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A Sustainable Study on the Efficiency of Tilapia Fish Scales as Bio-Piezoelectric Nanogenerator

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ABSTRACT

With the global reliance on toxic and environmentally harmful batteries, communities are actively seeking sustainable materials to lessen the reliance on finite resources to foster a circular economy. This paper aimed to create a sustainable and cost-efficient alternative energy source by harnessing mechanical energy from bodily movements. The tilapia fish scales underwent a demineralization process using different solvents (EDTA, Acetic Acid, and Hydrochloric Acid) to enhance their piezoelectric properties and were dried under reduced pressure. Three prototypes were fabricated, each demineralized with different chemical solutions. These prototypes were tested for their voltage output under different mechanical applications such as finger pressing, hand slapping and foot pressing. The highest-performing prototype, treated with 0.05M hydrochloric acid, produced a maximum open-circuit voltage of approximately 39V, demonstrating the effectiveness of the Bio-PENG in generating electricity from ambient mechanical energy. Findings suggest that tilapia fish scales Bio-PENG can serve as a sustainable, flexible, and portable power solution, particularly for regions with limited access to electricity.

INTRODUCTION

Piezoelectricity is the phenomenon where a potential difference (voltage) is generated across a piece of piezoelectric material when mechanical stress is applied to it. The piezoelectric effect was discovered in 1880 by two French physicists, brothers Pierre and Paul-Jacques Curie, in crystals of quartz, tourmaline, and Rochelle salt (potassium sodium tartrate). They took the name from the Greek word piezein, which means "to press" (Woodford, 2022). In piezoelectric crystals and materials, atoms are arranged in a manner that, when mechanical stress is applied, they bump into each other and are compressed and distorted. This causes the electrons in those atoms to separate thereby creating a net positive and net negative charge between two ends of the crystal. In the same way, when electricity is passed through the crystal, the charges oscillate and this causes the crystal to deform and modify its physical shape (Sekhar, 2021).

Tilapia is a freshwater fish that comes from the family Cichlid, and originated from Africa and the Mediterranean countries. Tilapia fishe are very firm and have an interrupted line along their body that is common to the Cichlid family. When preparing this fish, certain parts are discarded, including fins, maws, swim bladders, and scales, which are considered "bio-waste" materials. Fish Scales (FS), typically considered biowaste, are rich in collagen. Fish scales are composed of collagen fibers that possess a piezoelectric property which allows electric generation in response to an applied mechanical stress (Ghosh & Mandal, 2016). Collagen consists of three polypeptide chains that twist together to form a triple-helical structure. Hydrogen bonds between the polypeptide chains all orientate in the same direction and act as molecular dipoles, resulting in spontaneous electrical polarization and piezoelectric properties. Within fish scales, collagen nano-fibrils self-assemble and align (Zhao, 2024). Collagen is a structure of protein in the extracellular space and contains three polypeptide chains (x-chain) with two identical chains, x1 (I) chains and x2 (I) chains. Each chain is composed of repeated triplet amino acid sequences of Gly (Glycine)-X-Y, where X-Y are often proline (Pro) and hydroxyproline (Hyp). These three x-chains twist together into a unique triple-helical structure, forming tropocollagen (Ghosh & Mandal, 2016), which possesses piezoelectric properties, an electric charge that accumulates in response to mechanical stress applied to biological materials such as fish scale collagen (FSCs).

Electronic wastes are abundant in advancing communities due to the rapid development of technology. These wastes pose health hazards e.g. radiation, lead or mercury poisoning, miscarriage, birth deficiency, and skin problems, and their complex chemical properties make it hard to valorize the utilized materials, leading to a heavy reliance on finite materials. Additionally, developing countries such as the Philippines face energy poverty with issues concerning the availability, affordability, acceptability, reliability, quality, and adequacy of energy services (Sy & Mokaddem, 2022). A significant segment of the low-income people in the Philippines, a developing nation, lacks access to electricity due to their remote locations from the national grid, rendering the extension of electricity economically unfeasible. As such, most rural households rely on fuel wood to meet their basic energy requirements and lack access to electricity (Mendoza *et al.,* 2019).

The expansion in the usage of fossil fuels as a source of energy is primarily to blame for the global energy problem and environmental degradation. This has

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prompted researchers to delve into novel technologies that can collect ambient energy and convert it into useful forms. Continuous or intermittent motion produces mechanical vibrational energy, which is an endless source of energy that can be found anywhere. With the use of energy harvesters, this source can provide electricity to charge batteries or run electrical devices directly (Brusa *et al.,* 2023). With their large electromechanical coupling coefficients, high dielectric numbers, low losses, and higher electrical and mechanical constants than electromagnetic, electrostatic, magnetostrictive, dielectric elastomer, and frictional electric transducers, piezoelectric transducers are currently the most widely used technique for mechanical energy acquisition. As a result, scientists have focused a lot of emphasis on piezoelectric transducer research (Wang *et al.,* 2023).

Superior piezoelectric properties have been demonstrated by inorganic piezoelectric materials and ceramics, such as potassium sodium niobate ((K, Na)NbO3, KNN), zinc oxide (ZnO), lead zirconate titanate (Pb(ZrxTi1-x)O3, PZT), aluminum nitride (AlN), lithium niobate (LiNbO3, LN) (Khan *et al.,* 2024). Conversely, bio-piezoelectric materials provide several benefits over inorganic materials, such as biocompatibility, biodegradability, high flexibility, and comparatively straightforward processing methods that do not call for the initial use of hazardous substances. The most effective piezoceramics, based on lead, are harmful to the environment and are prohibited in many applications. Additionally, since biomaterials like fish scales, onion skin cells, and eggshell membranes are eaten in vast quantities and are now regarded as bio-wastes, they are affordable and sustainable sources of piezoelectricity. Utilizing these bio-wastes will also contribute to a decrease in the quantity of waste dumped in landfills (Lay *et al.,* 2021).

This study aims to develop and evaluate a sustainable bio-piezoelectric nanogenerator (Bio-PENG) derived from Nile Tilapia (Oreochromis niloticus) fish scales by assessing its electrical performance under various demineralization treatments and mechanical stress applications.

LITERATURE REVIEW

As the global demand for clean and sustainable energy sources grows, researchers are increasingly turning to innovative and eco-friendly alternatives. One such promising solution is the use of bio-piezoelectric materials, which can harvest mechanical energy from the environment and convert it into electrical energy.

Piezoelectricity—the phenomenon wherein mechanical stress generates an electric charge—was first discovered in 1880 by the Curie brothers in materials like quartz and Rochelle salt (Woodford, 2022). Traditionally, piezoelectric devices rely on inorganic materials such as lead zirconate titanate (PZT), zinc oxide (ZnO), and aluminum nitride (AlN) due to their strong electromechanical coupling and high dielectric constants. However, the environmental concerns associated with lead-based ceramics, such as toxicity and lack of biodegradability, have led researchers to explore more sustainable options.

In this context, bio-derived piezoelectric materials have gained significant attention. Among these, fish scales—particularly from tilapia—have emerged as a novel, low-cost, and biodegradable alternative. Fish scales are rich in collagen, a protein known for its intrinsic piezoelectric properties due to its triple-helical structure and molecular dipole alignment.

A groundbreaking study by Ghosh and Mandal (2016) demonstrated the potential of fish scale-based piezoelectric nanogenerators. Their research involved chemically treating fish scales to produce a flexible, transparent piezoelectric film. The device, fabricated with gold electrodes and polypropylene lamination, was capable of producing an output of 4 volts and 1.5 µA under mechanical stress. The study also showed that multiple devices connected in series could generate up to 14 volts, enough to power more than 50 LEDs, underscoring the real-world applicability of such bio-based systems (Ghosh & Mandal, 2016).

Another notable study by Zhao *et al.* (2024) introduced a flexible, wearable triboelectric nanogenerator (TENG) based on the lamellar structure of collagen fiber bundles in fish scales. This device was capable of capturing biomechanical energy from movements such as finger tapping and walking. Beyond energy harvesting, the study highlighted the potential of fish-scale-based devices in healthcare monitoring and self-powered sensing technologies (Zhao *et al.,* 2024).

These developments present a compelling case for using fish scale waste as a sustainable raw material for energy harvesting. By repurposing a commonly discarded biowaste, researchers not only reduce the volume of landfill material but also contribute to a circular economy approach to energy production. This is especially relevant in countries like the Philippines, where energy poverty remains a challenge, particularly in remote areas that lack reliable access to the national power grid. Solutions like fish-scale nanogenerators can offer decentralized, low-cost power generation for small devices in off-grid communities (Mendoza *et al.,* 2019).

In summary, the exploration of tilapia fish scales as bio-piezoelectric nanogenerators represents a promising convergence of sustainability, innovation, and practicality. By capitalizing on the piezoelectric nature of collagen, these systems provide a green alternative to conventional piezoelectric materials and pave the way for eco-friendly and accessible energy solutions in both rural and urban contexts.

MATERIALS AND METHODS

Research Design

This study is an applied type of research. The researcher produces an active Bio-Piezoelectric Nanogenerator made from Nile Tilapia (Oreochromis Niloticus) FSCs that will undergo the same solvent system with different solutions. There will be different solvent ratios of 100%, 50:50% and 25:75% concentration of demineralization. Scanning Electron Microscope will confirm the morphological structure of treat Oreochromis niloticus FSCs and test duration of 5 ms using digital oscilloscope. It is cost efficient and eco-friendly at the same time since the materials are from waste.

The study has 3 prototypes with different solvent, FSCs with 0.5M EDTA, FSCs with 1M CH3COOH and FSCs with 0.05M HCl that affects the capability of FSCs to produce electricity. Ratio of FSCs can change the voltage produced by Active Bio-PENG the more content of FSCs the higher voltage produced. The area where the electricity is effective will generate more electricity. Also duration and kinds of load pressure applied in Active Bio-PENG will exhibit different voltage output.

Input-Process-Output Framework

Table 1: Input-Process-Output Framework

Input	Process	Output
● **Raw Materials:** Nile Tilapia Fish Scales (FSCs) Chemicals for Demineralization and Treatment: 0.5M Ethylenediaminetetraacetic acid (EDTA): Used for breaking down calcium salts in fish scales. 1M Acetic Acid (CH3COOH): Another solution for demineralizing the scales and softening the structure. 0.05M Hydrochloric Acid (HCl): Provides additional treatment for removing minerals and preparing the scales as an active nanogenerator component. Sodium Chloride (NaCl): Cleans the fish scales before demineralization. Sodium Hydroxide (NaOH): Helps remove impurities from the scales. Conducting Copper Sheets: Used as electrodes on both sides of the treated fish scales to capture electrical charge. Conductive Adhesive: Used to attach the copper sheets securely to the fish scales. Polypropylene (PP) Film: Laminates the setup to provide flexibility and durability for the nanogenerator. ● **Equipment:** Stirring Rod and Beaker: For mixing solutions. Petri Dish: To dry and store the treated fish scales. Multimeter: To measure the electrical output of the nanogenerator. Oscilloscope: To record and analyze the voltage signals. Scanning Electron Microscope (SEM): To analyze the morphological changes in the fish scales after treatment. Magnetic Stirrer: For thorough mixing of the demineralization solutions.	● **Preparation of Fish Scales:** Collection and Cleaning: Pre-treatment: The cleaned fish scales are soaked in a solution of 1.0M NaCl and 0.05M NaOH for 48 hours. This pre-treatment helps to remove impurities before the demineralization process. ● **Demineralization Process:** The fish scales undergo a demineralization treatment using different chemical solutions: Prototype 1: Soaked in 0.5M EDTA for 24-72 hours. Prototype 2: Soaked in 1M Acetic Acid (CH3COOH) for 24-72 hours. Prototype 3: Soaked in 0.05M Hydrochloric Acid (HCl) for 24-72 hours. After the soaking period, the scales are dried in petri dishes under reduced pressure. ● **Fabrication of Bio-PENG:** Layering the Copper Electrodes: Copper sheets (100µm thick) are applied to both sides of the treated fish scales. Attaching Electrodes: Conductive adhesive is used to attach the copper sheets securely to the fish scales, ensuring efficient electrical conduction. Lamination: The entire setup is laminated with polypropylene (PP) film to make the device flexible and durable ● **Testing and Measurement:** Mechanical Stress Application: The Bio-PENG is subjected to different forms of mechanical stress: Finger Pressing, Hand Slapping, Foot Pressing	● **Active Bio-PENG Device:** The final output is a piezoelectric nanogenerator that converts mechanical energy (e.g., walking or pressing) into electrical energy. Key Features: Eco-friendly, lightweight and durable, cost-efficient ● Voltage Output: The device is capable of generating varying voltages based on the type of mechanical stress applied. ● **Energy Harvesting and Storage:** The Bio-PENG can charge capacitors, proving its capability to store energy generated from mechanical movements. ● **Potential Applications:** Wearable Energy Harvesters: The Bio-PENG can be embedded in clothing or shoes to capture energy from body movements. Portable Power Source: Can be used as a portable source of electricity for low-power devices such as LEDs, sensors, or mobile phone chargers, especially in areas where electricity is scarce.

	Voltage Measurement: The open-circuit voltage of each prototype is measured using an oscilloscope. ● **Charging Capabilities:** Capacitor Charging: The Bio-PENG is connected to an external capacitor to test its ability to store electrical energy	

Procedural Flowchart

Materials are gathered like the chemicals: 1.0M NaCI, 20.0mM EDTA, 0.5M EDTA, 0.05M HCL, 1M CH3COOH and NaOH; Nile tilapia FSCs; conducting copper; and conductive adhesive. Scrape the FSCs from tilapia and wash it thoroughly with distilled water. Using the chemicals brought, prepare the FSCs under a solvent system and then demineralise with 0.5M EDTA, 1M CH3COOH and 0.05M HCl with different concentration using magnetic stirrer and poured in a petri dish dried under reduced pressure. These treated FSCs serve as the active piezoelectric element used as the main component of Active Bio-PENG. Take a dimension of the conducting layer and apply it on both sides. Achieving the flexibility of Bio-PENG, a laminated polypropylene (PP) film is used. The voltage output of the device was calculated under different pressure and stress including finger pressing, hand slapping, and foot pressing as well as the open circuit peak to peak voltage from Active Bio-PENG, and charging capability. Then compare the device with commercialized PZT.

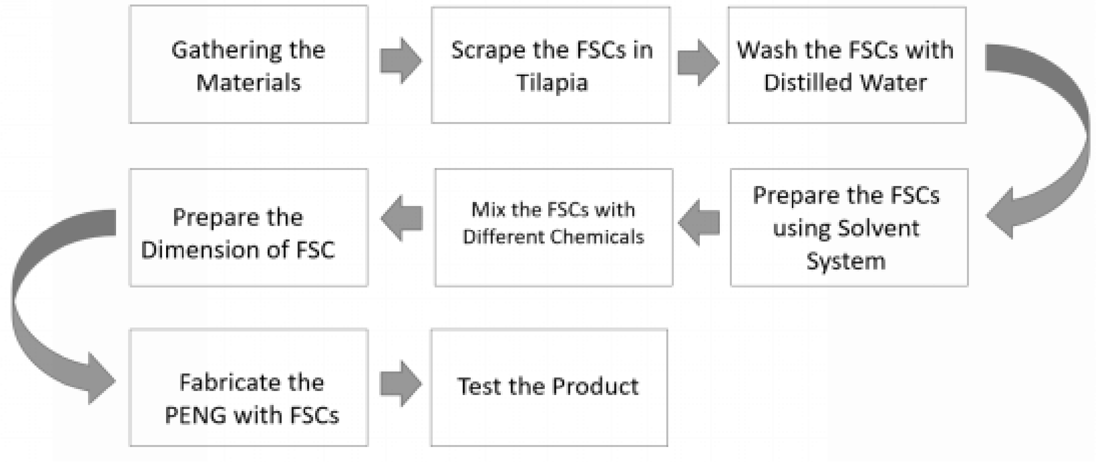

Figure 1: Flowchart for the General Procedure of Fabricating the Bio-PENG

3D Model of the treated Tilapia Fish Scale Bio-PENG

Active Bio-PENG is made out of nile tilapia FSCs with four layers. These FSCs are clean and prepared under a solvent system then covered on both sides with 2 copper sheets. When a certain pressure or stress hits the device, the FSCs embedded with copper sheet charge then produce electrical charges.

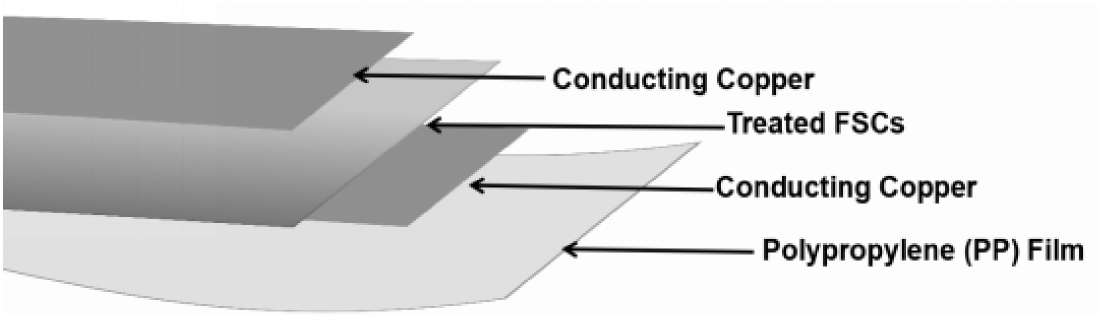

Figure 2: Flowchart for the General Procedure of Fabricating the Bio-PENG

Experimental

Fish Scale (FSCs) Preparation

The FSCs collected are cleaned thoroughly with distilled water. Followed by a solvent system of 50ml 1.0 M NaCI, 50ml 20.0 mM EDTA, 50 ml 0.05 M HCl and 50g NaOH of 200ml used to wash the FSCs for 48 h.

Then the treated FSCs are prepared for demineralisation. Prototype 1: soak with 0.5M EDTA solution, Prototype 2: soak with 1M CH3COOH solution and Prototype 3: soak with 0.05M HCL use as the solvent for 24-72 h. Then dried in a petri dish under reduced pressure.

Device Fabrication

The treated FSCs with different mixtures are taken and a layer of 100µm copper is applied to both sides making contact on FSCs and electrodes. In attaching these electrodes to the specimen, the researcher uses conductive adhesive then laminate with polypropylene (PP) film.

Research Materials

The materials used in this study are fish scales, NaCI, EDTA, HCI, NaOH, CH3COOH, H2O, conducting copper, conductive adhesive, polypropylene (PP) film, light bulb and LED.

Research Equipment

The equipment used to conduct the study are test tube, stirring rod, petri dish, multimeter, oscilloscope, weighing scale and beaker.

RESULTS AND DISCUSSION

The tilapia fish scales underwent different routes of demineralization solutions as well as ratio and percentage in the process.

As shown in Figure 3, prototype 1 exhibits a smooth surface whereas the fiber-like structure is evident but not completely scattered compared to Figure 4 which exhibits a complete dispersion of the structure. On the other hand, in prototype 3 in Figure 5, the fish scales exhibit a compact, smooth structure, with no trace of dispersion. The more compact and smooth the structures are, the more effective the voltage output it will produce. Prototype 2 used 50% 1M Acetic Acid and 50% Distilled Water which made the structures completely dispersed and perform poorly than other prototypes. Meanwhile, prototype 1 which has a smooth but also roughly dispersed structure, underwent 50% 0.5M EDTA and 50% Distilled Water and it performed better than prototype 2. At the same time, prototype 3 was immersed in 100% 0.05M HCl, which resulted in a compact and smooth structure, resulting in the highest voltage production above all prototypes.

Figure 3: Scanning Electron Microscope image of Prototype 1 Fishscale

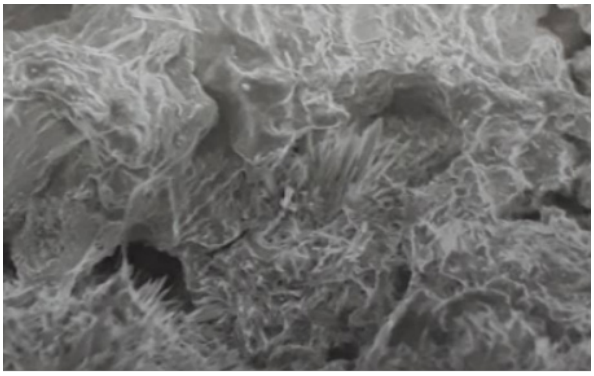

Figure 4: Scanning Electron Microscope image of Prototype 2 Fishscale

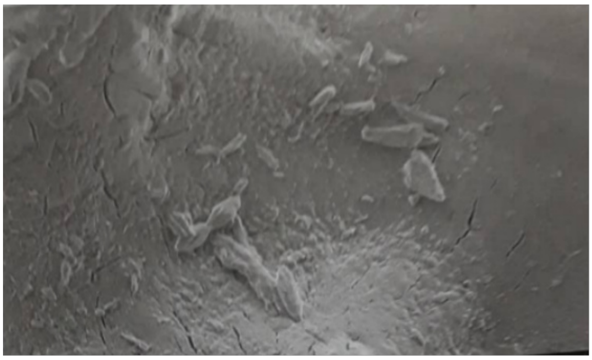

Figure 5: Scanning Electron Microscope image of Prototype 3 Fishscale

The figures 6 show the maximum peak to peak open circuit voltage Voc of different prototypes. Figure 7 shows a modest ~ 27V and Figure 6 prototype 1 showed 32V while prototype 3 in Figure 8 exhibits a maximum peak-to-peak open circuit ~ 39V as the highest performing prototype above all. Foot pressing method was used as the mechanical input with an average pressure of 1.7 MPa.

Figure 10 exhibits the lowest voltage among all the loads of applications with ~ 1.34V due to the sudden release of mechanical force applied. The finger pressing on the other hand is applied longer which produces 5.14V while Figure 11, prototype 1, exhibits 8.47V output voltage. Since prototype 1 used 0.5M EDTA for demineralization, the standard protocol in constructing effective and flexible Bio-PENG was confirmed to have high peak-peak voltage output (Ghosh & Mandal, 2016; Kumar, *et al*., 2018). Furthermore, utilizing EDTA as a solvent for demineralization exhibits more integrated secondary structure than other chemicals (Liu & Huang, 2014).

As shown in Figure 13, prototype 2 which was exposed to the hand slapping method with an average pressure of 0.17 MPa produced the lowest voltage output of ~ 1.56V for a span of 5 ms and finger pressing application of 0.05 MPa presented in Figure 12 are the same with ~ 1.71V. But the foot pressing in prototype 2 exhibits an

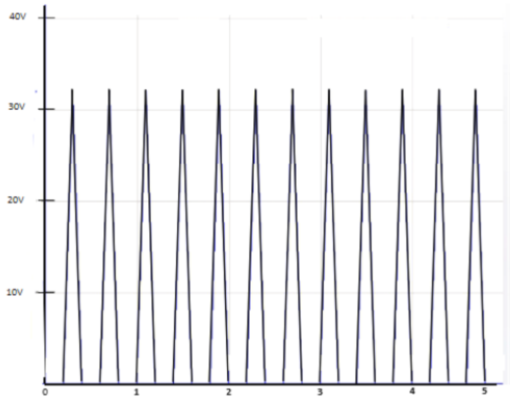

Figure 6: Open-circuit voltage from Prototype 1

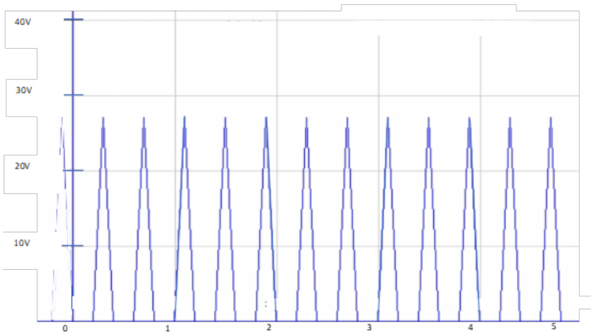

Figure 7: Open-circuit voltage from Prototype 2

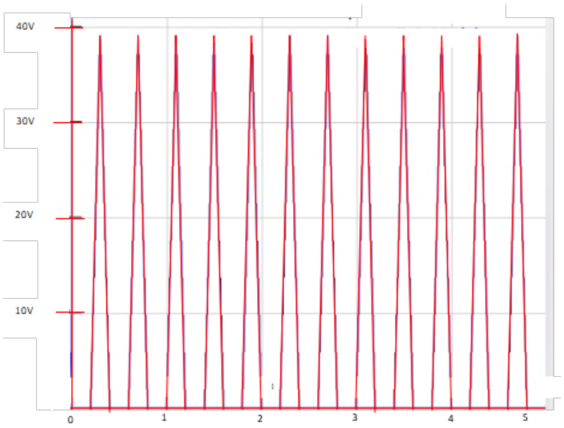

Figure 8: Open-circuit voltage from Prototype 3

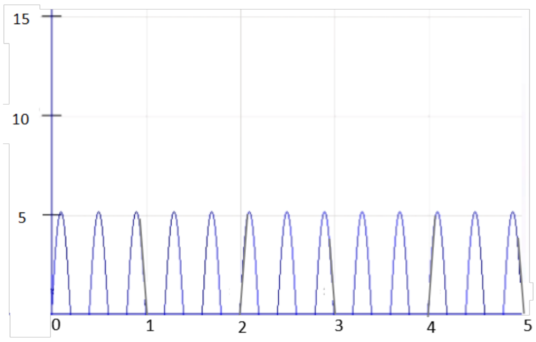

Figure 9: Output Voltage of Prototype 1 under pressure of Finger Pressing

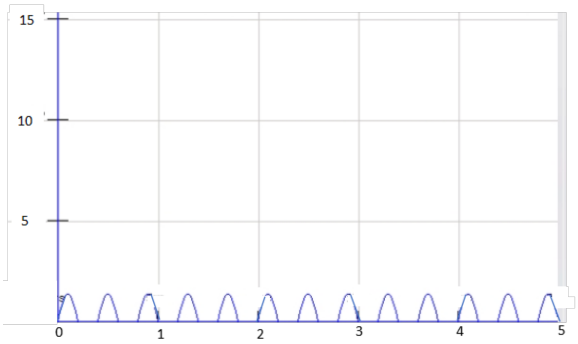

Figure 10: Output Voltage of Prototype 1 under pressure of Hand Slapping

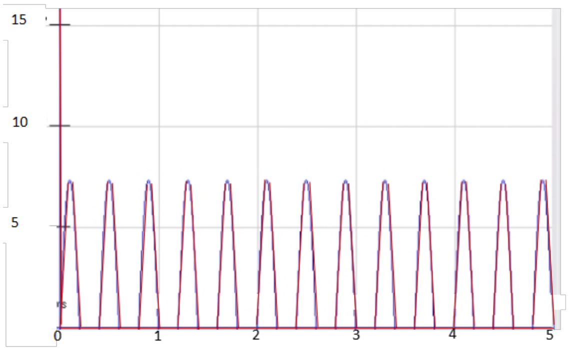

Figure 11: Output Voltage of Prototype 1 under pressure of Foot Pressing

Figure 12: Output Voltage of Prototype 2 under pressure of Finger Pressing

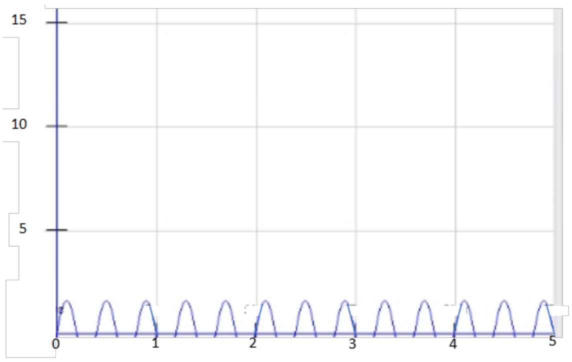

Figure 13: Output Voltage of Prototype 2 under pressure of Hand Slapping

open circuit voltage of 7.30V which is the most suitable method among others. Previous studies suggest when standing or walking, the plantar on the feet gets higher (Hills *et al.,* 2001). The pressure produced by foot pressing makes the bio-PENG more effective when inserted right under shoes.

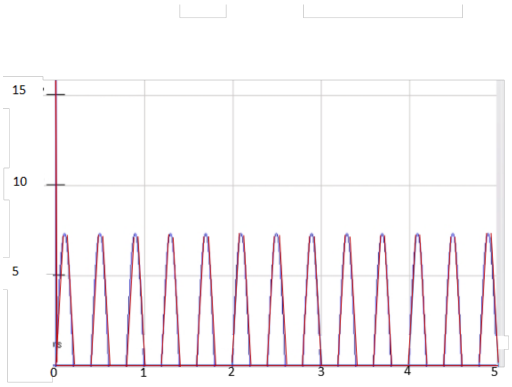

Figure 14: Output Voltage of Prototype 2 under pressure of Foot Pressing

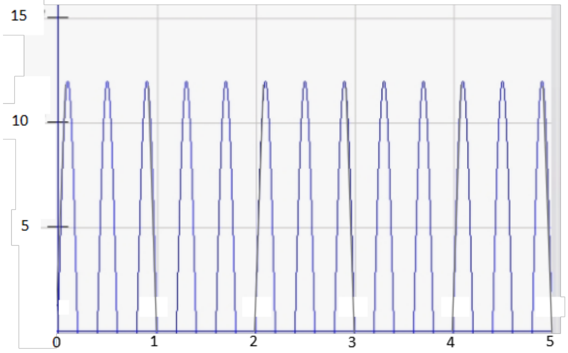

Figure 15: Output Voltage of Prototype 3 under pressure of Finger Pressing

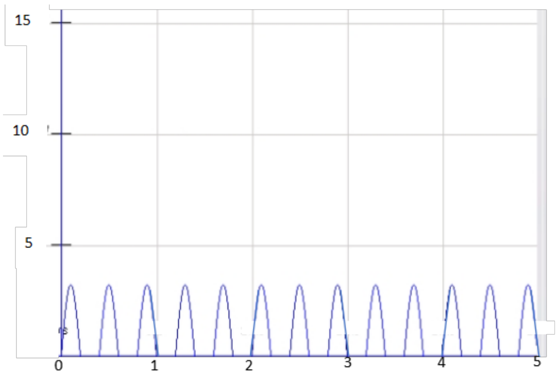

Figure 16: Output Voltage of Prototype 3 under pressure of Hand Slapping

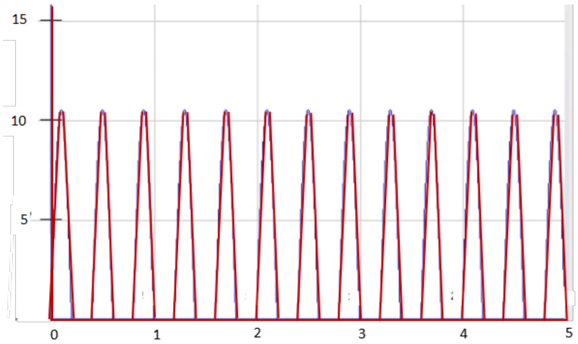

Figure 17: Output Voltage of Prototype 3 under pressure of Foot Pressing

Above figures show the output voltage of prototype 3 under different loads of application. Figure 17 shows a high voltage output of ~10.48V under foot pressing while under hand slapping shown in Figure 16 resulting in a modest voltage of ~ 3.17V in 5ms. Furthermore, the highest output voltage among all prototypes is shown in Figure 15 with a voltage of ~ 11.95V under finger pressing. HCl solution yielded a high demineralization of scales with 92.7+ 1.32 %, "which was well consistent with the value predicted by the model" (Feng, 2013). The output voltage makes the prototype 3 with 1M HCl 100% suitable and effective under all loads of application compared to other prototypes.

Figure 18 shows that the charging time of treated Bio-

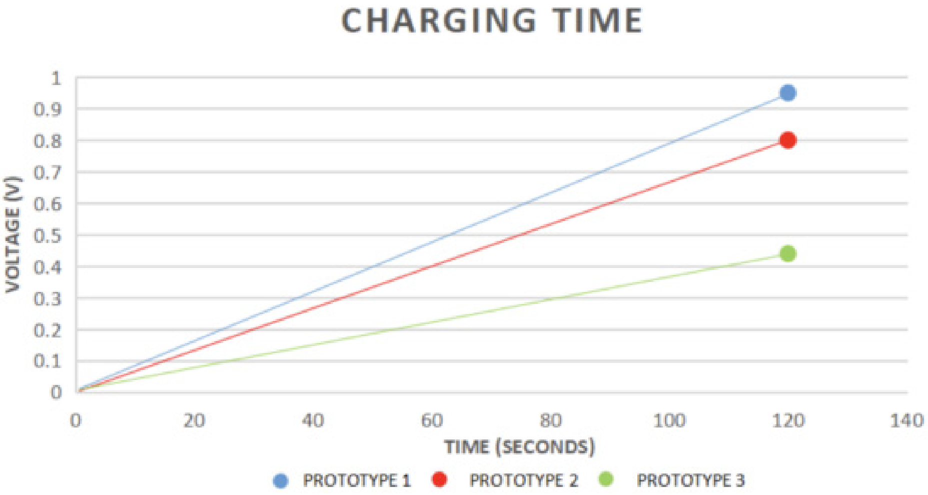

Figure 18: Transient Response of an External Capacitor Connected to Active Bio-PENG

PENG in a rectified open circuit along 6.3V with 47μF capacitor under 0.05 MPa finger pressing is effective and efficient. Prototype 1 exhibits 0.95V which has the highest voltage output in 120 seconds while prototype 2 produces 0.80V stored in the capacitor. On the other hand prototype 3 has the lowest voltage of 0.44V all in direct current. The longer the pressure and time exerted on the Bio-PENG, the higher the voltage stored in the capacitor. The device is capable enough to charge gadgets such as mobile phones for a long period under continuous pressure.

CONCLUSIONS

The study demonstrates that Tilapia fish scales exhibit promising potential as bio-piezoelectric materials for nanogenerators. The scales possess inherent piezoelectric properties due to their natural composition of collage fibers and hydroxyapatite crystals. When subjected to mechanical stress, the scales generate electrical signals, validating their suitability for energy harvesting applications. The efficiency of tilapia fish scales as a piezoelectric nanogenerator is further supported by their biodegradable nature, cost-effectiveness, and sustainability, which compare favorably to traditional piezoelectric materials such as lead zirconate titanate (PZT). While the energy output may be lower than synthetic counterparts, optimization in extraction and alignment of collagen fiber may enhance overall performance. Overall, tilapia fish scales offer a viable, eco-friendly alternative for developing a low-cost and sustainable energy source that will greatly contribute to fostering the rising circular economy.

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