and validating such a novel approach for clinical use.

Fig. 7 explains that implantable energy harvesters (IEHs) and real-

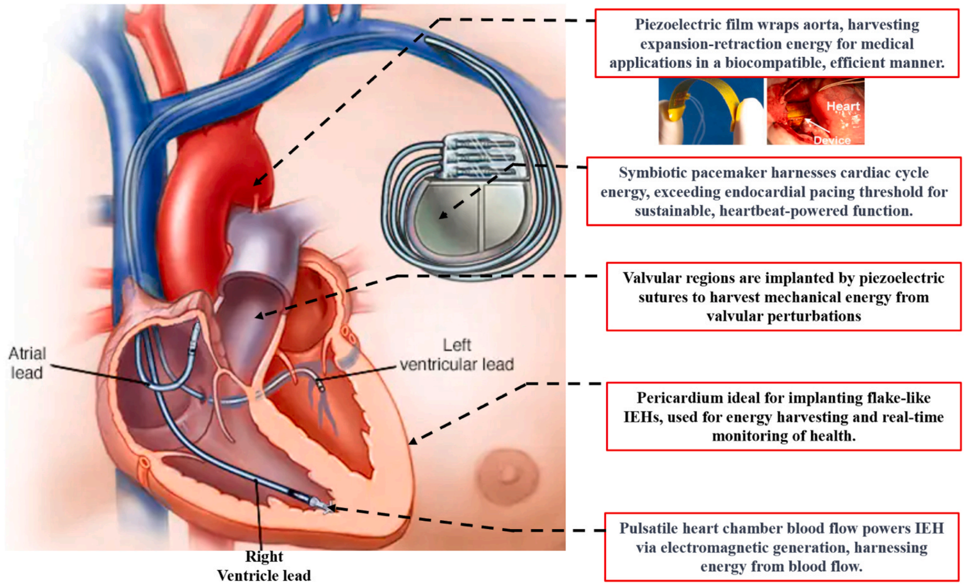

Fig. 7. Summary of biomedical vibration of piezoelectric energy harvester in cardiography [199].

time physiological and pathological signs monitoring are exciting research areas with potential applications in medicine and healthcare. However, using the pericardium as a suitable material for implanting flake-like IEHs (energy harvesters) is subject to several considerations and challenges. Biocompatibility and durability of pericardium is a double-walled sac that surrounds the heart. It comprises connective tissue and plays a crucial role in protecting the heart. While it is biocompatible to a certain extent, using pericardium for implanting electronic devices requires careful consideration of its biocompatibility. Any material implanted within the human body should ideally be non-toxic, non-inflammatory, and not provoke an immune response. Special coatings or materials may be required to ensure the pericardium does not cause adverse reactions [95–97]. The pericardium is relatively thin and delicate compared to other tissues in the body. It may not provide the mechanical support needed for implantable electronic devices' long-term stability and durability, especially if designed to harvest energy through motion or other mechanical means. Device robustness is crucial to ensure it can withstand the stresses and strains of the cardiac environment.

Energy Harvesting and Monitoring Sensors of implantable energy harvesters typically rely on piezoelectric, electromagnetic, or thermoelectric principles to capture energy from physiological processes. The choice of the pericardium as a substrate for such devices would depend on its mechanical properties and the feasibility of energy harvesting within this environment. Real-time monitoring of physiological and pathological signs involves the integration of sensors into the device. The placement of these sensors within or around the pericardium may be challenging due to limited space and potential interference with cardiac function.

Safety and Regulatory Approval and Biodegradability of Any implantable medical device must undergo rigorous safety testing and receive regulatory approvals before it can be used in humans. Using novel materials like pericardium for such applications would require comprehensive testing to ensure safety and efficacy. Depending on the intended duration of use, it may be essential to consider whether the device or its components should be biodegradable to minimise the need for surgical removal. While the pericardium may offer particular advantages as a substrate for implantable energy harvesters and monitoring devices, its suitability depends on various factors, including biocompatibility, durability, energy harvesting capabilities, and safety considerations [97–99]. Research in this area is ongoing, and any potential applications should be thoroughly studied and tested to ensure they meet the necessary standards for medical implantation. Collaboration between materials science, cardiology, and medical device engineering experts would be essential in developing such innovative solutions.

Implanting piezoelectric sutures in valvular regions to harvest mechanical energy from valvular perturbations is an intriguing concept that could have potential applications in energy harvesting and monitoring within the cardiovascular system. However, it also poses several challenges and considerations. Location and placement in the choice of valvular regions for implantation are crucial. Suturing or embedding piezoelectric materials within or near heart valves should be carefully planned to avoid interference with valve function. The placement should not hinder the opening and closing of the valves or lead to valve dysfunction.

Piezoelectric Materials selection of piezoelectric materials is essential; they should be biocompatible, durable, and capable of efficiently converting mechanical energy from valvular perturbations into electrical energy. Proper encapsulation and protection of the piezoelectric components are necessary to prevent degradation or damage. Any materials in direct contact with the cardiovascular system must be biocompatible to avoid adverse reactions or thrombosis [99–101]. The sutures should be made from materials that do not provoke an immune response or cause inflammation. Energy Conversion is the efficiency of piezoelectric energy conversion vital. The design should maximise the conversion efficiency to generate sufficient electrical energy for the intended applications.

Real-Time Monitoring and Device Integration is the electrical energy harvested from valvular perturbations that could be used to power real-time monitoring sensors or therapeutic devices. Integration of these components should be seamless and reliable. Safety and Reliability and Regulatory Approval ensuring the safety and reliability of the piezoelectric sutures is essential. They will be subject to continuous mechanical stress and should be designed to withstand the dynamic cardiac environment over an extended period. As with all medical devices, piezoelectric sutures for implantation in valvular regions must undergo rigorous safety testing and regulatory approvals before clinical use. Compliance with relevant medical device standards is crucial [101–103].

Longevity and Biodegradability of Minimally Invasive Implantation is a consideration that should be given to the longevity of the implanted sutures. Depending on the intended duration of use, options such as biodegradability or retrievability through minimally invasive means should be explored. Developing minimally invasive surgical techniques for implanting these sutures could reduce the risks of invasive procedures. Implanting piezoelectric sutures in valvular regions to harvest mechanical energy from valvular perturbations is an innovative concept with potential benefits for energy harvesting and cardiovascular monitoring. However, it presents complex engineering and medical challenges, requiring careful planning, biocompatible materials, efficient energy conversion, safety, and regulatory approval. Collaboration between cardiology, materials science, and medical device engineering experts would be essential to develop and validate such a novel approach for clinical use.

4.3. Pericardial nanogenerator real-time monitoring and harvesting

An interesting concept is using the pericardium for implanting flake-like implantable energy harvesters (IEHs) made of nanogenerators (NGs) for real-time physiological and pathological signs monitoring. Let us break down some considerations for this application, biocompatibility and mechanical compatibility. The pericardium is relatively biocompatible as it is a natural tissue surrounding the heart. However, using it as a substrate for NG-based IEHs would require careful engineering to ensure that the NGs and associated components do not cause any adverse reactions, inflammation, or immune responses when implanted in contact with the pericardium. The pericardium experiences continuous motion and deformation with the heart's beating [104–107]. This dynamic environment might suit NGs designed to harvest energy from mechanical movement. However, the mechanical properties of the NGs, such as flexibility and durability, must be carefully designed to withstand these conditions without damaging the pericardium or themselves.

Energy Harvesting is Real-Time Monitoring that helps nanogenerators harness energy from mechanical movements or vibrations, such as those generated by the heart's beating. If designed appropriately, NGs embedded in the pericardium could potentially harvest energy from these motions for powering monitoring sensors and other medical devices. Integrating sensors for real-time physiological and pathological signs monitoring is critical. These sensors must be carefully placed and embedded within the pericardium or attached to the NGs, ensuring accurate data collection without interfering with cardiac function. Depending on the intended duration of use, consideration should be given to whether the NG-based IEHs should be biodegradable or retrievable through minimally invasive means. Safety Regulatory Approval and Long-Term Viability is paramount, as with any medical implant, the safety of such a device and its components. Comprehensive safety testing and regulatory approval would be necessary before human use [108–110].

The long-term viability and stability of NGs within the pericardium must be thoroughly studied to ensure they continue to function effectively over time without causing any harm. The use of the pericardium for implanting flake-like IEHs made of NGs for energy harvesting and real-time monitoring of physiological and pathological signs is a concept with potential benefits. However, it also presents significant engineering and medical challenges that must be carefully addressed. Collaboration between materials science, cardiology, and medical device engineering experts would be essential to develop and test such innovative solutions, ensuring they meet safety and efficacy standards for medical implantation.

The concept of a symbiotic cardiac pacemaker powered by the energy harvested during a cardiac cycle is intriguing. It represents a potential advancement in the field of cardiac devices. Let us explore the key considerations and advantages of such a device. Energy Harvesting is the primary advantage of this concept: using the body's mechanical energy, generated during each cardiac cycle, to power the pacemaker. This can eliminate the need for a battery or external power source, potentially reducing surgical battery replacements. Higher Energy Output, which is mentioned, the harvested energy exceeds the required endocardial pacing threshold [109–111]. This is crucial for ensuring the pacemaker can reliably deliver electrical stimuli to the heart's tissues, maintaining proper cardiac rhythm and preventing arrhythmias.

Reduced Surgical Interventions with an autonomous energy source would eliminate the need for periodic battery replacement surgeries typically required for traditional pacemakers. This can reduce the risks associated with surgical procedures and improve the patient's quality of life. The device should be designed with biocompatible materials and safe for long-term implantation within the heart. This includes choosing materials for the pacemaker components and any interfaces with surrounding tissues.

Real-time monitoring is to pace the heart effectively. The symbiotic pacemaker should include sensors to monitor the heart's electrical activity and adjust the pacing rate as needed. Real-time monitoring can help ensure the heart remains in sync with the body's needs. The device must be designed with a high level of safety and reliability. Any malfunctions or failures could have life-threatening consequences, so rigorous testing and quality control are essential. Like all medical devices, a symbiotic cardiac pacemaker must undergo extensive safety testing and receive regulatory approvals before it can be used in clinical practice. Meeting medical device standards is critical [111–113].

Longevity is the device that should be designed to have a long operational lifespan, ideally matching the patient's lifespan. This would reduce the need for device replacements, which can be risky and costly. Patient Selection criteria should be well-defined. Not all patients with cardiac rhythm disorders may be suitable candidates for this type of pacemaker, so careful evaluation is necessary. Ethical considerations regarding patient consent, privacy, and the potential for device hacking or misuse should be addressed. A symbiotic cardiac pacemaker powered by the energy harvested during a cardiac cycle represents an innovative approach to cardiac pacing. It can potentially reduce the need for surgical interventions and improve the quality of life for patients with cardiac rhythm disorders. However, developing such a device requires rigorous engineering, extensive testing, regulatory approvals, and careful consideration of ethical and safety issues[112–114]. Collaborative efforts between cardiology, materials science, and medical device engineering experts would be essential in realising this concept.

With a focus on Sustainable Development Goals (SDGs), hybrid piezoelectric-triboelectric devices can efficiently harvest mechanical energy when repeatedly squeezed and stretched, contributing to clean and affordable energy production. A Li-doped ZnO-based hybrid generator demonstrated a significant increase in voltage output, from 10.1 V to 60.0 V, and a 75 A current without electrical poling. Similarly, a ZnO-PDMS-based hybrid generator produced 470 V and 60 A/cm2 under typical hand compression, sufficient to power 180 commercial LED lights [115–118]. Adding a third electrode to the hybrid device can record triboelectric and piezoelectric currents during stretching, enhancing the device's power output [108–110]. A structure using piezoelectric polyvinylidene fluoride (PVDF) and polytetrafluoroethylene (PTFE) generated enough pressure to light 600 LEDs [119–121]. Further optimisation using pillar micro-patterns on a triboelectric MWCNT-PDMS membrane increased TEG voltage from 20.08 V to 30.06 V. Hybrid sensors with enhanced designs like arc-shaped PEG and TEG can improve sensitivity and deformation range [118–120]. An alternative technique that overcomes the limitations of a single dielectric piezoelectric material for TEG involves alternating PEG and TEG connections, enabling mutual output reinforcement [121–123]. For instance, a simplified piezo-triboelectric hybrid generator using P(VDF-TrFE) nanofibers achieved a peak output of 96 mV and 3.8 mA peak current, providing better performance, space-saving, and robustness than a purely piezoelectric output [124–127]. In summary, hybrid piezo-triboelectric generators hold promise for sustainable mechanical energy harvesting, effectively converting everyday mechanical actions into clean and affordable energy and contributing to achieving SDGs focused on sustainable energy solutions.

4.4. Solar energy harvesting for Biomedical Applications and SDG

The sun generates an immense amount of energy, making it the most efficient and reliable renewable energy source, with the potential to significantly contribute to the Sustainable Development Goals (SDGs) [128–130]. Photovoltaic cells, widely utilised in wearable biomedical devices, offer a sustainable solution for powering these devices [131]. Compared to other energy harvesting systems, photovoltaic cells require less energy and can generate higher outputs than PEGs [132–134]. Combining PEGs with solar materials can enhance the power production of both technologies, offering a continuous energy supply even during cloudy or low-light conditions [135–137]. Photovoltaic cells convert solar energy into electricity through the photovoltaic effect, which occurs when n- and p-type semiconductors form p-n junctions [138–140]. PV cells' power conversion efficiency (PCE) can be calculated using various factors, such as maximum power output, solar energy input, open circuit voltage, short circuit current, and fill factor [141–143]. Due to the simplicity and affordability of solar cells and piezoelectric generators, these technologies can contribute to achieving SDGs by providing accessible renewable energy solutions [144–146]. Hybrid generators combining solar energy harvesting with piezoelectric materials have improved performance. For example, a PVDF-based PEG integrated with a ZnO quantum dot solar cell showed a significant increase in output voltage and current [147–149]. Such advancements in solar energy harvesting for biomedical applications hold promise for a sustainable future, contributing to the global effort toward achieving SDGs focused on clean and affordable energy.

A proposed hybrid system, aligned with Sustainable Development Goals (SDGs), combines photovoltaic and piezoelectric components in a tree-like structure, with leaves representing the energy harvesting elements [150–152]. A solar cell sheet of 110 mm by 50 mm can deliver a maximum of 3.42 mW of electricity under 2k loading resistance. However, due to the hybrid system's variability, additional rectifiers may be necessary to manage the energy collected from each piezoelectric component [152–154]. ZnO, a non-toxic piezoelectric n-type semiconductor, offers an excellent integration choice for PV cells due to its piezoelectric and photovoltaic properties. Fig. 8 showcases a naturally combined photovoltaic-piezoelectric hybrid generator composed of n-type ZnO NWs and a p-type P3HT-based blend [155–158]. In this structure, mechanical stress on ZnO NWs generates a voltage to enhance the overall output, producing positive pulses [159–161].

Architecture II in Fig. 8(b) employs a unique core-shell optical fibre structure to transfer light in low-light or overcast conditions, directing light into a dye-sensitised solar cell [162–164]. The hybrid system produces increased output when the piezoelectric and photovoltaic voltage polarities match. To overcome the incompatibility between piezoelectric alternating current and direct photovoltaic current, rectifying current flows at the metal-semiconductor interface to convert the piezoelectric output to DC [164–166]. By integrating photovoltaic and piezoelectric technologies, this innovative hybrid system offers a sustainable solution to energy harvesting, contributing to the global effort towards achieving SDGs focused on clean and affordable energy.

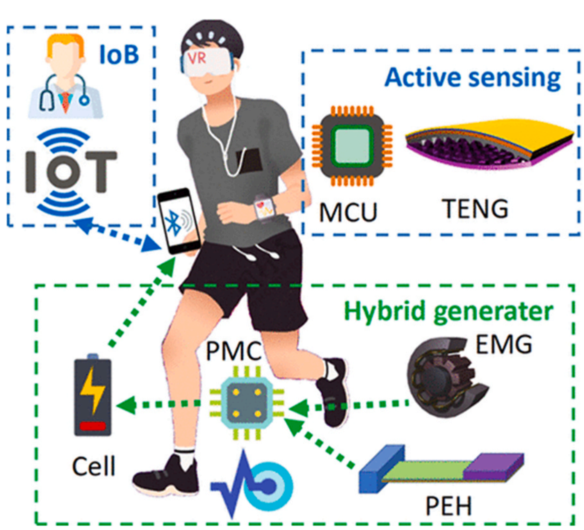

Fig. 8. Prospects of human kinetic energy harvesting[16].

In the context of Sustainable Development Goals (SDGs), the Schottky barrier is an effective gate, allowing forward bias and limiting reverse discrimination, enabling electrons to transition from high to low-energy states. By placing a Schottky barrier between a piezoelectric semiconductor and a metal electrode, alternating current in the semiconductor can be rectified without external rectifiers [166–168]. This approach is demonstrated in a piezoelectric-photovoltaic hybrid system utilising the Schottky barrier, consisting of a solar cell made from ZnO NWs on top of a piezoelectric generator made of ZnO NWs [168–170]. Hybrid energy harvesters that use multiple energy collection methods, such as trio-pyro-photo-piezoelectric hybrid generators, can provide reliable energy sources from mechanical, thermal, or solar inputs, offering a stable and predictable power supply for various applications [171–173]. Flexible piezoelectrics provide potential applications in biological energy harvesting, which can absorb mechanical energy from the human body to power biomedical sensors or actuators. These energy sources are reliable, environmentally friendly, and maintenance-free, contributing to the global effort towards achieving clean and affordable energy [174–176].

Emerging organic-inorganic piezoelectric materials represent a significant advancement in the field of bioengineering. These materials combine the benefits of both organic and inorganic compounds, offering unique properties and versatile applications in healthcare and beyond. One prominent group of organic-inorganic materials is organic-inorganic hybrid perovskites. These materials exhibit remarkable piezoelectric properties while being relatively easy to synthesize and customize. In bioengineering, they hold immense potential for various applications. Organic-inorganic hybrid perovskite-based piezoelectric sensors can detect subtle mechanical changes, such as pulse or muscle contractions[177–179]. They are employed in wearable health monitoring devices, providing real-time data on a person's physiological state. These materials are suitable for creating biocompatible, implantable sensors and energy harvesters. They can power and communicate with medical implants, enabling continuous monitoring and treatment adjustments. Organic-inorganic piezoelectric materials can be used to develop smart drug delivery systems. By responding to specific physiological cues (e.g., pH or temperature changes), they release drugs at precise locations and times within the body.

Researchers are exploring using these materials in tissue engineering to stimulate cell growth and tissue regeneration. Mechanical stimuli from piezoelectric materials can enhance the development of artificial organs and prosthetic tissues. Organic-inorganic piezoelectric materials can harvest biomechanical energy, such as motion or muscle contractions, and convert it into electrical energy [179–181]. This is particularly useful for powering medical devices and implants without external batteries. These materials can be employed in bioengineering to create biodegradable sensors for environmental monitoring. They can measure parameters like soil moisture, pollution levels, or water quality, aiding ecological research and conservation efforts. Moreover, the tunable nature of organic-inorganic hybrids allows researchers to optimize their properties for specific bioengineering applications. This versatility makes them highly adaptable and suitable for addressing various healthcare challenges. Emerging organic-inorganic piezoelectric materials, particularly organic-inorganic hybrid perovskites, can potentially revolutionize bioengineering [182–184]. Their biocompatibility, tunability, and exceptional piezoelectric properties make them invaluable for developing advanced sensors, drug delivery systems, tissue engineering solutions, and energy harvesters, contributing to improved healthcare outcomes and sustainable biomedical technologies.

5. Challenge, outlook, and discussion

This article reviews the practical secondary applications of flexible piezoelectrics and explores innovative methods for performance enhancement. Examining the relationship between fundamental properties and performance offers insights for future research to expand secondary functions (Fig. 8). Solutions such as stretchability, hybrid energy harvesting, and self-healing are discussed, along with conclusions and strategies to address remaining challenges in secondary function development [185–187].

Various polymers find applications in biomedical engineering due to their unique properties and biocompatibility. These polymers play a crucial role in fabricating devices for a wide range of biomedical applications, and their sensitivity can vary depending on the specific requirements of each application. Due to its flexibility and biocompatibility, Polydimethylsiloxane (PDMS) is widely used for microfluidic devices and soft lithography. It is suitable for applications involving cell culture and organ-on-a-chip systems. Its sensitivity lies in its ability to replicate fine microstructures and provide a microenvironment that mimics physiological conditions. Polylactic Acid (PLA) and Polycaprolactone (PCL) are biodegradable polymers used in tissue engineering and drug delivery systems [188–190]. Their sensitivity to biomedical engineering applications lies in their ability to degrade over time, making them suitable for implantable devices that gradually release drugs or scaffold materials that promote tissue regeneration.

Polyethylene Glycol (PEG) is often used for surface modification of biomaterials to improve their biocompatibility. It has also been used in drug delivery systems and tissue engineering. Its sensitivity lies in its hydrophilic nature and capacity to reduce the immune response to implanted materials. Polyurethane (PU) is employed in applications like catheters and vascular grafts. Its sensitivity in biomedical engineering is related to its mechanical properties, biocompatibility, and resistance to degradation within the body [191–193]. Polyvinyl Alcohol (PVA) hydrogels are used for wound dressings, drug delivery, and tissue engineering. Their sensitivity is due to their high water content, which mimics natural tissues and promotes cell growth. Poly(ethylene terephthalate) (PET) fabricates medical implants and prosthetics. Its sensitivity is attributed to its excellent mechanical properties and long-term biocompatibility. Each polymer offers distinct advantages and sensitivities depending on the specific requirements of the biomedical application. The choice of polymer is critical to ensuring that the device or material functions effectively, is biocompatible, and aligns with the desired biomedical outcome [194–196].

6. Discussion key insights include

Focusing on Sustainable Development Goals (SDGs), the market value of piezoelectric materials is expected to reach $27.5 billion by 2026 [197–200] due to their desirable properties, such as high biocompatibility, ease of processing, durability, reliability, and sensitivity. Lightweight and flexible piezoelectric devices can be attached to human joints and organs to harvest mechanical energy for biosensors, contributing to the development of clean and affordable energy [201–204].

FPM must adapt to the human body's curvilinear shape to sustainably capture mechanical energy. Enhancing biological energy harvesting requires additional functionalities to address challenges that improved piezoelectric efficiency alone cannot solve. This review systematically examines the secondary functions of stretchability, hybrid energy harvesting, and self-healing for FPM, exploring the mechanisms, strategies for development, and the relationships between structural characteristics and properties [203–205].

i. Wireless communication technologies' stability can significantly facilitate commercialising stretchable piezoelectric systems and devices with 3D flexible microstrip antennas.
ii. Hybrid energy harvesting requires careful design to prevent unintended interference between energy systems, as strain can induce the "strain effect" in thermoelectric materials, affecting local heat flux delivery and the efficiency of the harvester.
iii. Stretchable materials with Young's modulus, similar to human skin, provide greater comfort. Developing consumer-focused products requires consistent wearability metrics, and advanced mechanical models are necessary for designing sophisticated 3D stretchable structures, as piezoelectric responses are directly linked to load transfer and circulation[206–208].
iv. Enhancing the elastic piezoelectric material, electrode circuit, and substrate leads to more effective stretchability. A lower Young's modulus than skin results in a more natural skin feel.
v. Enhancing the substrate, electrode circuit, and stretchability of piezoelectric materials makes them suitable for wear. With time, Young's modulus of human skin increases. When the modulus is reduced, it returns to its normal texture and feels.

In conclusion, focusing on stretchability, hybrid energy harvesting, and self-healing functionalities is crucial for developing FPM in line with the SDGs, particularly in pursuing clean and affordable energy solutions.

7. Conclusion

In conclusion, this research has explored the potential of FPM to address Sustainable Development Goals, particularly in the context of clean and affordable energy solutions. By examining the secondary functions of stretchability, hybrid energy harvesting, and self-healing, the study has provided valuable insights into the mechanisms and strategies for developing these materials and the relationships between structural characteristics and properties. The novelty of this research lies in its systematic examination of the challenges and opportunities in designing piezoelectric materials that can adapt to the human body's curvilinear shape, sustainably capturing mechanical energy and providing a reliable, environmentally friendly, and maintenance-free energy source for various applications, such as biosensors and actuators.

Furthermore, the research has identified critical areas for future investigation, including the commercialisation of stretchable piezoelectric systems, the careful design of hybrid energy harvesters to prevent unintended interference, the development of consistent wearability metrics, and the enhancement of the elastic piezoelectric material, electrode circuit, and substrate to improve stretchability and comfort. Overall, this study paves the way for developing and implementing FPM in line with the SDGs, offering a promising and innovative approach to sustainably harnessing clean, affordable energy.

7.1. Summary of findings

The findings from the information above can be summarized as the importance of Flexible Piezoelectric Materials (FPM), which have emerged as a promising solution for energy harvesting in biomedical equipment. They offer the ability to capture mechanical energy efficiently, aligning with the United Nations' Sustainable Development Goals (SDGs). Alignment with SDGs is that FPM has the potential to contribute significantly to several SDGs. These goals include clean and affordable energy (SDG 7), sustainable industrial development (SDG 9), and advancements in healthcare (SDG 3). The secondary Functions of FPM are studied, emphasising the importance of secondary functions such as stretchability, hybrid energy harvesting, and self-healing in FPM. These functions are crucial for adapting to the human body's movements and deformations.

The research identifies critical areas for future exploration, including the commercialization of stretchable piezoelectric systems, prevention of interference in hybrid energy harvesters, development of consistent wearability metrics, and enhancement of piezoelectric materials and substrates for improved performance and comfort. FPM can be used for various applications, including biosensors and actuators, providing a reliable, environmentally friendly, and maintenance-free source of mechanical energy. The research discusses innovative approaches, such as hybrid piezoelectric-triboelectric devices and combining piezoelectric and photovoltaic materials, to enhance energy harvesting capabilities and contribute to the SDGs. FPM has significant potential in bioengineering, which can be applied to harness mechanical energy from the human body for various purposes, aligning with healthcare and clean energy SDGs. The findings highlight the multifaceted potential of Flexible Piezoelectric Materials in contributing to the SDGs, particularly in the context of clean and affordable energy solutions and advancements in healthcare and sustainable industrial development. Further research and development in this field hold promise for addressing these global goals.

7.2. Contributions to the field

The contributions of the research on Flexible Piezoelectric Materials (FPM) to the field can be summarized. The analysis introduces innovative concepts and materials related to energy harvesting, specifically in the context of FPM. Exploring secondary functions like stretchability, hybrid energy harvesting, and self-healing offers new avenues for developing efficient and sustainable energy harvesting devices. This innovation is crucial for addressing the global challenge of clean and affordable energy (SDG 7).

The study underscores the alignment of FPM research with the United Nations' SDGs. It demonstrates how FPM can directly contribute to several SDGs, including clean and affordable energy (SDG 7), industry, innovation, and infrastructure (SDG 9), and good health and well-being (SDG 3). This alignment emphasizes the potential of FPM to address pressing global issues. The research explores the practical applications of FPM, particularly in the biomedical field, such as biosensors and actuators. These applications have the potential to revolutionize healthcare by offering reliable and sustainable energy sources, contributing to the goal of ensuring healthy lives and promoting well-being for all (SDG 3).

The study identifies critical areas for future investigation, guiding researchers and industry stakeholders. These areas include commercialization strategies for stretchable piezoelectric systems, enhancing wearability metrics, and improving the materials and substrates for FPM. These insights facilitate the advancement of FPM technology. FPM research inherently involves interdisciplinary collaboration between materials science, engineering, and biomedical fields. This multidisciplinary approach fosters knowledge exchange and innovation, vital for addressing complex global challenges related to sustainability and healthcare. The research promotes sustainable innovation by focusing on environmentally friendly, maintenance-free energy sources. This aligns with the broader goal of sustainable industrialization and responsible consumption and production (SDG 12). The contributions of FPM research extend beyond the scientific realm. They have the potential to drive innovation, address global challenges, improve healthcare, and contribute to the achievement of multiple Sustainable Development Goals outlined by the United Nations.

7.3. Future research directions

The research on Flexible Piezoelectric Materials (FPM) has illuminated several future research directions that can further advance this field and contribute to sustainable development goals. Here are key areas for future investigation to make FPM-based energy harvesting systems widely accessible. Research should focus on developing effective commercialization strategies. This includes exploring cost-effective manufacturing techniques, scalability, and market penetration strategies. Ensuring affordability aligns with providing clean and affordable energy (SDG 7). Hybrid energy harvesting systems combining FPM with other technologies should be optimized to prevent unintended interference. Research can delve into improving the integration of different energy sources while maintaining efficiency and reliability, particularly in applications where precision is crucial.

Developing consistent wearability metrics is essential for assessing the practicality of FPM-based devices in bioengineering applications. Research should aim to standardize and refine metrics that evaluate comfort, durability, and user-friendliness, which are critical for achieving the highest quality healthcare (SDG 3). Future research should improve the elastic piezoelectric material, electrode circuits, and substrates to enhance stretchability and comfort. This includes exploring novel materials with improved piezoelectric properties and mechanical resilience to optimize energy harvesting efficiency. Ensuring the long-term reliability of FPM-based devices is essential. Research should investigate the materials' durability and performance over extended periods, especially in biomedical applications where consistency and longevity are paramount.

As FPM technologies advance, research should address scalability challenges in manufacturing. Economies of scale can be achieved by optimizing production processes, which will be critical for meeting global energy and healthcare demands. Assessing the environmental impact of FPM production and usage is crucial to align with sustainable development goals (SDG 12). Future research should include life cycle assessments to minimize the environmental footprint of FPM materials and devices. Research can contribute to developing regulatory frameworks and standards for FPM-based devices. This ensures safety, quality, and adherence to ethical guidelines, essential in healthcare applications. Promoting awareness and understanding of FPM technologies among researchers, healthcare professionals, and the general public can accelerate their adoption. Education and outreach efforts can bridge the knowledge gap and facilitate widespread acceptance.

Encouraging cross-disciplinary collaboration between materials science, engineering, and healthcare sectors can foster innovation. Interdisciplinary teams can tackle complex challenges more effectively and accelerate progress. Future research in Flexible Piezoelectric Materials (FPM) should encompass various areas, from technical enhancements to commercialization strategies and ethical considerations. By addressing these directions, FPM can significantly contribute to achieving Sustainable Development Goals, particularly in clean energy and bioengineering.

Declaration of Competing Interest

The authors declare that they have no known competing for financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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