# Biodegradable Nanofiber-based Piezoelectric Transducer

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## Abstract

A fascinating class of electroactive materials, biodegradable piezoelectrics combine mechanical-electrical coupling properties with a special biodegradable property that removes pointless material retention and reduces related infection concerns. The piezoelectric characteristics of typical organic biodegradable piezoelectric materials, such as polysaccharides, peptides, proteins, amino acids, and synthetic polymers, are reviewed. The use of biodegradable piezoelectric materials for bioelectronics has recently advanced, and strategies to encourage this activity are also reviewed. At the conclusion, views and difficulties are presented to illuminate potential future paths.

**Keywords:** Biodegradable, Nanofiber, Piezoelectric, Transducer

## Introduction

Due to their remarkable capacity to produce the current and voltage output in response to the external pressure, piezoelectric materials—including traditional rigid piezoelectric ceramics and flexible energy-harvesting polymers—have been proposed for a variety of cutting-edge technology, including pressure sensors, personal healthcare devices, and flexible electronics. Inorganic Pb(ZrxTi1-x)O3, BaTiO3, and ZnSnO3 are the most typical piezoelectric materials offering stable polarisation, where the asymmetric atomic arrangement in the crystals achieved by high voltage poling plays a crucial role in controlling the response to external pressure. Due to their extreme stiffness, these ceramic materials, however, are far from being incorporated into flexible electronics of the present day. In order to meet the flexible needs of soft electronics, it is thus important to investigate novel, soft-type piezoelectric materials.

Solution-processed poly(vinylidene fluoride) (PVDF) and its copolymers, such as poly(vinylidene fluoride-co-trifluoroethylene) (PVDF-TrFE), poly(vinylidene fluoride-co-chlorotrifluoro ethylene) (PVDF-CTFE), and poly(vinylidene fluoride-co-trifluoroethylene-co-chlorotrifluoro ethylene) (PVDF-TrFE-CTFE), have attracted great interest as flexible piezoelectric materials because they are strongly polarized under pressure due to the negatively charged fluorine atoms and positively charged hydrogen atoms in the chain backbones of these polymers.

The most significant drawback in fluorine-based polymers is the evolution of toxic gases like hydrogen fluoride. Although the piezoelectric responses of these materials have been improved by a variety of clever techniques including electrospinning-assisted fibre alignment, crystal orientation control, and blending with inorganic piezoelectric and conductive carbon materials for future applications such as electronic skins, haptic sensors, pulse sensors, and self-powered pacemakers.

Proteins (like silk) and polysaccharides (like cellulose and chitin) have drawn interest as flexible electronic substrates among non-synthetic biocompatible piezoelectric materials due to their high optical transparency and practicable bending capabilities. Despite having comparable piezoelectric capabilities (because to intrinsic molecular polarisation), polysaccharide polymers have only seldom been used in piezoelectric devices. Chitin is the second-most common natural polysaccharide, with a production rate of 100 billion tonnes per year, and is known to have piezoelectric capabilities (owing to inherent molecular polarisation resulting from the non-centrosymmetric crystal structure of both - and -chitin polymorphs). Since 1975, they have hardly ever been properly explored, and even their piezoelectric capabilities have only sometimes been included in piezoelectric devices. Because chitin polymers lack thermoplasticity and have a low solubility in most organic solvents, there hasn't been much research done on their capacity to operate as piezoelectric materials.

Due to chitin's intractability, it is challenging to create dense chitin films that are void-free and of a high purity that can be used to reliably and systematically analyse chitin's molecular polarisation and piezoelectric performance. Additionally, prior research has only briefly examined the piezoelectric capabilities of chitin in two antecedents, both of which continue to emphasise the piezoelectric response of -chitin in naturally demineralized crab shells as an example [1].

**Piezoelectrets**

After suitable poling, polymer films with cellular structure demonstrated high piezoelectric activity; these electroactive substances are known as piezoelectrets. By using corona polarisation and the piezoelectric constant d33, a biodegradable polylactic acid (PLA) piezoelectret may achieve a maximum value of 600 pC/N. In the first 20 days following polarisation, the piezoelectric effect was reduced by half relative to the original value, but it remained steady for the next 130 days. Transparent cellulose nanopaper (t-paper) and PLA piezoelectret layer are used to create a biodegradable paper-based electret nanogenerator.

The mechanical-electrical reaction was ascribed to the PLA piezo-electret layer because it can be highly polarised and consistently sustain the charges, according to a comparison of output current with and without the PLA piezo-electret layer under periodic pressing. Cellular structure (cell density, shape, and size), relative density, elastic stiffness, electrical breakdown strength, service temperature, and other factors primarily determine the piezoelectric action of piezo-electrets. A different approach to creating biodegradable devices with acceptable piezoelectricity that can adapt to a variety of biological applications is to use piezoelectrets. However, more research is required to confirm the piezoelectrets' long-term durability in humid settings, which is crucial for biological applications [2].

## Biodegradation of piezoelectric materials

Not only do the aforementioned materials exhibit piezoelectric activity important for bioelectronics, but they also have a biodegradable nature that can prevent superfluous material retention in biological systems. Many biological processes depend heavily on amino acids, peptides, or proteins. Proteins and peptides can break down into amino acids, which are then converted to ammonia through transamination. Studies have revealed that the M13 bacteriophage degrades well in a variety of bodily fluids and tissues, including mouse stomach, jejunum, and colon homogenates as well as blood, urine, saliva, and artificial gastric juice (AGJ).

With a high concentration of proteolytic enzymes, jejunum homogenate had the highest rate of destruction (almost 100% after 45 minutes). In terms of biosafety, the M13 bacteriophage interacts with host bacterial cells specifically and doesn't target mammalian cells. In biomedicine, synthetic biodegradable polymers are already widely employed. For instance, PLLA has been used to make biodegradable sutures, cardiovascular stents, and implants that have received approval from the US Food and Drug Administration (FDA). Lactic acid is produced when PLLA is hydrolyzed, and the remaining byproducts are water and carbon dioxide.

After the subcutaneous implantation of PLLA samples in the rats, a considerable loss in molecular weight and mass was seen within the first three months, and full disintegration took place over the course of at least four years. Additionally, although cellulose can only be digested by microbial and fungal enzymes, which limits its potential in vivo uses, polysaccharides like chitosan and chitin may be easily degraded by lysozyme, which is frequently present in mammals [3].

## Applications

Piezoelectric materials are widely employed in sensors and energy harvesting because they allow the conversion of external mechanical stimuli into electrical energy and vice versa. Additionally, piezoelectric materials' surface charges might perhaps be used in electronic medicine to control how cells and tissues behave. Piezoelectric materials that degrade naturally after use have the benefit of removing the possibility of material retention and the accompanying hazards of infection.

## Energy Harvesting

In order to transform mechanical motions into electrical energy, biodegradable piezoelectric materials have been investigated as nanogenerators. Due to their similar piezoelectric capabilities to PVDF, FF peptides have been developed into reliable piezoelectric nanogenerators (PENGs). Under the same force, peptide nanowires may produce greater voltages than ZnO, PZT, and BTO nanowires. With an open-circuit voltage of 0.6 V and a short-circuit current of 7 nA under cyclic displacement, a flexible peptide nanogenerator was produced. For the production of horizontally aligned PNTs with significant unidirectional polarisation, a meniscus-driven self-assembly technique is used.

The created nanogenerator could produce up to 2.8 V, 37.4 nA, and 8.2 nW of output. FF peptide nanotubes were transferred from silicon substrates using a flexible, biodegradable PENGs with FF PNTs and PLA. The composite film's d33 value was 12.4 pm/V, and it produced voltage and current under various applied pressures. The power density of the PENGs, which was 1.56 W/m3, was higher than that of several previously reported PENGs made of biodegradable biomaterials. a double-layer, heat-treated PLLA film-based cantilever beam energy harvester. In this study, following tensile stretching (4-fold), the PLLA films were heated to 140 °C for 5–24 hours, resulting in a high piezoelectric constant (d14) of around 9.57 pC/N.

A lithium battery may be charged and several light-emitting diodes can be powered by the cantilever device's output voltage and power of up to 9.4 V and 14.45 W, respectively. Most biodegradable piezoelectric materials have strong shear piezoelectricity but weak transverse and longitudinal piezoelectric properties. As a result, they frequently need specialised structures to convert normal stress to in-plane shear stress, which results in a lower energy output than traditional energy-harvesting devices like non-degradable piezoelectric nanogenerators and triboelectric nanogenerators, which may restrict their potential use as power sources [4].

**Actuators, Biosensors and Transducers**

Piezoelectric materials have the electromechanical conversion properties that enable the conversion of mechanical stimuli (pressure, bend, twist, etc.) into electrical signals, enabling real-time sensing (for example, pressure and strain) in biological environments, and providing a crucial engineering foundation for smart devices, bionic prostheses, and healthcare monitoring. When correctly developed, piezoelectric materials, which are based on inverse piezoelectricity, also play a crucial role as actuators and transducers, which is crucial for applications like controlled medication administration and soft robotics. The biodegradable nanofiber-based piezoelectric transducer is depicted in Figure 1.

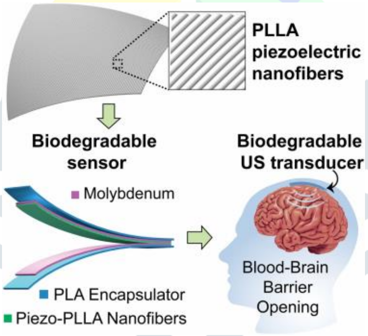

Figure 1. Biodegradable nanofiber-based piezoelectric transducer.

Different actuators, sensors, and transducer systems have been constructed using biodegradable piezoelectric materials. As intelligent tweezers, for instance, actuators built of piezoelectric PLLA have been developed. When an AC voltage between 50 and 300 V and a frequency between 0.1 and 150 Hz were applied to PLLA fibres made by the dry jet spinning process, substantial vibration created. These fibres might be used as electrically controlled conduits and micro tweezers.

It was shown how the PLLA fibre catheter exfoliated a blood artery sample with suspected thrombosis. A "Finger-joint-shaped" electrical tweezer made of PLLA that had undergone sc-CO2 treatment and had a higher piezoelectric constant was able to do sophisticated movements like gripping polystyrene beads and perform operations in tiny blood arteries [5]. For the construction of biodegradable sensors, ideal flexible biodegradable piezoelectric materials that can create substantial deformation under modest stresses are great choices. PLLA sheet that has been physically stretched to create a biodegradable pressure sensor that has successfully exhibited in vivo pressure monitoring in mouse abdominal diaphragms. A wide pressure range (0–18 kPa) related with physiological pressure may be properly measured by the sensor, allowing for self-monitoring of vital indicators including intracranial pressure, intraocular pressure, intraarticular pressure, etc. A flexible and biodegradable pressure sensor with a sensitivity of 2.82 0.2 mV kPa-1 is based on a composite film of -glycine crystals and chitosan matrix.

The suggested gadget might be used for electrical stimulation for wound healing and wearable diagnostics. A ferroelectric pigskin gelatin electronic skin (e-skin) with a microdome interlocking structure outperformed non-biodegradable nanogenerators by achieving extremely high sensitivity (41 mVPa-1) at low pressures with a detection limit close to 0.005 Pa. The gadget may be used for pressure mapping and texture perception, which are essential for healthcare monitoring, and sense the surface texture and spatially resolved pressure of an unknown item. A silk fibroin electrospun pressure sensor. Surface-engineered electrodes made by transfer printing using a metal mesh as a template can increase the stress that is transferred from the electrode to the piezoelectric layer, and the overall sensitivity of the device reached 30.6 mV/N. The device also has the advantages of a quick response time of 3.4 ms, a long cycle life of 3000 cycles, and good linearity, making it suitable for real-time detection applications like oral cavity monitoring. Another type of gadget that can employ biodegradable piezoelectric materials is the transducer. -chitin from squid and produced a piezoelectric film using centrifugal casting and hot pressing (120 °C) with a piezoelectric constant of around 3.986 pm/V.

A new path towards environmentally friendly piezoelectric devices was opened up by the flexible piezoelectric transducer's success with paper-style speakers and microphones and its synchronisation rate with the original sound source of roughly 70%. Using ultrasound to break down the blood-brain barrier (BBB), it has been established that a highly orientated PLLA nanofiber film may be electrospun and used for essential physiological pressure monitoring in vivo. The biodegradable ultrasonic transducer has a frequency range of 1 MHz and a maximum sound pressure of 0.3 MPa.

The blood protein was completely absent in cases with non-piezoelectric films implanted, suggesting that the sound pressure produced by the biodegradable piezoelectric transducer can induce the opening of BBB. The closer the coronary tissue of the mouse brain was to the implanted transducer, the more autofluorescent signals of blood protein (green stain, indicating leakage due to disrupted BBB). To further create biodegradable transducers, piezoelectrets with high longitudinal piezoelectric constants are a different choice. a biodegradable piezoelectret-based piezoelectric ultrasonic transducer. For driving voltages between 30 and 70 Vrms, the transducer produced sound pressures between 98 and 106 dB with a broad bandwidth of around 45 kHz and a fractional bandwidth of 70% [6, 7].

## Conclusions

Biodegradable piezoelectric materials are receiving a lot of interest for prospective use in bioelectronics because of their good biocompatibility, desired biodegradability, and adjustable piezoelectric characteristics. We list the piezoelectric characteristics of representative organic biodegradable piezoelectric materials, such as proteins, synthetic polymers, and polysaccharides, as well as tiny molecules with high order structures like amino acids and dipeptides. Applications for energy harvesting, actuators, sensors, transducers, and therapeutic devices are addressed along with piezoelectric activity enhancement techniques.

All things considered, further advancements will make it possible to optimise biodegradable organic piezoelectric materials, which will open up new possibilities for creating cutting-edge bioelectronics like energy devices, sensors, transducers, and electronic medicine that can be fully resorbable, eliminating potential infection risks, and may play important roles in healthcare.

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