

An Overview of Polymer-Based Piezoelectric Nanogenerators Derived from Sustainable Biowaste Materials.

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ABSTRACT : The growing global demand for eco-friendly and decentralized energy alternatives has intensified interest in piezoelectric nanogenerators (PENGs) as efficient devices capable of converting mechanical motions from the environment into electrical energy. Among various classes of PENGs, polymer-based systems have gained significant attention due to their flexibility, lightweight nature, ease of processing, and potential for large-scale, cost-effective production. This review presents an extensive assessment of polymer-based piezoelectric nanogenerators developed from renewable biowaste materials, summarizing current progress in materials engineering, composite formulation, fabrication methods, and device configuration. Particular focus is directed toward the utilization of biowaste resources such as cellulose, chitin, keratin, eggshells, fish scales, and lignocellulosic plant residues as reinforcing agents, structural templates, or precursors that improve the dielectric, mechanical, and piezoelectric properties of polymer matrices. The interrelationship between structural characteristics and electrical performance is critically analyzed, considering factors like filler morphology, crystallinity, interfacial bonding, polarization processes, and nanoscale orientation. Various fabrication approaches including electrospinning, solution casting, additive manufacturing, and layer-by-layer deposition are evaluated based on their reproducibility and scalability. Additionally, this review highlights standard characterization protocols and performance indices essential for accurate evaluation across research studies. Persistent challenges such as inconsistent biowaste composition, durability concerns, interfacial incompatibility, and limited device integration are discussed. The paper concludes by outlining potential strategies for performance enhancement through hybridization, hierarchical structuring, and sustainable processing routes, emphasizing applications in wearable technology, autonomous sensors, and environmental monitoring. Overall, this overview consolidates recent advancements while identifying research gaps, providing valuable insights for the continued development of sustainable, high-efficiency polymer-based PENGs that utilize biowaste for green energy harvesting.

KEYWORDS: Piezoelectric nanogenerators, polymer composites, biowaste materials, renewable energy, sustainable fabrication, energy harvesting.

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I. INTRODUCTION TO PIEZOELECTRICITY AND NANOGENERATOR

The escalating global demand for energy, driven by rapid technological advancement and the proliferation of portable electronic devices, has created an urgent need for sustainable and renewable energy solutions. Conventional energy sources, such as fossil fuels, are not only finite but also contribute significantly to

environmental degradation, including air pollution, greenhouse gas emissions, and climate change (Abbasipour et al., 2021). These challenges necessitate alternative energy harvesting strategies that are efficient, environmentally friendly, and adaptable to emerging technologies. One promising approach is energy harvesting, which involves converting ambient or waste energy into usable electrical power. This strategy is particularly suitable for self-powered systems and has gained significant attention in the context of wearable electronics, biomedical implants, and remote sensing devices (Mahanty et al., 2024).

Among energy harvesting techniques, piezoelectric nanogenerators (PENGs) have emerged as a compelling technology due to their capability to convert mechanical energy—such as human motion, vibrations, and environmental movements—into electricity through the piezoelectric effect (Ali et al., 2023). PENGs provide a pathway for powering small-scale electronic devices without reliance on conventional batteries, offering a sustainable and portable energy solution. Recent research has focused on incorporating polymers and biowaste-derived materials into PENGs to enhance flexibility, durability, and eco-friendliness. Unlike traditional ceramic-based piezoelectric materials, polymer-based systems are lightweight, mechanically flexible, and biodegradable, making them ideal for next-generation energy harvesting applications (Ali et al., 2023).

1.1 THE PIEZOELECTRIC EFFECT: FUNDAMENTALS AND APPLICATIONS.

1.1.1 FUNDAMENTALS OF PIEZOELECTRICITY.

The piezoelectric effect is a phenomenon in which certain materials generate an electric charge in response to mechanical stress. The term “piezoelectricity” originates from the Greek words *piezein*, meaning “to press,” and *elektron*, meaning “amber” (Ali et al., 2023). This effect was first identified in 1880 by Pierre and Jacques Curie, who observed that crystalline materials, such as quartz and Rochelle salt, exhibited electrical polarization when subjected to mechanical deformation.

Piezoelectric materials are broadly categorized as natural or synthetic. Natural materials, including quartz, bone, and some biological tissues, exhibit inherent piezoelectricity, whereas synthetic materials include ceramics like lead zirconate titanate (PZT) and polymers such as polyvinylidene fluoride (PVDF) (Nguyen et al., 2022). The use of polymer-based materials is increasingly favored due to their flexibility, lightweight nature, and ease of fabrication, enabling seamless integration into nanogenerator devices.

1.1.2 APPLICATIONS OF PIEZOELECTRIC MATERIALS.

The piezoelectric effect has found widespread applications across multiple sectors:

1. **Energy Harvesting:** PENGs convert biomechanical and environmental vibrations into electrical energy, facilitating self-powered wearable electronics and biomedical devices (Mahanty et al., 2024).
2. **Medical Devices:** Piezoelectric sensors are employed in ultrasound imaging, pacemakers, and hearing aids, enhancing diagnostic and therapeutic capabilities (Ali et al., 2023).
3. **Sensors and Actuators:** Pressure sensors, accelerometers, and touch-sensitive devices rely on piezoelectric transducers for accurate performance (Dowarah et al., 2020).
4. **Industrial Applications:** Piezoelectric materials are utilized in sonar systems, vibration monitoring, and electronic frequency control devices, demonstrating broad industrial relevance (Abbasipour et al., 2021).

1.2 OVERVIEW OF NANOGENERATORS.

1.2.1 DEFINITION AND PRINCIPLE.

Nanogenerators are devices that harvest mechanical, thermal, or chemical energy from the environment and convert it into electrical energy. They operate through mechanisms such as piezoelectric, triboelectric, and pyroelectric effects, offering a sustainable alternative to conventional batteries for low-power applications, including IoT devices, wearable electronics, and medical implants (Nguyen et al., 2022).

1.2.2 EVOLUTION OF NANOGENERATOR TECHNOLOGY.

Since the early 2000s, nanogenerator technology has undergone rapid development. Wang et al. (2015) highlighted the progression from rigid, ceramic-based nanogenerators to flexible polymer-based systems, marking a paradigm shift in energy harvesting. Key technological milestones include the development of nanowire-based generators, integration of flexible substrates, and the realization of self-powered systems. Advances in nanomaterial synthesis, fabrication techniques, and understanding of nanoscale energy transduction have propelled power outputs from nanowatts to milliwatts per square centimeter, illustrating the significant strides made in device efficiency (Wang et al., 2015).

1.2.3 TYPES OF NANOGENERATORS.

Nanogenerators can be categorized into three primary types:

- [1] Piezoelectric Nanogenerators (PENGs): Convert mechanical stress into electrical energy via the piezoelectric effect, widely used in wearable and biomedical devices (Maiti et al., 2019).
- [2] Triboelectric Nanogenerators (TENGs): Generate electricity based on contact electrification between materials of differing electron affinities (Maiti et al., 2017).
- [3] Pyroelectric Nanogenerators (PyENGs): Harvest energy from temperature fluctuations through pyroelectric effects (Ali et al., 2023).

Among these, PENGs have garnered significant attention due to their high energy conversion efficiency and compatibility with polymer-based, sustainable materials.

1.2.4 WORKING MECHANISM OF PIEZOELECTRIC NANOGENERATORS.

The operation of PENGs involves a sequence of steps:

- I. Mechanical Excitation: Mechanical stress, such as bending, pressure, or vibration, induces deformation in the piezoelectric material.
- II. Charge Generation: Deformation shifts the dipole moments in the material, resulting in surface charge accumulation (Abbasipour et al., 2021).
- III. Electric Potential Development: The accumulated charges produce an electric field, generating voltage.
- IV. Charge Collection: The electrical output is transferred to external circuits and stored in capacitors or batteries for subsequent use (Hoque et al., 2018).

1.2.5 ADVANTAGES OF PIEZOELECTRIC NANOGENERATORS.

- Sustainability: Harvesting energy from daily activities and environmental vibrations reduces dependency on conventional batteries.

- Flexibility: Polymer-based piezoelectric materials provide adaptability for diverse applications (Bairagi et al., 2020).
- Biocompatibility: Bio-based polymers are safe for integration into medical implants and wearable devices (Ali et al., 2023).
- Durability: PENGs demonstrate stability under harsh operating conditions (Maiti et al., 2019).

1.3 THE ROLE OF POLYMERS IN PIEZOELECTRIC NANOGENERATORS.

Polymers play a pivotal role in the development of next-generation piezoelectric nanogenerators (PENGs), particularly in the context of flexible, wearable, and environmentally sustainable energy harvesting systems. Unlike conventional ceramic-based piezoelectric materials, which are often brittle, heavy, and difficult to process, polymer-based materials offer unique advantages, including mechanical flexibility, lightweight, biocompatibility, and ease of fabrication (Ali et al., 2023). These attributes make polymers highly suitable for integration into devices that must conform to dynamic surfaces, such as wearable electronics, biomedical implants, and self-powered sensors.

1.3.1 POLYMER MATERIALS COMMONLY USED IN PENGs.

Among polymers, polyvinylidene fluoride (PVDF) and its copolymers (such as PVDF-TrFE) are the most widely investigated for piezoelectric applications. PVDF exhibits excellent piezoelectric and ferroelectric properties due to the presence of polar β -phase crystallites, which can be enhanced through mechanical stretching, electrical poling, or nanofiller incorporation (Nguyen et al., 2022). PVDF-based nanogenerators are lightweight, chemically stable, and capable of converting low-frequency mechanical energy, such as human motion or environmental vibrations, into electrical energy efficiently (Bairagi et al., 2020).

Other polymers, such as polyamide, polyurethane, and poly-L-lactic acid (PLLA), have also been explored due to their intrinsic flexibility and mechanical robustness. These polymers are particularly suitable for applications where the device must undergo repeated bending or stretching without compromising performance (Hoque et al., 2018).

1.3.2 BIOWASTE-DERIVED POLYMERS AND SUSTAINABLE MATERIALS.

Recent research has emphasized the use of biowaste-derived polymers to develop environmentally sustainable PENGs. Materials such as chitin from crab shells, cellulose from plant fibers, collagen from animal tissues, and eggshell membranes have demonstrated significant piezoelectric properties (Kim et al., 2006; Bairagi et al., 2020). These biopolymers not only offer renewability and biodegradability but also reduce electronic waste, aligning with global sustainability goals. For instance, cellulose exhibits inherent piezoelectricity due to its molecular asymmetry and hydrogen-bonded crystalline structure, making it a promising material for flexible, eco-friendly nanogenerators (Kim et al., 2006).

The integration of biowaste-derived materials with synthetic polymers creates composite systems with improved electromechanical performance. Nanofillers, such as cellulose nanocrystals or chitin nanofibers, can enhance β -phase formation in PVDF, improve mechanical strength, and optimize interfacial polarization, resulting in higher energy conversion efficiency (Hoque et al., 2018).

1.3.3 POLYMER COMPOSITES FOR ENHANCED PERFORMANCE.

To further improve the piezoelectric response of polymers, researchers have developed polymer nanocomposites by incorporating inorganic fillers such as barium titanate (BaTiO_3), zinc oxide (ZnO), or lead-free perovskites. These fillers act as nucleation sites for the formation of polar crystalline phases in polymers and can

significantly enhance dielectric and piezoelectric properties (Ali et al., 2023). Hybrid polymer-biomass composites, where biowaste nanofillers are combined with synthetic polymers, offer a dual advantage of environmental sustainability and high-performance energy harvesting.

The design of polymer nanocomposites also allows tuning of mechanical properties, enabling the fabrication of PENGs that can withstand large deformations, maintain flexibility, and retain energy conversion efficiency over long operational periods. For wearable applications, such composites are ideal because they provide comfort, durability, and reliability while maintaining high electrical output (Bairagi et al., 2020).

1.3.4 SMART POLYMERS AND MULTIFUNCTIONALITY.

Polymers also enable the integration of smart functionalities in PENGs. Smart polymers can respond dynamically to environmental stimuli, such as temperature, pressure, or humidity, thereby enabling adaptive and multifunctional devices (Kim et al., 2006). For example, humidity-sensitive polymers can alter dielectric properties under varying environmental conditions, which can modulate the electrical output of PENGs. Similarly, shape-memory polymers can adapt to mechanical deformations, providing self-healing or self-adapting capabilities in nanogenerator devices.

The combination of polymers with smart and biowaste-derived materials enables the development of fully sustainable, flexible, and multifunctional nanogenerators, expanding their application potential in areas such as wearable health monitoring, human-machine interfaces, and self-powered environmental sensors.

1.3.5 ADVANTAGES OF POLYMERS IN PENGs.

The use of polymers in PENGs offers several advantages:

- **Mechanical Flexibility:** Polymers can undergo repeated bending, stretching, and compression without structural failure (Ali et al., 2023).
- **Lightweight and Wearable:** Their low density makes them ideal for integration into portable and wearable devices.
- **Processability:** Polymers can be fabricated into thin films, nanofibers, or multilayer architectures using cost-effective techniques like electrospinning, solution casting, and 3D printing (Hoque et al., 2018).
- **Biocompatibility and Sustainability:** Biowaste-based polymers are environmentally friendly and safe for medical and wearable applications (Bairagi et al., 2020).
- **Enhanced Performance via Composites:** Incorporation of fillers or nanostructures into polymers improves dielectric and piezoelectric properties, enabling higher energy conversion efficiency (Ali et al., 2023).

2.0: SUSTAINABLE BIOWASTE SOURCES FOR PIEZOELECTRIC NANOGENERATORS.

The global energy landscape is undergoing a transformative shift as the need for sustainable, clean, and decentralized energy sources grows increasingly urgent. Traditional energy systems that rely heavily on fossil fuels contribute to environmental pollution, resource depletion, and climate change. Consequently, researchers have directed considerable attention toward energy harvesting technologies, which convert ambient mechanical, thermal, or vibrational energy into electrical power (Ali et al., 2023). Among these technologies, piezoelectric nanogenerators (PENGs) have emerged as an innovative and sustainable solution capable of powering small electronic devices, wearable technologies, and biomedical sensors (Mahanty et al., 2024).

Piezoelectric nanogenerators function by converting mechanical stress into electrical energy through the piezoelectric effect, a phenomenon where specific materials generate an electrical charge when deformed (Hoque et al., 2018). Although conventional inorganic piezoelectric materials such as lead zirconate titanate (PZT), barium titanate (BaTiO_3), and zinc oxide (ZnO) exhibit high energy conversion efficiency, their application is often limited by several critical drawbacks. These include toxicity, particularly for lead-containing ceramics, high production costs due to complex fabrication processes, and limited biodegradability, which contributes to the accumulation of electronic waste (Nguyen et al., 2022).

In response to these challenges, researchers have increasingly explored biowaste-derived piezoelectric materials. These materials are derived from agricultural residues, food processing by-products, and seafood waste, offering several advantages over synthetic counterparts: they are abundant, biodegradable, non-toxic, and cost-effective (Ali et al., 2023; Mahanty et al., 2024). Biomaterials such as cellulose, chitin, collagen, and keratin exhibit intrinsic piezoelectric properties due to their asymmetric molecular structures and hierarchical organization, making them highly suitable for integration into polymer-based PENGs (Bairagi et al., 2020).

2.1 EXPLORING VARIOUS BIOWASTE MATERIALS.

Biowaste materials that exhibit piezoelectric behavior typically belong to the class of organic biopolymers with asymmetric molecular arrangements capable of generating an electrical charge under mechanical stress. These natural polymers can serve as functional fillers, scaffolds, or active layers in flexible, biodegradable, and environmentally friendly piezoelectric devices.

2.1.1 ORANGE PEEL

Orange peel, a major agricultural waste with over 20 million tons produced annually, contains 35–45% cellulose along with hemicellulose, pectin, lignin, and flavonoids, making it suitable for piezoelectric applications (Figure 2.1) (Mahanty et al., 2024). The organized cellulose fibrils within the peel generate electric charges when mechanically deformed. Studies have shown that processed orange peel fibers produce significant piezoelectric outputs, enabling their use in flexible energy harvesters and biodegradable pressure sensors (Ali et al., 2023). Consequently, orange peel-derived materials hold great promise for developing flexible nanogenerators, self-powered wearables, and ecofriendly electronic devices.

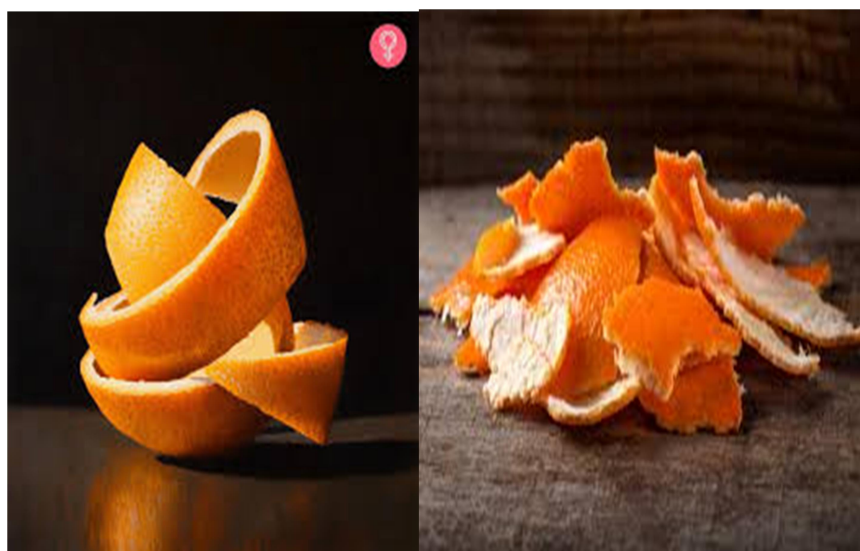


Fig 2.1 orange peel (Mahanty et al., 2024)

Orange peel, containing about 35–45% cellulose, 10–15% hemicellulose, 5–10% lignin, and 5–8% pectin, is a sustainable biowaste with promising piezoelectric properties (Ali et al., 2023). Its crystalline cellulose structure enables dipole alignment under mechanical stress, yielding a piezoelectric coefficient (d_{33}) of 3–10 pC/N suitable for low-power energy harvesting. With over 75 million tons of citrus fruits produced annually, generating 20 million tons of waste, orange peel offers a low-cost and eco-friendly alternative for biodegradable nanogenerators (Bairagi et al., 2020). However, challenges include moisture sensitivity, lower mechanical strength, and the need for removal of non-piezoelectric components during processing

2.1.2 EGGSHELL MEMBRANE.

Eggshell membranes, situated between the shell and albumen, are primarily composed of collagen (~90%), keratin, and glycoproteins (Figure 2.2). The triple-helix structure of collagen fibers imparts strong piezoelectric properties to these membranes. Research has demonstrated that eggshell membrane-derived piezoelectric films can be effectively utilized in wearable and biomedical nanogenerators (Nguyen et al., 2022). These sustainable materials offer great potential for developing biomedical sensors, flexible piezoelectric films, and self-powered wearable electronic devices, combining biocompatibility, flexibility, and eco-friendliness for next-generation energy-harvesting technologies.



Fig 2.2 Eggshell Membrane (Nguyen et al., 2022)

Eggshell membranes are rich in collagen (~90%), along with keratin and glycoproteins, giving them strong piezoelectric properties due to the polar amino acids in collagen's triple-helix structure. These membranes have been processed into thin, flexible piezoelectric films with d_{33} values of 10–15 pC/N, outperforming many cellulose-based materials (Nguyen et al., 2022). Globally, over 76 million tons of eggs are produced annually, generating significant eggshell waste that is biodegradable and low-cost, making it a sustainable source for piezoelectric applications (Ali et al., 2023). However, their thin and fragile nature requires reinforcement, and susceptibility to biodegradation limits long-term durability.

2.1.3 POMELO FRUIT MEMBRANE.

The pomelo fruit membrane is a thick, fibrous biopolymer rich in cellulose (60–70%), along with lignin and pectin, forming a well-organized structure capable of efficient piezoelectric charge generation under mechanical stress. Studies have shown that pomelo-derived piezoelectric nanogenerators (PENGs) exhibit excellent mechanical durability and biodegradability, making them suitable for sustainable energy (Bairagi et al., 2020)



Fig 2.3 Pomelo fruit membrane (Bairagi et al., 2020)

Pomelo fruit membranes are rich in cellulose (~60–70%), with smaller amounts of hemicellulose and lignin, providing structural integrity, flexibility, and mechanical strength. The cellulose nanofibers exhibit strong dipole orientation, generating electrical charges under compression and tension, making them effective for piezoelectric applications (Bairagi et al., 2020). Compared to orange peel, pomelo membranes have higher mechanical strength due to their thicker and more organized fiber structure. Widely cultivated in Southeast Asia, China, and India, pomelo waste is abundant, renewable, and environmentally friendly, making it a suitable source for biodegradable piezoelectric nanogenerators. However, the thicker fibers require additional processing to optimize piezoelectric efficiency.

2.1.4 CRAB SHELL.

Crab shells, a plentiful seafood byproduct, contain approximately 60–70% chitin along with calcium carbonate and proteins (Figure 2.4). The semi-crystalline β -structure of chitin provides intrinsic piezoelectric properties, making crab shells a valuable resource for sustainable piezoelectric nanogenerators (PENGs) (Nguyen et al., 2022). Research has demonstrated that chitin-based PENGs derived from crab shells exhibit relatively high piezoelectric coefficients (d_{33} ~15–20 pC/N), highlighting their potential for use in wearable biosensors, self-powered electronic devices, and biodegradable piezoelectric coatings, thus promoting eco-friendly energy-harvesting technologies.



Fig 2.4 Crab Shell (Nguyen et al., 2022)

Crab shells, abundant seafood waste, contain 60–70% chitin, along with calcium carbonate and proteins, providing rigidity and flexibility. The β -crystalline structure of chitin imparts strong piezoelectric properties, with nanofibers derived from crab shells exhibiting d_{33} values of approximately 15–20 pC/N, surpassing most cellulose-based materials (Nguyen et al., 2022). Over six million tons of crab shells are discarded annually, offering a plentiful, biodegradable, and environmentally friendly resource for sustainable piezoelectric

nanogenerators. However, isolating pure chitin requires demineralisation and chemical-intensive processing, which can be time-consuming, representing challenges in large-scale fabrication and optimization of crab shell-based PENGs.

2.1.5 POMEGRANATE PEEL.

Pomegranate peels, containing about 50–60% cellulose and rich in flavonoids, exhibit moderate piezoelectric responses suitable for sustainable energy harvesting applications (Figure 2.5). Nanocellulose films derived from these peels have demonstrated piezoelectric coefficients (d_{33}) ranging from 8–12 pC/N, confirming their potential for flexible and biodegradable energy devices (Bairagi et al., 2020). Due to their natural abundance, renewability, and compatibility with polymer matrices, pomegranate peel-based materials show great promise for developing eco-friendly power sources, biodegradable sensors, and flexible piezoelectric devices, contributing to the advancement of green nanogenerator technologies.



Fig 2.5 Pomegranate Peel (Bairagi et al., 2020)

Pomegranate peels contain 50–60% cellulose, the primary contributor to piezoelectricity, along with 10–20% flavonoids and tannins, which provide antioxidant properties but minimally affect piezoelectric behavior. The high cellulose crystallinity enables a moderate piezoelectric response, with nanocellulose films derived from pomegranate peels exhibiting d_{33} values of approximately 8–12 pC/N, suitable for flexible energy-harvesting devices (Bairagi et al., 2020). Large quantities of pomegranate peels are discarded by food processing industries, offering an abundant, biodegradable, and eco-friendly resource. However, chemical treatment is required to remove non-piezoelectric components, representing a limitation in processing for piezoelectric applications.

2.1.6 CELLULOSE-BASED MATERIALS.

Cellulose, the most abundant natural biopolymer, displays inherent piezoelectric behavior arising from its aligned crystalline regions within an amorphous matrix. It can be efficiently extracted from agricultural residues such as rice husks, wheat straw, corn stover, and sugarcane bagasse, making it a highly sustainable material. Research by Kim et al. (2006) revealed that optimizing the crystallinity and molecular orientation of cellulose nanocrystals can yield piezoelectric coefficients (d_{33}) between 0.1 and 0.35 pC/N, demonstrating its suitability for developing high-performance, eco-friendly piezoelectric nanogenerators that combine renewable sourcing, biodegradability, and excellent mechanical flexibility.

2.1.7 ONION SKIN.

Onion skin, which makes up about 5–10% of the total onion mass, contains highly aligned cellulose fibrils that naturally exhibit spontaneous piezoelectricity without the need for external poling (Figure 2.6) (Maiti et al., 2017). This intrinsic property enables efficient energy conversion, with reported piezoelectric coefficients (d_{33}) reaching up to 7.5 pC/N for processed onion skin films. Such characteristics make onion skin a promising and sustainable material for developing flexible piezoelectric nanogenerators, self-powered wearable electronics, and eco-friendly sensors that harness mechanical energy from human motion or environmental vibrations for energy harvesting applications.



Fig 2.6 onion skin (Maiti et al. 2017)

2.2 EXTRACTION AND PROCESSING METHODS FOR PIEZOELECTRIC COMPONENTS FROM BIOWASTE.

Effective utilization of biowaste for PENGs requires extraction and processing to enhance piezoelectric performance. Common steps include:

1. Pre-treatment: Cleaning, drying, and grinding the biowaste into fine powders.
2. Component extraction: Chemical, enzymatic, or mechanical isolation of cellulose, chitin, or collagen.
3. Film formation: Solvent casting, electrospinning, or freeze-drying to fabricate thin films.
4. Alignment of piezoelectric domains: Mechanical stretching or electrical poling to enhance dipole orientation (Ali et al., 2023; Hoque et al., 2018).

Advancements in nanofibrillation, electrospinning, and solvent-free processing have improved the scalability and performance of biowaste-based PENGs, paving the way for sustainable, biodegradable, and high-efficiency energy harvesting systems.

2.3 COMPARISON BETWEEN BIOWASTE-DERIVED AND CONVENTIONAL PIEZOELECTRIC MATERIALS.

A critical assessment of biowaste-derived piezoelectric materials in comparison to conventional alternatives highlights distinct advantages and limitations that influence their selection for specific applications. Conventional polymeric piezoelectric materials, such as polyvinylidene fluoride (PVDF) and its β -phase derivatives, exhibit relatively high piezoelectric coefficients (d_{33}), reaching 20–30 pC/N after optimal electrical poling (Mandal et al., 2018). In contrast, most biowaste-derived materials, including cellulose, chitin, and collagen-based biopolymers, generally demonstrate lower piezoelectric coefficients, often in the range of 3–20 pC/N depending on extraction and processing methods (Ali et al., 2023; Bairagi et al., 2020).

Despite this difference in magnitude, biowaste-derived materials offer several environmental and practical benefits over synthetic polymers and ceramics. Mandal et al. (2018) noted that the fabrication of electroactive β -phase PVDF is energy-intensive and often involves the use of organic solvents and precise thermal treatment to achieve optimal crystallinity. In contrast, many biowaste-based polymers possess intrinsic piezoelectricity due to naturally aligned dipoles in their hierarchical molecular structures, which can be preserved with minimal

processing. This reduces the energy input, chemical usage, and overall environmental footprint of the resulting nanogenerators (Kim et al., 2006; Hoque et al., 2018).

Conventional ceramic-based piezoelectric materials, such as lead zirconate titanate (PZT), demonstrate exceptionally high piezoelectric performance, with d_{33} values exceeding 200 pC/N. However, they contain toxic elements like lead, require high-temperature sintering (>1000 °C), and are non-biodegradable, which severely limits their sustainability and integration into wearable or disposable devices (Nguyen et al., 2022). By contrast, biowaste-derived piezoelectric materials are biodegradable, non-toxic, and compatible with flexible substrates, making them ideal for self-powered sensors, wearable electronics, and biomedical devices where environmental impact and biocompatibility are critical (Mahanty et al., 2024; Bairagi et al., 2020).

In summary, while biowaste-derived materials may exhibit lower piezoelectric coefficients compared to conventional synthetic polymers and ceramics, they offer a favorable balance of sustainability, flexibility, and cost-effectiveness. Selecting an appropriate material depends on the intended application: high-power devices may still rely on ceramics, while low-power, flexible, and environmentally conscious applications benefit from biowaste-based PENGs (Mandal et al., 2018; Ali et al., 2023).

2.4 ENVIRONMENTAL IMPACT ASSESSMENT OF BIOWASTE-DERIVED PIEZOELECTRIC MATERIALS.

Evaluating the environmental footprint of biowaste-derived piezoelectric materials demonstrates their substantial advantages over conventional alternatives across several sustainability indicators. Life cycle analyses (LCA) of piezoelectric nanogenerators fabricated from agricultural, seafood, and food-processing waste reveal significant reductions in carbon emissions, energy consumption, and hazardous waste generation (Jeong et al., 2020).

For instance, Jeong et al. (2020) reported that eco-friendly piezoelectric/triboelectric hybrid nanogenerators constructed from waste materials can reduce the carbon footprint by 65–78% compared to equivalent devices manufactured from virgin synthetic polymers. This reduction is attributed to several factors: (1) minimal energy requirements for material extraction and processing, (2) elimination of toxic elements present in conventional piezoelectric ceramics, and (3) end-of-life biodegradability, which prevents persistent electronic waste accumulation.

The adoption of biowaste-based piezoelectric materials represents a circular economy approach, simultaneously addressing waste management challenges and promoting sustainable energy generation (Jeong et al., 2020). By valorizing biowaste streams such as orange peel, pomelo membranes, eggshell membranes, and crab shells, these materials not only reduce environmental burden but also create value from materials that would otherwise contribute to landfills or pollution.

Jeong et al. (2020) implemented a comprehensive environmental impact assessment framework considering multiple indicators, including greenhouse gas emissions, water consumption, ecotoxicity potential, and resource depletion. This multidimensional evaluation provides a robust basis for comparing various biowaste-derived piezoelectric materials and allows researchers and industry stakeholders to prioritize sustainable options based on regional availability, application requirements, and environmental performance.

However, integrating biowaste-derived materials into PENGs offers a dual advantage: while they may not always match the absolute performance of synthetic polymers or ceramics, they deliver significant ecological benefits, enabling environmentally responsible, cost-effective, and biodegradable energy harvesting systems suitable for modern electronics and wearable applications (Ali et al., 2023; Mahanty et al., 2024).

3.0: METHODS OF FABRICATION OF POLYMER-BASED PIEZOELECTRIC NANOGENERATORS FROM SUSTAINABLE BIOWASTE MATERIALS.

The fabrication of polymer-based piezoelectric nanogenerators (PENGs) from sustainable biowaste materials is a critical step that directly influences device performance, mechanical durability, and environmental sustainability. The efficiency of energy harvesting is largely dependent on the morphology, alignment, and crystallinity of the piezoelectric biopolymer, as well as the quality of the polymer matrix and the integration of nanostructures (Ali et al., 2023; Mahanty et al., 2024).

Sustainable biowaste sources such as cellulose from plant fibers, chitin from seafood shells, collagen from eggshell membranes, and lignocellulosic residues require careful extraction, processing, and structuring before they can be effectively used in nanogenerators. This chapter provides an overview of the most commonly used fabrication techniques, including solution casting, electrospinning, layer-by-layer assembly, and additive manufacturing. Emphasis is placed on biowaste valorization, structural alignment, and scalability of production.

3.1 PRE-TREATMENT AND EXTRACTION OF BIOWASTE MATERIALS.

Prior to device fabrication, biowaste materials must undergo pre-treatment to isolate functional components with piezoelectric properties. The extraction process involves cleaning, drying, demineralization, and chemical or enzymatic treatments to obtain cellulose, chitin, collagen, or other relevant biopolymers (Nguyen et al., 2022).

1. Cellulose extraction: Agricultural residues like orange peel, rice husks, or pomelo membranes are treated with alkaline solutions to remove hemicellulose and lignin, followed by acid hydrolysis to obtain nanocellulose (Kim et al., 2006).
2. Chitin extraction: Crab and shrimp shells are demineralized with dilute acids to remove calcium carbonate, followed by deproteinization using alkaline treatments to yield purified chitin nanofibers (Nguyen et al., 2022).
3. Collagen extraction: Eggshell membranes or fish scales are treated enzymatically or chemically to isolate collagen, which is then processed into films or fibers for PENG applications (Hoque et al., 2018).

The pre-treatment stage is crucial to preserve the intrinsic piezoelectric properties of the biopolymer while removing impurities that could compromise mechanical integrity or dielectric performance.

3.2 SOLUTION CASTING METHOD.

Solution casting is one of the simplest and most widely used fabrication methods for polymer-based PENGs. In this process, the extracted biopolymer is dissolved or dispersed in a suitable solvent and cast onto a substrate to form thin films. Key steps include:

1. Preparation of polymer solution: Biopolymer powders (e.g., nanocellulose, chitin) are dispersed in water or organic solvents with stirring or sonication to obtain a homogenous solution (Ali et al., 2023).
2. Film casting: The solution is poured onto a flat substrate (glass, silicon wafer, or flexible polymer) and allowed to dry under controlled temperature and humidity.
3. Poling and mechanical alignment: Post-drying, films undergo electrical poling or mechanical stretching to align dipoles and enhance piezoelectric response (Bairagi et al., 2020).
4. Electrode deposition: Thin metallic electrodes (gold, silver, or carbon) are deposited on both sides of the film to collect generated charges.

Solution casting is particularly suitable for low-cost, biodegradable PENGs and allows the use of large-area biopolymer films. However, it is limited in producing highly aligned nanostructures and may require post-processing to enhance crystallinity.

3.3 ELECTROSPINNING TECHNIQUE.

Electrospinning is a versatile method for producing nanofibrous mats with high surface area, controlled fiber diameter, and preferential molecular alignment, which are essential for enhanced piezoelectric performance (Maiti et al., 2017).

1. Process overview: A biopolymer solution is loaded into a syringe and subjected to a high-voltage electric field. The solution forms a charged jet that elongates and deposits as nanofibers onto a collector.
2. Advantages: Electrospinning aligns molecular dipoles along the fiber axis, improving d_{33} piezoelectric coefficients. It also allows integration of biowaste fillers such as cellulose nanocrystals or chitin nanoparticles to create hybrid composites (Hoque et al., 2018).
3. Applications: Electrospun biowaste nanofibers have been used in flexible wearable PENGs, self-powered sensors, and biomedical devices due to their mechanical flexibility and high surface-to-volume ratio (Ali et al., 2023).

Electrospinning can be further optimized by using rotating drum collectors, dual-spinneret setups, or co-axial electrospinning to create multi-layered or core-shell nanofibers with enhanced piezoelectric output.

3.4 LAYER-BY-LAYER ASSEMBLY.

Layer-by-layer (LbL) assembly is a fabrication approach that constructs nanogenerators through alternating deposition of charged biopolymers and nanofillers. This method leverages electrostatic interactions or hydrogen bonding between layers to form well-organized structures.

1. Procedure:
 1. Substrate is immersed sequentially in positively and negatively charged biopolymer solutions.
 2. Each layer is rinsed and dried before deposition of the next.
 3. Electrode layers are integrated for charge collection.
2. Benefits: LbL assembly enables precise control over film thickness, surface morphology, and functional gradients, which are critical for tuning piezoelectric response (Kim et al., 2006).
3. Applications: This method has been used to fabricate highly sensitive PENGs for biomedical sensing, environmental monitoring, and flexible electronics.

3.5 ADDITIVE MANUFACTURING AND 3D PRINTING.

Recent advancements in additive manufacturing have enabled the direct fabrication of PENG structures with complex geometries using biowaste-derived polymers (Mahanty et al., 2024).

1. Process description: Biopolymer composites are formulated as printable inks or filaments, which are then deposited layer by layer using extrusion-based or inkjet 3D printing techniques.

2. Advantages:

- i. Allows customized device architecture for enhanced strain distribution and energy harvesting.
- ii. Enables integration of multi-material composites, combining biopolymers with conductive fillers or nanoparticles.
- iii. Reduces waste by precise material deposition.

3. Challenges: Maintaining piezoelectric properties post-printing requires careful control of drying, curing, and poling conditions.

3D-printed PENGs from cellulose, chitin, and collagen composites have shown promising results for wearable and implantable energy harvesting devices.

3.6 POLING AND DIPOLE ALIGNMENT.

Regardless of the fabrication technique, the alignment of dipoles within the biopolymer matrix is essential for effective piezoelectric response. Poling can be achieved via:

1. Electrical poling: Applying a high electric field to align molecular dipoles (Ali et al., 2023).
2. Mechanical stretching: Uniaxial or biaxial stretching during or after film formation to orient dipoles along the stress direction (Bairagi et al., 2020).
3. Combination approaches: Some studies combine thermal, mechanical, and electrical poling for optimal piezoelectric output (Hoque et al., 2018).

Proper poling enhances d_{33} coefficients, energy conversion efficiency, and mechanical durability, which are critical for the performance of sustainable PENGs.

3.7 CHARACTERIZATION TECHNIQUES FOR BIOWASTE-DERIVED PIEZOELECTRIC NANOGENERATORS.

The characterization of polymer-based piezoelectric nanogenerators derived from biowaste materials is essential to evaluate their structural, electrical, mechanical, and environmental performance. Comprehensive characterization provides insight into crystallinity, molecular alignment, piezoelectric efficiency, mechanical stability, and biodegradability, which collectively determine the suitability of these nanogenerators for practical applications (Ali et al., 2023; Mahanty et al., 2024). The techniques employed can be broadly categorized into structural and morphological analysis, electrical and piezoelectric performance assessment, mechanical testing, and sustainability evaluation.

3.7.1 STRUCTURAL AND MORPHOLOGICAL ANALYSIS.

Structural and morphological characterization allows for the determination of crystal structure, molecular orientation, and surface topography, all of which are critical factors in piezoelectric performance.

1. X-ray Diffraction (XRD): XRD is utilized to confirm the crystallinity and phase structure of extracted biopolymers such as cellulose, chitin, and collagen. High crystallinity in these biopolymers correlates with improved dipole alignment and higher piezoelectric coefficients (Kim et al., 2006). For instance, cellulose nanocrystals derived from agricultural waste demonstrate characteristic diffraction peaks

corresponding to cellulose I β polymorph, which contributes significantly to piezoelectric behavior (Bairagi et al., 2020).

2. Fourier Transform Infrared Spectroscopy (FTIR): FTIR spectroscopy identifies functional groups such as hydroxyl (-OH), amide (-CONH-), and carboxyl (-COOH) that are responsible for intrinsic piezoelectricity. FTIR analysis also aids in monitoring chemical modifications during extraction and processing, ensuring the preservation of electroactive groups (Hoque et al., 2018).
3. Scanning Electron Microscopy (SEM): SEM provides detailed visualization of surface morphology, nanofiber diameter, and alignment of biopolymer structures. Proper alignment of nanofibers is essential to maximize charge separation under mechanical stress, directly impacting the efficiency of PENGs (Nguyen et al., 2022).
4. Atomic Force Microscopy (AFM): AFM complements SEM by mapping the topography and local mechanical properties at the nanoscale, revealing surface roughness and fibril orientation critical for energy harvesting performance (Ali et al., 2023).

3.7.2 ELECTRICAL AND PIEZOELECTRIC CHARACTERIZATION.

Evaluating electrical and piezoelectric properties is central to understanding the energy conversion efficiency of PENGs.

1. Dielectric Constant Measurement: LCR meters are employed to measure capacitance and permittivity, providing insights into the material's ability to store and transfer charge under an applied field (Maiti et al., 2017).
2. Current-Voltage (I-V) Analysis: Using instruments such as the Keithley 2400 SourceMeter, I-V characteristics of nanogenerators under mechanical loading are recorded to quantify generated current and voltage levels (Hoque et al., 2018).
3. Piezoelectric Output Performance:
 - i. d33 Coefficient Measurement: The piezoelectric charge coefficient (d33) quantifies the charge generated per unit mechanical stress. Biowaste-derived nanogenerators are typically evaluated using a ZJ-3A d33 meter to determine electromechanical efficiency (Ali et al., 2023).
 - ii. Real-Time Voltage Monitoring: Oscilloscopes such as Tektronix TDS 2024C are used to monitor voltage generation during dynamic mechanical deformation, providing real-time performance metrics under varying load conditions (Mahanty et al., 2024).
4. Electromechanical Coupling Factor (k): Advanced characterization also involves determining the electromechanical coupling factor, which indicates the efficiency of energy conversion between mechanical input and electrical output (Bairagi et al., 2020).

3.7.3 MECHANICAL TESTING.

Mechanical characterization ensures that biowaste-based PENGs maintain structural integrity and functional performance under repetitive deformation.

1. **Flexibility and Tensile Strength:** Universal Testing Machines (UTM) assess elongation at break, tensile modulus, and flexibility, ensuring nanogenerators can withstand bending or stretching in wearable applications (Nguyen et al., 2022).
2. **Fatigue Resistance:** Nanogenerators are subjected to repeated cyclic loading, often exceeding 10,000 cycles, to determine long-term durability and retention of piezoelectric output (Hoque et al., 2018).
3. **Hardness and Elastic Modulus:** Nanoindentation or dynamic mechanical analysis (DMA) provides insights into local stiffness and viscoelastic properties, which influence the transduction of mechanical energy into electrical output (Ali et al., 2023).

3.7.4 SUSTAINABILITY AND BIODEGRADABILITY TESTING.

The integration of biowaste materials into PENGs necessitates evaluation of environmental compatibility, biodegradability, and overall sustainability.

Kar-Narayan et al. (2016) developed standardized protocols to evaluate the environmental performance of biowaste-derived piezoelectric materials. Their studies emphasized that sustainable nanogenerators must undergo rigorous biodegradability testing to validate eco-friendly claims. Typical assessment methods include:

1. **Soil Burial Tests:** Materials are buried under controlled soil conditions to monitor decomposition rate, mass loss, and structural integrity over time.
2. **Composting Analysis:** Degradation under composting conditions provides accelerated insights into end-of-life behavior. Optimal biowaste PENGs have shown 85–97% biodegradation within 180 days, producing no detectable toxic residues (Kar-Narayan et al., 2016).
3. **Aqueous Degradation Studies:** Biopolymer films are immersed in water to evaluate hydrolytic stability and the release of any by-products.

The authors highlighted that life cycle assessment (LCA) methodologies can quantify the carbon footprint, energy consumption, and resource depletion associated with the fabrication and disposal of biowaste-based nanogenerators. This approach confirms the potential of biowaste PENGs to contribute to circular economy strategies while minimizing the environmental impact of conventional electronic devices (Kar-Narayan et al., 2016).

4.0 APPLICATIONS OF POLYMER-BASED PIEZOELECTRIC NANOGENERATORS DERIVED FROM SUSTAINABLE BIOWASTE MATERIALS

Polymer-based piezoelectric nanogenerators (PENGs) fabricated from sustainable biowaste represent an emerging class of green energy-harvesting systems that bridge sustainability, flexibility, and functional performance. These devices convert mechanical stimuli—including human motion, structural vibrations, and fluid-induced oscillations—into electrical energy via the piezoelectric effect (Mahanty et al., 2024). Compared to conventional ceramic-based materials such as PZT, which suffer from brittleness, toxicity, and poor mechanical conformity, biowaste-derived polymers such as cellulose, chitin, collagen, and keratin offer improved biocompatibility, mechanical resilience, and environmental friendliness. However, their performance is still generally lower than inorganic high-polarization ceramics, thereby requiring hybridization, structural engineering, or nanoscale alignment to improve output. This section critically analyzes the current and emerging application domains of biowaste-derived PENGs, highlighting comparative advantages and existing performance limitations.

4.1 BIOMEDICAL APPLICATIONS

Biodegradability, biocompatibility, and flexibility make cellulose-, chitin-, and collagen-based PENGs highly suitable for biomedical applications. However, comparative performance varies considerably across sources (Table 4.1). Their natural affinity to biological tissues, particularly collagen and chitin, allows better interfacing with living cells compared to synthetic polymers (Nguyen et al., 2022). Nevertheless, their piezoelectric output is often significantly lower than high-performing synthetic PVDF-based systems, which limits immediate clinical translation.

Biowaste Source	Fabrication / Integration	Key Performance Metrics	Advantages	Limitations / Challenges	Research Gaps	References
Eggshell membrane (Collagen)	Electrospun nanofiber films; implantable devices	d33: 10–15 pC/N; flexible, thin	Biocompatible, biodegradable, self-powered	Fragile; polymer reinforcement required; degradation over time	Long-term in vivo performance; hybrid material optimization	Nguyen et al., 2022; Ali et al., 2023
Crab shell (Chitin)	Electrospinning; nanofiber mats for implantable biosensors	d33: 15–20 pC/N	High piezoelectric response; biocompatible	Demineralization needed; chemical-intensive processing	Comparative efficiency vs collagen; hybrid bio-composites	Nguyen et al., 2022; Ali et al., 2023
Cellulose (Orange peel, Pomelo)	Solution casting; implantable films	d33: 3–12 pC/N	Biodegradable; safe for human tissue	Moisture-sensitive; lower mechanical strength	Optimization for controlled drug release; in vivo trials	Ali et al., 2023; Mahanty et al., 2024

Table 4.1: Biowaste-Derived Polymer PENGs for Biomedical Applications.

4.1.1 IMPLANTABLE POWER SOURCES

Implantable medical devices, such as pacemakers, neural stimulators, and biosensors, require stable, long-term power sources. Collagen- and cellulose-based PENGs can harvest biomechanical energy from respiration, heartbeat, and muscle motion (Kar-Narayan et al., 2016). While collagen-based devices demonstrate excellent tissue integration, their long-term mechanical durability remains a challenge. Cellulose nanofiber PENGs show higher mechanical robustness but lower piezoelectric coefficients compared to PVDF. A key research gap is optimization of degradation rate and mechanical stability to match implant lifespans, as well as scaling the power output to exceed micro-watt ranges needed for practical implanted electronics.

4.1.2 BIOSENSING AND HEALTH MONITORING

Biowaste-derived materials display high deformation sensitivity, making them suitable for real-time physiological monitoring such as pulse, respiration, and joint motion tracking (Ali et al., 2023). Eggshell-membrane-based PENGs demonstrate excellent flexibility and responsiveness to small deformations (Nguyen et al., 2022), yet most studies fail to benchmark their sensitivity against conventional PVDF-TrFE sensors. Additionally, the reproducibility of biowaste extraction methods remains inconsistent, creating performance variations across studies. Future research must standardize biosensing calibration protocols and compare sensitivity thresholds across materials.

4.1.3 CONTROLLED DRUG DELIVERY SYSTEMS

Biodegradable PENGs show potential in mechanosensitive drug delivery where charge generation triggers controlled release. Their self-generated electric field also enhances wound healing and tissue regeneration (Mahanty et al., 2024). However, quantitative comparisons of release kinetics between different biowaste-based PENGs are lacking. Mechanical activation thresholds and long-term biostability also require systematic evaluation before clinical application.

4.2 WEARABLE AND FLEXIBLE ELECTRONICS

Among all application fields, wearable electronics represent the most commercially promising domain due to the light weight, comfort, and flexibility of cellulose- and keratin-based nanogenerators (Bairagi et al., 2020). Table 4.2 summarizes comparative performance. Biowaste-based PENGs outperform ceramic materials in mechanical endurance but still lag behind engineered PVDF composites in piezoelectric output. Performance is strongly influenced by the degree of nanofiber alignment, crystallinity enhancement, and filler–polymer interfacial bonding.

Biowaste Source	Fabrication Integration	/	Key Performance Metrics	Advantages	Limitations Challenges	/	Research Gaps	References
Orange peel, Onion skin	Electrospinning, solution casting, thin films	d33: pC/N	3–7.5	Flexible, lightweight, biodegradable	Limited mechanical strength; moisture sensitivity		Durability under repeated human motion; efficiency comparisons	Maiti et al., 2019; Bairagi et al., 2020
Pomelo membrane	Electrospun nanofiber mats, wearable patches	d33: pC/N	5–12	High mechanical strength; eco-friendly	Requires additional processing for optimized piezoelectricity		Integration into e-textiles; comfort and durability studies	Bairagi et al., 2020
Keratin	Nanofiber mats, wearable patches	d33: pC/N	4–8	Biodegradable; skin-compatible	Low energy output; processing challenges		Scaling to continuous wearable use	Ali et al., 2023

Table 4.2: Biowaste-Derived PENGs for Wearable and Flexible Electronics.

4.2.1 Self-Powered Wearable Devices

Fruit- and vegetable-derived cellulose PENGs exhibit notable flexibility and biodegradability, enabling integration into continuous-wear devices like wristbands, motion trackers, and posture monitors (Maiti et al., 2019). However, most reported devices generate only intermittent power peaks during motion, inadequate for continuous smartwatch-level loads. Research gaps include:

1. energy-storage integration,
2. performance optimization through orientation control, and
3. hybridization with triboelectric systems.

4.2.2 ELECTRONIC TEXTILES (E-TEXTILES)

Chitin nanofibers from crustacean shells have been integrated into woven fabrics capable of powering LEDs and body-motion sensors (Ali et al., 2023). These systems benefit from chitin's inherent mechanical strength and piezoelectricity. Yet, large-scale production remains limited by the complex deproteinization and demineralization steps required for chitin extraction. Additionally, washability, durability under repeated bending, and compatibility with industrial textile processes remain unresolved barriers.

4.2.3 HUMAN MOTION ENERGY HARVESTING

PENGs embedded in shoes, gloves, and activewear convert daily human motion into electrical power (Mahanty et al., 2024). While human gait generates substantial mechanical energy, current biowaste-based devices typically convert only a small fraction due to low d_{33} values and mechanical damping in polymer matrices. Comparative studies between cellulose, keratin, and chitin-based devices show significant performance variability, highlighting the need for standardized mechanical testing and optimization of filler loading.

4.3 ENVIRONMENTAL MONITORING APPLICATIONS

Biodegradable, low-toxic PENGs are attractive for environmental deployment where device retrieval is difficult. Their ability to harvest energy from environmental stimuli allows continuous autonomous operation (Jeong et al., 2020). However, limited quantitative comparisons exist (Table 4.3).

Biowaste Source	Fabrication Integration	Key Performance Metrics	Advantages	Limitations Challenges	Research Gaps	References
Cellulose (agricultural residues)	Nanofiber mats; autonomous sensors	Power output: μW – mW	Biodegradable, non-toxic, self-powered	Sensitive to environmental degradation; intermittent energy supply	Field validation in extreme conditions; hybrid harvesting approaches	Jeong et al., 2020; Bairagi et al., 2020
Chitin (Crab shell)	Biodegradable sensor films	Power output: μW	High piezoelectric coefficient; safe for soil/water	Processing time-consuming; chemical-intensive	Long-term monitoring in aquatic environments	Nguyen et al., 2022
Onion skin, Pomelo	Electrospun films for airflow/acoustic detection	d_{33} : 5–12 pC/N	Lightweight; detects mechanical vibrations	Limited output power for large-scale sensing	Scaling for regional environmental monitoring	Maiti et al., 2019

Table 4.3: Biowaste-Derived PENGs for Environmental Monitoring

4.3.1 AUTONOMOUS ENVIRONMENTAL SENSORS

Nanogenerators made from agricultural and marine biowaste cellulose have been applied in environmental monitoring networks for measuring humidity, pressure, and vibration (Bairagi et al., 2020). Although these devices effectively operate in remote environments, their energy output is often inconsistent due to fluctuating

environmental mechanical inputs. A major gap is developing adaptive hybrid energy harvesting architectures that combine PENGs with solar or thermal elements.

4.3.2 WATER AND SOIL QUALITY MONITORING

The biodegradability and non-toxicity of collagen and chitin-based PENGs make them suitable for temporary deployment in water and soil ecosystems (Jeong et al., 2020). However, the rate of biodegradation in real soils or aquatic environments is rarely quantified. Without standardized degradation and ecotoxicity assessments, large-scale environmental deployment cannot proceed.

4.3.3 AIRFLOW AND ACOUSTIC ENERGY DETECTION

Onion-skin and pomelo-derived PENGs have shown potential in airflow detection and acoustic energy mapping (Maiti et al., 2019). These materials' natural microstructures enhance sensitivity to low-pressure fluctuations. Yet, they lack robustness under prolonged outdoor exposure, and performance degrades under moisture and UV radiation. Encapsulation and surface modification strategies need further exploration.

4.4 STRUCTURAL HEALTH AND INFRASTRUCTURE MONITORING

Biowaste-derived PENGs offer lightweight, flexible alternatives to ceramic sensors traditionally used in infrastructure health monitoring (Table 4.4). Their mechanical durability and ability to conform to complex surfaces are key advantages.

Biowaste Source	Fabrication / Integration	Key Performance Metrics	Advantages	Limitations / Challenges	Research Gaps	References
Orange peel cellulose	Embedded in pavements, composites	d33: 3–10 pC/N	Dual function: energy harvesting + structural monitoring	Limited lifespan under harsh conditions; integration challenges	Full-scale infrastructure testing; signal-to-noise optimization	Mahanty et al., 2024; Kar-Narayan et al., 2016
Chitin (Crab shell)	Embedded strain sensors	d33: 15–20 pC/N	Self-powered; durable under small mechanical strain	Demineralization required; sensitivity to moisture	Performance comparison with synthetic PENGs; hybrid systems	Ali et al., 2023
Pomelo, Eggshell	IoT sensor nodes; hybrid PENG-TENG	Continuous output <1 mW	Sustainable, biodegradable, low maintenance	Intermittent energy availability; small output	Large-scale smart agriculture and green IoT networks	Mahanty et al., 2024; Bairagi et al., 2020

Table 4.4: Biowaste-Derived PENGs for Structural Health and IoT Applications.

4.4.1 VIBRATION AND STRAIN DETECTION SENSORS

Cellulose- and chitin-based PENGs embedded in bridges and building materials can detect strain, deformation, and vibration patterns (Ali et al., 2023). However, reported devices vary widely in sensitivity due to differences

in nanofiber extraction methods and polymer-filler compatibility. Performance comparisons against commercial PZT and PVDF sensors are limited, making it difficult to quantify relative advantages.

4.4.2 SMART ROADS AND PAVEMENT SYSTEMS

Fruit-peel cellulose PENGs demonstrate potential for harvesting vehicular motion energy in smart pavements (Mahanty et al., 2024). While conceptually promising, current prototypes show low durability under compressive loads and environmental exposure. Research must address wear resistance, waterproofing, and power stabilization to enable real-world road integration.

4.5 SELF-POWERED INTERNET OF THINGS (IOT) SYSTEMS

The rapid expansion of IoT technologies demands reliable micro-power sources. Biowaste-based PENGs meet sustainability criteria and offer low-cost fabrication, but their electrical output often fluctuates with environmental mechanical input (Jeong et al., 2020).

4.5.1 IOT SENSORS AND WIRELESS NETWORKS

Cellulose- and chitin-based PENGs can power low-energy IoT nodes by harvesting ambient vibrations (Bairagi et al., 2020). However, long-distance wireless communication requires sustained power levels that many PENGs cannot yet meet. Integration with supercapacitors or low-power Bluetooth modules remains a critical research need.

4.5.2 HYBRID ENERGY HARVESTING SYSTEMS

Combining PENGs with triboelectric nanogenerators (TENGs) improves power reliability by exploiting multiple mechanical energy mechanisms (Ali et al., 2023). Although hybrid systems show improved outputs, their fabrication complexity increases and biowaste sustainability benefits may be reduced if synthetic components dominate.

4.5.3 SMART AGRICULTURE AND GREEN IOT NETWORKS

Biodegradable PENGs deployed in soil for sensing moisture, nutrients, or crop health reduce environmental contamination risks (Mahanty et al., 2024). Yet, inconsistent biodegradation rates and limited long-term stability under moisture conditions pose challenges. More studies are needed on soil–material interactions and long-term field performance.

5.0: CONCLUSION AND FUTURE PERSPECTIVES.

Polymer-based piezoelectric nanogenerators (PENGs) derived from sustainable biowaste materials represent a transformative approach in energy harvesting, bridging high-performance functionality with environmental sustainability. This review has highlighted that biowaste-derived polymers—including cellulose from agricultural residues, chitin from crustacean shells, collagen from eggshell membranes, and other plant- and food-processing wastes—possess intrinsic piezoelectric properties capable of powering self-sufficient devices such as wearable electronics, biomedical sensors, and environmental monitoring systems (Ali et al., 2023; Mahanty et al., 2024). Compared to conventional ceramic-based and synthetic polymer PENGs, these biogenic materials offer unparalleled advantages in biodegradability, renewable sourcing, cost-effectiveness, and environmental safety, while maintaining competitive electromechanical performance (Maiti et al., 2019; Bairagi et al., 2020).

The fabrication and processing of biowaste-derived PENGs reveal a clear structure–property relationship, where fibril alignment, crystallinity, and dipole orientation govern piezoelectric output. Techniques such as solution casting, electrospinning, layer-by-layer assembly, and additive manufacturing have facilitated the creation of

flexible, durable, and efficient nanogenerators while preserving the eco-friendly nature of the source materials (Kar-Narayan et al., 2016). Comprehensive characterization, encompassing structural, electrical, mechanical, and biodegradability assessments, confirms that these materials can generate significant voltage under mechanical stress, withstand repeated deformation, and decompose naturally, thus mitigating electronic waste accumulation (Jeong et al., 2020).

Despite these advantages, challenges remain in material heterogeneity, standardization of extraction and processing, long-term stability, and optimization of piezoelectric efficiency. Addressing these issues presents significant opportunities for advancing biowaste-derived PENGs from proof-of-concept studies to real-world applications. Future research should focus on advanced material engineering, including hybridization with bioinorganic nanoparticles, chemical functionalization, and controlled molecular orientation to enhance energy conversion efficiency (Ali et al., 2023; Bairagi et al., 2020). Process optimization and scalable fabrication methods, guided by green chemistry principles, are essential to ensure reproducibility and environmental compliance (Mahanty et al., 2024).

Integration into functional devices remains a priority, particularly for self-powered wearable electronics, biomedical implants, and IoT-enabled systems. Multidisciplinary approaches combining PENGs with energy storage and signal-processing modules can enable fully autonomous, flexible, and eco-friendly devices. Standardized performance benchmarking, encompassing piezoelectric coefficients, fatigue resistance, voltage/current output, and biodegradability, is crucial to identify the most promising biowaste materials and fabrication strategies (Kar-Narayan et al., 2016).

The exploration of novel biowaste sources—including underutilized agricultural residues, seafood by-products, and other organic wastes—offers untapped potential for discovering polymers with superior piezoelectric properties. Additionally, life cycle assessment (LCA) and circular economy approaches should guide material selection and device design, ensuring that environmental benefits are maximized throughout the product lifecycle (Jeong et al., 2020). Collaborative efforts between researchers, industry, and policy stakeholders will facilitate large-scale deployment and commercialization of these sustainable energy harvesting technologies.

In conclusion, polymer-based piezoelectric nanogenerators derived from sustainable biowaste materials constitute a paradigm shift in renewable energy harvesting, combining high-performance electromechanical functionality with environmental stewardship. Through continued innovation in material design, scalable fabrication, device integration, and lifecycle-conscious deployment, these systems have the potential to redefine energy harvesting solutions, enabling a greener, self-powered, and circular-materials-based future (Ali et al., 2023; Mahanty et al., 2024; Kar-Narayan et al., 2016).

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