

Research Article

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Biodegradable Piezoelectric Nanogenerators Used as Wearable Electronic Device

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ABSTRACT

This study explores the sustainable conversion of waste Catla (Catla catla) fish scales into bio-piezoelectric materials for wearable energy harvesting applications. Utilizing the natural piezoelectric properties of collagen-rich fish scales, we developed a flexible nanogenerator through a simple demineralization and lamination process. The device was integrated into the heel of a shoe, where it successfully generated electrical energy from walking movements, demonstrating its viability as a self-powered solution for wearable electronics. It has the broader potential of monitoring the pressure on heels, thus providing the insights into activity levels, beneficial for athletes and rehabilitation patients using the embedding such bio- piezoelectric systems into shoes. This approach not only adds value to aquaculture waste but also offers a biodegradable, eco-friendly alternative to conventional piezoelectric materials, paving the way for next-generation sustainable smart textiles and self-powered wearable devices.

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Introduction

The rapid advancement of wearable electronics and portable devices has intensified the demand for sustainable, lightweight, and flexible energy sources capable of harvesting ambient mechanical energy. Piezoelectric materials, which generate electrical charges under mechanical stress, have emerged as promising candidates for self-powered systems. However, conventional piezoelectric materials such as lead zirconate titanate (PZT) and polyvinylidene fluoride (PVDF) often involve toxic components, complex manufacturing processes, and environmental concerns related to their disposal. These challenges have motivated research into eco-friendly alternatives derived from natural and biodegradable resources [1-7].

Fish scales, a byproduct of the aquaculture and seafood industries, represent an abundant and underutilized source of bio-waste. In particular, the scales of Catla catla s- a widely farmed freshwater fish in South Asia- contain a hierarchical collagen structure exhibiting intrinsic piezoelectric properties. Collagen, a natural protein with a highly ordered triple-helix configuration, generates electrical charges when subjected to mechanical deformation, making fish scales a viable natural piezoelectric material. Utilizing Catla fish scales not only addresses the environmental burden of fishery waste disposal but also offers a sustainable pathway to develop biodegradable and biocompatible piezoelectric devices. Recent studies have demonstrated the feasibility of converting fish scale biowaste into flexible bio-piezoelectric nanogenerators (BPNG)

through simple chemical treatments such as demineralization and acid processing, which preserve the collagen's piezoelectric β -phase while enhancing flexibility [1-7].

This paper explores the fabrication and integration of a bio-piezoelectric system derived from Catla fish scales, into a shoe heel prototype for energy harvesting.

Fish Scale Treatment Process

To utilize the piezoelectric properties of Catla catla fish scales, a systematic multi-step treatment was employed to isolate and enhance the collagen nanofibrils, which are primarily responsible for piezoelectric behavior. Initially, raw scales were collected from local fish markets and thoroughly rinsed under running tap water to eliminate residual organic material and surface contaminants. Once cleaned, the scales were subjected to a controlled drying process in a laboratory oven at approximately 70°C for several hours, ensuring complete moisture removal while preserving structural integrity.

Following drying, the scales underwent demineralization to remove embedded calcium-based compounds that contribute to their natural rigidity. This was achieved by immersing the dried scales in a 0.5 M solution of ethylenediaminetetraacetic acid (EDTA) for 24 hours. EDTA acts as a chelating agent, effectively extracting mineral components without disrupting the collagen matrix. After demineralization, the scales were immersed in a 0.1 M acetic acid solution. This mild acid treatment served to further purify the material and enhance the flexibility of the collagen fibers by gently loosening inter-fibrillar cross-links [4].

The resulting softened and purified collagen material was then cast into thin films. The acetic acid-collagen suspension was poured into a flat plate and allowed to air-dry under ambient conditions, forming flexible, transparent membranes composed predominantly of aligned collagen nanofibrils. These films retain the natural piezoelectric characteristics of collagen and serve as the active layer in the final device. This treatment method not only enhances mechanical pliability and electroactive response but also ensures that the processed material is lightweight, biodegradable, and suitable for integration into flexible electronic systems.

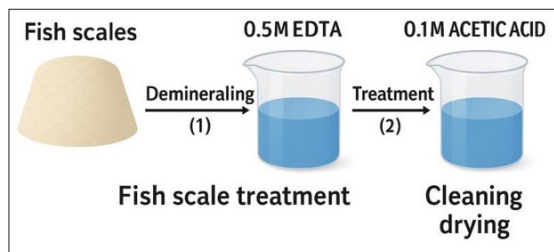


Figure 1: Schematic of Fish Scale Treatment Showing Demineralization With 0.5 M Edta Followed by Acid Treatment With 0.1 M Acetic Acid [4].

Device Fabrication and Electrode Assembly

Following the preparation of flexible collagen films derived from *Catla catla* fish scales, the treated films were converted into functional piezoelectric elements through electrode assembly. Both sides of each collagen film were coated with a thin layer of commercially available conductive paste, and covered it with plastic thin sheet which served as the electrodes for generation of electricity. While conductive paste was used in the present study due to its ease of application and flexibility, alternative materials such as silver nanoparticle ink or aluminium foil could also be employed as done in our previously reported results[5] or improved conductivity in future designs. Once dried, copper wires were affixed to each side of the film using conductive adhesive or tape, creating a complete electrical connection. The electrodes were then wired in a parallel configuration, where all positive terminals were connected together and all negative terminals likewise joined, to increase the overall current output of the system—ideal for powering low-resistance sensors. A series connection could alternatively be used to boost voltage output depending on specific application needs. To protect the assembly, the electrode-coated films were encapsulated between two thin acrylic sheets, forming a stable, pressure-responsive layer. This encapsulated unit was then embedded into the heel section of a shoe sole, ensuring effective energy harvesting during heel strikes while walking. The pressure applied during each step deformed the collagen film, inducing a potential difference across the electrodes due to its intrinsic piezoelectric properties.

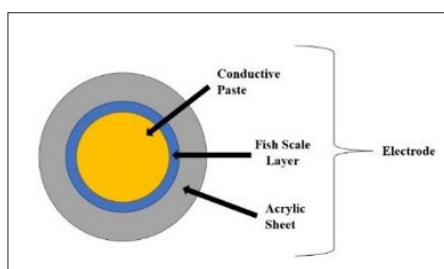


Figure 2A: Top View of the Electrode Assembly

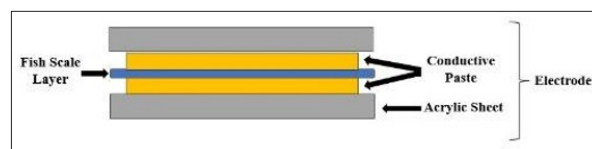


Figure 2B: Front View of the Electrode Assembly

Circuit Diagram

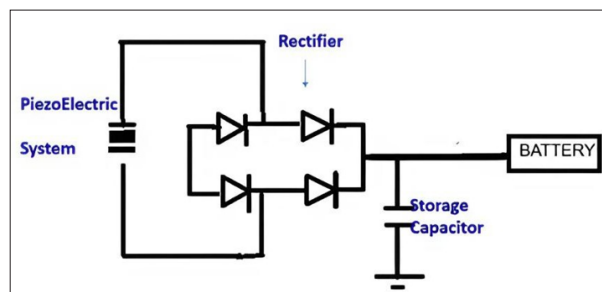


Figure 3: Circuit Diagram of the Energy Harvesting Unit Connected to the Piezoelectric System. the System Comprises a Full-Wave Schottky Diode Bridge Rectifier, Storage Capacitor and a Rechargeable Battery.

To efficiently harvest and store the electrical energy generated by the piezoelectric fish scale system, a dedicated energy harvesting circuit was constructed, as shown in Figure 3. This circuit integrates a full-wave rectifier, a storage capacitor, a voltage-sensing switch, and a rechargeable battery. The electrodes were connected in parallel to enhance current output while maintaining voltage levels, ensuring maximum charge extraction from the piezoelectric fish scales. This configuration allows simultaneous contribution of multiple electrodes, improving energy harvesting efficiency. The alternating current (AC) output generated by mechanical deformation of the fish scale was passed through a full-wave bridge rectifier consisting of four 1N5822 Schottky diodes. The 1N5822 diodes were selected for their low forward voltage drop (~ 0.3 V) and fast switching capability, both critical for capturing low-amplitude piezoelectric signals with minimal power loss. The rectified direct current (DC) output was then routed to a storage capacitor (typically in the range of a few hundred microfarads, depending on design) which smooths out voltage fluctuations and temporarily stores the harvested energy. Once the voltage across the capacitor exceeds a defined threshold, a voltage-sensing switch activates, transferring the stored energy to a 3.7 V rechargeable lithium-ion battery. This smart switching prevents inefficient energy transfer and protects the battery from under-voltage charging.

This compact, low-loss circuit is essential for demonstrating the viability of biocompatible nanogenerators in real-world energy harvesting applications, such as wearable electronics and implantable biomedical devices.

Results

Table 1: Output Characteristics of Catla Fish Scale-Based Piezoelectric System for Single, Parallel, and Series Electrode Configurations

No. of Electrodes	Connection Type	Material	Area(cm ²)	Voltage Range (V)	Current Range (μA)	Power Output (μW)
1	Single	Fish Scale	2	0.7-4	0.5-1.5	0.4-6
4	Parallel	Fish Scale	8	0.7-4	2-6	1.4-24
4	Series	Fish Scale	8	3-12	0.5-1.5	1.5-18

The results tabulated in Table 1 summarizes the electrical output characteristics of Catla fish scale-based piezoelectric devices under different electrode configurations. For a single electrode, the peak voltage ranged from 0.7 to 4 V and the peak current from 0.5 to 1.5 μA. When four electrodes were connected in parallel, the voltage remained similar, but the current increased to 2–6 μA, resulting in a higher power output. In series configuration, the peak voltage increased to 3–12 V while the current remained similar to the single electrode case. These results demonstrate that parallel connections are effective for increasing current, while series connections are more suitable for boosting voltage output.

To evaluate the efficacy of our fish-scale-based piezoelectric nanogenerator, we compared its output power density with other reported bio-piezoelectric and synthetic materials. the Catla fish-scale device achieved a power density of 0.70 μW/cm², surpassing that of other natural materials such as silk-based systems (0.50 μW/cm²) and cellulose-based nanogenerators (0.60 μW/cm²). However, it remains below the benchmark performance of PVDF-based synthetic devices, which typically generate around 1.00 μW/cm² under similar mechanical conditions [1].

The superior performance over silk and cellulose biopolymers may be attributed to the high degree of aligned dipoles in the preserved collagen triple-helix structure, as well as the effective demineralization technique enhancing piezoelectric activity. Despite PVDF’s higher power output, it lacks the biodegradability, sustainability, and bio-compatibility offered by the fish-scale-derived material-making our approach highly suitable for wearable and implantable low-power electronics.

Conclusion

Catla fish scale-based piezoelectric nanogenerators demonstrate promising electrical output for medical devices. It has the broader potential of monitoring the pressure on heels, thus providing the insights into activity levels, beneficial for athletes and rehabilitation patients using the embedding of such bio-piezoelectric systems into shoes. Their flexibility, biocompatibility, and biodegradability make them ideal for wearable energy harvesting and self-powered health monitoring. By upcycling fish waste, this approach directly supports the United Nations Sustainable Development Goals- specifically SDG 3 (Good Health and Well-being), SDG 9 (Industry, Innovation and Infrastructure), and SDG 12 (Responsible Consumption and Production), while also contributing to reduced electronic waste and climate action (SDG 13).

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Clinical Trial Number: Not Applicable.

Ethics, Consent to Participate, and Consent to Publish
Declarations: The study involved only waste fish scales obtained from local markets, with no live animal experiments; therefore, ethical approval and consent are not applicable.

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