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**Description:**

Fabrication of graphene based touch sensors.

**INTUITIVE Project deliverable report (ESR 9)**

**Deliverable 4.2: Graphene Based Touch Sensor and its benchmarking**

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- Introduction to touch sensors for E-skin
- State of the art touch sensors and its benchmarking
- Fabrication of chitosan-alginate-graphene based dynamic touch sensors towards the E-skin applications.
- Conclusion

## 1. Introduction:

Human skin is the largest organ of the body and helps in interacting with the outside world around us using the different types of sensor array embedded inside it [1]. Various receptors such as mechanoreceptors, thermoreceptors, chemoreceptors, nociceptor etc. were present inside the skin to detect different types of senses like touch, feel, vibrations, texture, stretch, temperature, pain, etc. A biological sensory system consists of the skin with various mechanoreceptors interconnected with the brain via nerves. The receptors generate a potential based on the signal strength which will be passed to the nerves and will be converted it to the action potential based on the strength of the signal [2]. The generated action potential signals will be passed on to the synapses inside the brain for further processing of the information and then the corresponding signal will be sent it to the motor nerves in the human body for detecting the specific objects, texture discrimination, and various sensory feedback. Researchers have inspired by such biological sensory systems which exhibit numerous advantages in terms of the parallel processing, robust to noise, accuracy, efficiency, and event driven computations [3]. An artificial sensory nervous system offers a multitude of potential advantages. By replicating or augmenting human sensory capabilities, it can revolutionize various fields. Advantages include enhanced functionality and control of prosthetic limbs, enabling users to regain a sense of touch and perform daily tasks more effectively. In robotics and automation, artificial sensory systems can improve perception, allowing robots to navigate and interact with their environment with precision and safety. They can also enhance virtual and augmented reality experiences by providing haptic feedback, creating more immersive and realistic simulations. In healthcare, artificial sensory systems enable pain management, vital sign monitoring, and rehabilitation feedback, contributing to improved patient care. Furthermore, they can assist in environmental monitoring, aid the visually or hearing impaired, and enhance navigation and safety in autonomous vehicles. These advantages have the potential to transform industries, improve quality of life, and lead to innovative advancements in technology and healthcare [4].

Researchers have explored a variety of materials and systems in the development of artificial sensory nervous systems. These include electronic skin (E-skin), nanowires, nanotubes, conductive polymers, graphene, carbon-based materials, organic electronics, and microelectrode arrays. E-skin is a flexible material incorporating pressure, temperature, and strain sensors [5]. Nanowires and nanotubes exhibit high sensitivity to mechanical, electrical, and chemical stimuli. Conductive polymers can be tailored to sense touch, pressure, and temperature. Graphene and carbon-based materials offer exceptional properties for flexible sensors [6]. Organic electronics enable lightweight and flexible sensor arrays. Microelectrode arrays interface with nerve cells for sensory feedback or control. Furthermore, machine learning and artificial intelligence are vital for processing and interpreting sensory data. Continued exploration and advancements in these materials and systems hold great potential for the development of artificial sensory nervous systems. As an example, Benjamin *et.al* demonstrated a skin inspired digital mechanoreceptor using pressure sensors integrated with the odd number of printed organic ring oscillators [7]. Here, multiwalled CNTs have been used as the active layer of the piezoresistive pressure sensor array to detect the external mechanical vibrations and the ring oscillator convert sensor output signals to the pulse trains [8]. Similarly, Fanfai *et.al* has demonstrated an artificial mechanoreceptor i.e., mainly slow-adapting mechanoreceptors for tactile enhancement and integration using polypyrrole based resistive pressure sensors and niobium based volatile memristors [9]. The micro-pyramidal structures were introduced to improve the sensitivity of the pressure sensors and the artificial nerve functionality was emulated using the threshold based memristors. Recently, a self-powered neuromorphic tactile system composed of triboelectric nanogenerator (TENG) which provide biomechanical energy generation along with the dynamic sensing capability is integrated with the non-volatile memristor. The TENG device uses the ionic conductor as the electrode and generate a power density of $35mWm^{-2}$ and an open circuit voltage of 182V and exhibit a stable output voltage for almost $5x10^3$ cycles [10].

## 2. State of the art touch sensors and its benchmarking:

Touch sensors Graphene-based touch sensors have emerged as a promising technology in the field of touch-sensitive devices, offering several advantages over traditional touch sensor technologies. As a result, the benchmarking of state-of-the-art graphene-based touch sensors has become a crucial aspect of evaluating their performance and potential for practical applications. One area of benchmarking focuses on the sensitivity and resolution of graphene-based touch sensors [11]. Graphene's high electrical conductivity and atomic-scale thickness make it an excellent candidate for achieving high sensitivity and precise touch detection. Benchmarking studies assess the sensor's ability to detect and distinguish various touch inputs, ranging from light touches to heavier interactions, and evaluate the resolution and accuracy of touch detection across the sensor surface [12]. These benchmarks provide insights into the sensor's performance in terms of touch sensitivity and its potential for delivering fine-grained touch sensing capabilities. Another aspect of benchmarking involves evaluating the durability and reliability of graphene-based touch sensors. The mechanical flexibility and robustness of graphene allow for the development of flexible and durable touch sensors. Benchmarking studies assess the sensor's ability to withstand mechanical stress, repeated touch inputs, and various environmental conditions without performance degradation [13]. They examine factors such as the sensor's resistance to physical damage, stability over time, and resistance to external factors such as temperature variations, humidity, and exposure to moisture. These benchmarks provide critical information about the long-term reliability and suitability of graphene-based touch sensors for real-world applications.

| **Active materials** | **Sensing Mechanism** | **Deformation detection** | **Detected range** | **Sensitivity** | **Ref** |
|---|---|---|---|---|---|
| Wrinkled CVD Graphene | Piezoresistivity | Pressure | 100Pa to 4.5kPa | 6.92 $kPa^{-1}$ | [14] |
| rGO/PU sponge | Piezoresistivity | Pressure | 5Pa to 10kPa | 0.26 $kPa^{-1}$ | [15] |
| rGO/nano-cellulose films | Piezoresistivity | Strain | 0-100% | 7.1 (ε=100%) | [16] |
| rGO/PDCy fiber | Piezoresistivity | Strain | 0-650% | 3.7 (ε<50%) | [17] |
| Graphene/PS sponge | Capacitance | Pressure | 2.3Pa to 4kPa | 1.04 $kPa^{-1}$ | [18] |
| GO foam | Capacitance | Pressure | 0.24Pa to 4kPa | 0.8 $kPa^{-1}$ | [19] |
| CVD-Graphene/AgNWs | Capacitance | Strain | 0-200% | 22.9 | [20] |
| AgNWs/rGO/PU composites | Capacitance | Strain | 0-60% | 0.1 | [21] |
| Interlocked microdome PVDF/rGO | Piezoelectricity | Pressure Vibration | 0-17.15 kPa | 35 $mAPa^{-1}$ | [22] |
| $PbTiO_3$ NWs/CVD-Graphene | Piezoelectricity | Pressure | 0-1.4kPa | 0.094 $kPa^{-1}$ | [23] |

## 3. Chitosan-Graphene-Alginate based dynamic touch sensors:

### 3.1 Background:

In recent years, there has been a significant surge in the demand for self-powered touch sensors. These sensors can harvest energy from human touch or pressure and convert it into electrical power, eliminating the need for external power sources or batteries [24]. The development of self-powered touch sensors holds great potential for applications in various fields, including wearable devices, consumer electronics, and healthcare systems. Piezoelectric nanogenerators (PENGs) have emerged as a promising technology for energy harvesting from mechanical stimuli. The piezoelectric effect, observed in certain materials, refers to the generation of an electrical charge in response to applied mechanical stress or deformation [25]. This unique property allows PENGs to efficiently convert mechanical energy into electrical energy. By integrating PENGs into touch sensors, it becomes possible to generate electrical power simply by interacting with the sensor through touch or pressure. Chitosan, a natural biopolymer derived from chitin, has gained attention as a potential material for piezoelectric applications [26]. Chitosan exhibits desirable properties, such as biocompatibility, biodegradability, and low toxicity, making it suitable for use in biomedical and wearable devices. Additionally, chitosan possesses inherent piezoelectric properties, enabling it to generate electrical charges in response to mechanical stress. Chitosan-based PENGs offer several advantages for self-powered touch sensors [27]. Firstly, chitosan can be processed into flexible films, allowing for the integration of PENGs onto various surfaces, including textiles, plastics, and even human skin. This flexibility enables the development of touch-sensitive devices that can conform to different shapes and be seamlessly incorporated into everyday objects. Furthermore, chitosan is an abundant and cost-effective material, making it attractive for large-scale production of PENG devices. To enhance the performance and functionality of chitosan based PENGs, researchers have explored various fabrication techniques and material combinations [28]. These techniques involve the integration of chitosan with other materials, such as alginate or graphene, to optimize the piezoelectric properties and enhance the electrical output of the devices. Through these advancements, chitosan based PENGs have shown promising results in terms of output voltage, power density, and mechanical stability. The integration of chitosan based PENGs into self-powered touch sensors opens a wide range of applications. In the field of wearable devices, touch-sensitive clothing and accessories can be powered by the user's movements or touch interactions, eliminating the need for external batteries. In consumer electronics, touch-sensitive surfaces, such as touchscreens and touchpads, can be self-powered, reducing energy consumption and enhancing user convenience [29]. Additionally, in healthcare systems, chitosan based PENGs can be utilized for self-powered biomedical sensors, monitoring devices, and smart prosthetics. Despite the significant progress made in chitosan based PENGs for self-powered touch sensors, there are still challenges to overcome. The stability and longevity of chitosan based PENGs under various environmental conditions need to be addressed. Scalability and manufacturing processes must be optimized to enable large-scale production. Integration of PENGs into miniaturized devices and the development of hybrid systems with other energy-harvesting technologies are areas of ongoing research.

In recent years, there has been a growing interest in developing innovative technologies that can harness energy from the environment and convert it into usable electrical power. Piezoelectric nanogenerators (PENGs) have emerged as promising candidates in this field, offering a sustainable solution for self-powered electronic devices. Among the various materials explored for PENG fabrication, chitosan-alginate-graphene composites have gained significant attention due to their unique properties and suitability for touch sensor applications. Chitosan, derived from chitin, a natural biopolymer found in the exoskeletons of crustaceans and insects, exhibits excellent biocompatibility, biodegradability, and low toxicity [30]. Alginate, on the other hand, is a polysaccharide extracted from brown seaweed, possessing similar desirable properties. By combining these two materials, researchers have created a chitosan-alginate matrix that offers enhanced mechanical strength, flexibility, and biocompatibility, making it an ideal candidate for the development of piezoelectric nanogenerators. The piezoelectric effect, observed in certain materials, refers to the generation of an electrical charge in response to applied mechanical stress or deformation. This unique characteristic has been widely exploited in various applications, including touch sensors [31]. In touch sensor applications, the chitosan-alginate-based PENGs can serve as an energy-harvesting component, converting the mechanical energy generated by human touch or pressure into electrical energy. The advantages of utilizing chitosan-alginate composites in piezoelectric nanogenerators for touch sensor applications are numerous. Firstly, their biocompatible nature ensures safe and non-toxic interactions with the human body, making them suitable for wearable devices and biomedical applications. Secondly, the flexibility of the chitosan-alginate-graphene matrix enables the integration of PENGs into various surfaces, such as textiles, skin patches, and flexible electronics [32]. This flexibility allows for the creation of touch-sensitive devices that can be seamlessly incorporated into our daily lives. Moreover, the abundance, low cost, and ease of fabrication of chitosan and alginate make them attractive materials for large-scale production of PENGs. This scalability further enhances the potential for widespread adoption of chitosan-alginate-based PENGs in touch sensor applications. In this report, we aim to explore the sensing properties in chitosan-alginate-based PENGs and their potential for e-skin applications. We will delve into the fabrication techniques, device performance, and the challenges faced in implementing these nanogenerators for touch-sensitive devices. Furthermore, we will discuss potential future directions and applications that can benefit from the integration of chitosan-alginate-based PENGs.

**3.2 Objectives:**

The main objectives for the Chitosan-alginate-graphene based PENG Device towards self-Powered and flexible touch sensor are given below.

a. optimize the fabrication process of chitosan-alginate-based PENG devices for efficient energy conversion and high performance.

b. enhance the piezoelectric performance of the device to maximize energy conversion efficiency, including improving the composite material and incorporating suitable additives or nanostructures.

c. achieve flexibility and conformability in the PENG device to enable integration into various touch-sensitive surfaces and wearable applications.
d. enable self-powered operation by effectively harvesting and utilizing mechanical energy from touch or pressure.
e. ensure the longevity and stability of the device, addressing material degradation, mechanical fatigue, and environmental factors.
f. ensure biocompatibility and safety for applications in wearable devices and biomedical sensors.
g. develop scalable and cost-effective manufacturing processes for mass production of self-powered touch sensors.

### 3.3 Material preparation and device fabrication:

#### 3.3.1 Preparation of Chitosan-Alginate-Graphene composite:

To prepare sodium alginate – chitosan-Graphene film, a low molecular weight chitosan powder (Sigma Aldrich 9012-76-4, C18H35N3O13 was selected which was made from 75-85% deacetylated chiton. The schematic representation of the preparation of the large-area flexible chitosan films is illustrated in figure 1a. First, the chitosan powder was mixed with acetic acid solution and deionized water in a beaker at a ratio of 2:1:100 to obtain a 2 wt.% chitosan solution, after which a magnetic stir bar was added to the solution. The solution was placed on a magnetic stirrer and heated to 60-70°C. The chitosan solution was then sonicated at 37 kHz for 30 min, and after thorough mixing the prepared solution was placed in a vacuum pump and degassed for 1-2 hours until all the air bubbles in the solution had disappeared. After this, the chitosan solution prepared are finished. Subsequently, 5g of sodium alginate was added to the prepared chitosan solution mentioned above, and the preparation steps for the chitosan solution were repeated to ensure thorough mixing and defoaming under vacuum. This resulted in a mixture solution of chitosan and sodium alginate, as shown in figure 1b.

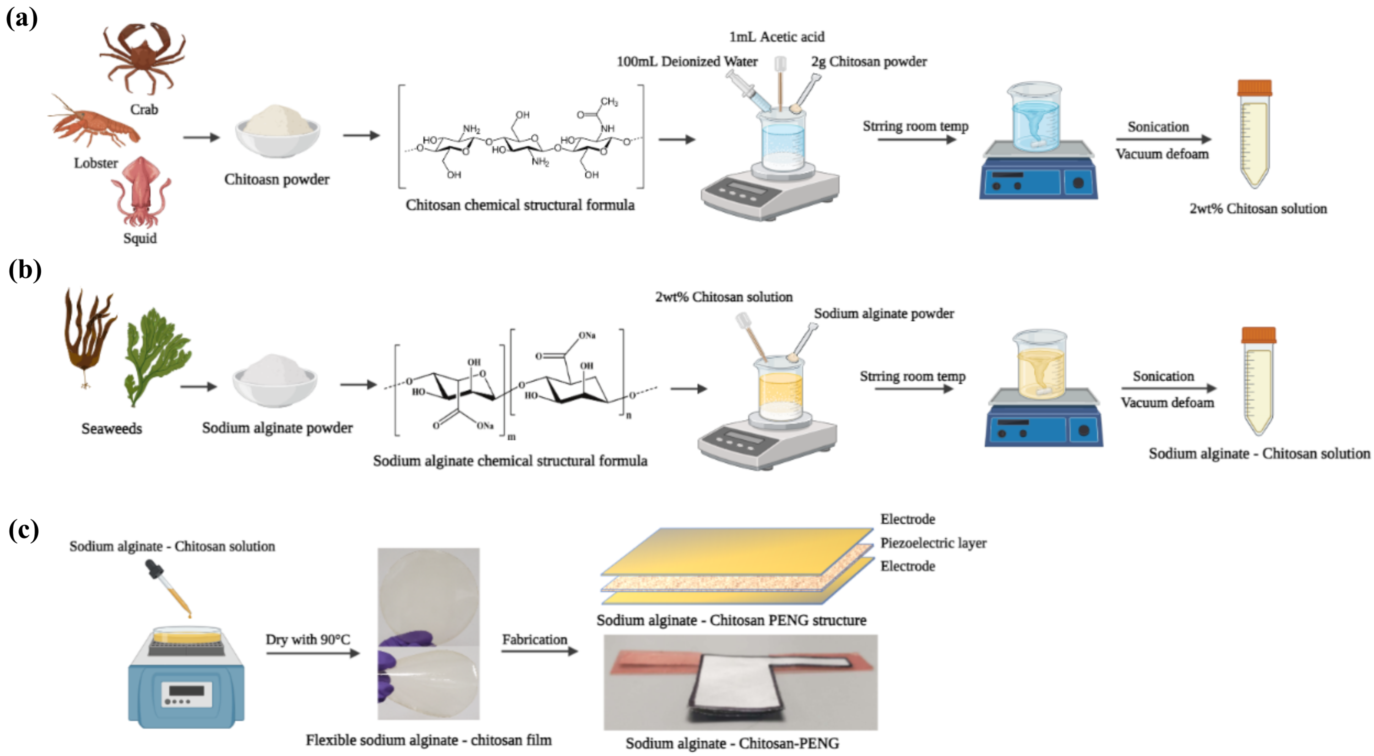


**Figure 1:** (a) preparation of the chitosan solution using the acetic and deionized water (b) preparation of sodium alginate powder and chitosan composite solution and (c) device fabrication of the self-powered pressure sensor using the composite mixture of chitosan-alginate and graphene.

Then, the mixed solution was drop-casted onto a polystyrene petri dish and subsequently inserted into a spin coating cycle for 30 s at a speed of 1000 rpm, to ensure uniform spreading throughout the dish. This was followed by a drying process in a heater at 90°C for 5 hours. When the film completely dried, the required morphology and crystalline phases were obtained. as shown in figure 1c, the biodegradable chitosan film is mechanically flexible and optically transparent, and it exhibits relatively high flexibility and mechanical robustness under repetitive mechanical bending and twisting. Finally, the graphene has been added to the composite mixture at a different weight percentage varying from 0.1 wt.% to the 0.5 wt.% to form a hybrid composite film.

### 4.3.2 Measurement setup:

A custom-made setup was prepared using a linear motor connected to the mixed signal oscilloscope to characterize the sensor which. is shown in figure xx. An isolation was provided under the sensor to avoid any electromagnetic effects and metal shielding related noise effects. Measurement using the TIRA shaker as a linear motor provides a reliable and controlled means to evaluate the performance of piezo-based sensors.

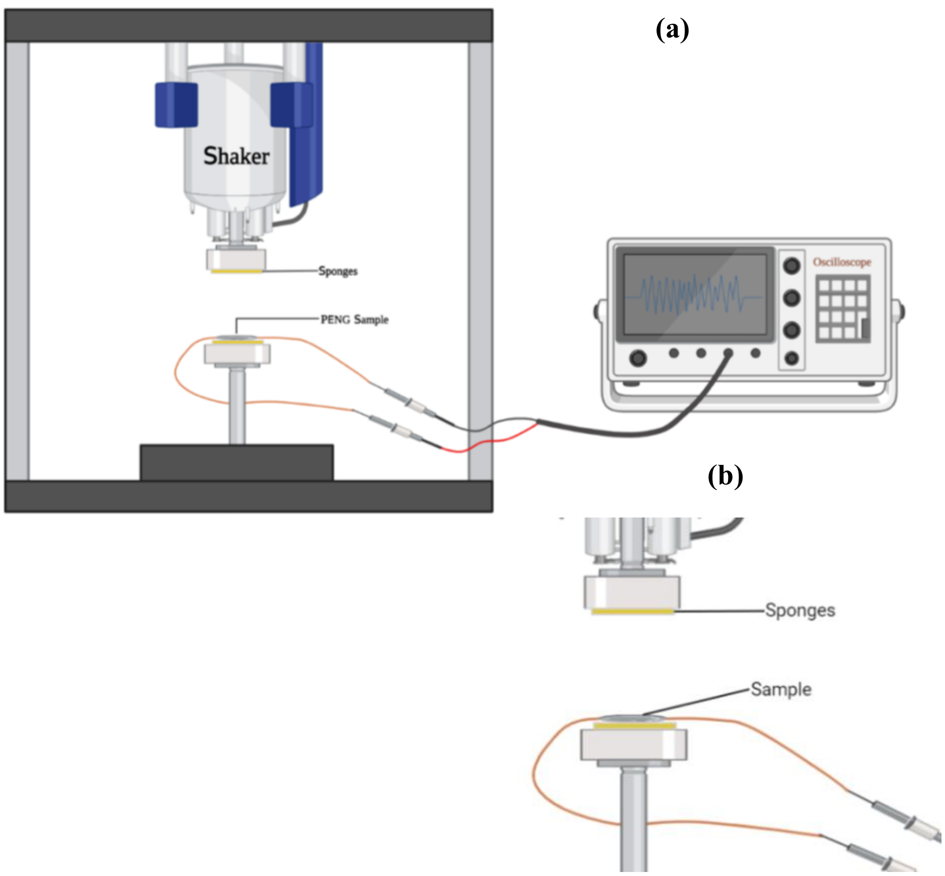


**Figure 2:** (a) and (b) characterization setup for the piezoelectric nanogenerator using customized test using a linear motor connected to an oscilloscope.

By securely mounting the sensor on the shaker's platform, controlled mechanical vibrations can be applied, simulating real-world conditions, and enabling precise measurement of the sensor's electrical response which is shown in figure 2a and 2b. Measurements conducted using the TIRA shaker include frequency response, amplitude response, sensitivity and calibration, dynamic performance, and linearity and hysteresis. The shaker allows for precise control of vibration parameters, facilitating accurate calibration and characterization of the sensor. This setup enables researchers and engineers to assess the sensor's sensitivity, resonant frequency, linearity, dynamic range, stability, and accuracy. By utilizing the TIRA shaker as a linear motor for testing piezo-based sensor measurements, the performance and piezoelectric properties of the sensor can be thoroughly evaluated, aiding in design optimization and application-specific requirements.

### 3.3.3 Fabrication of Chitosan-Alginate-Graphene based Touch Sensor:

The PENG device was created using a spin coating process, which is a simple and cost-effective technique. The device follows a sandwich structure as depicted in figure 1c. The electrodes consist of aluminum, serving as both the top and bottom layers, while the active piezoelectric layer is made of chitosan composite film. To fabricate the device, the chitosan composite film is first prepared and then peeled off from the petri dish and then cut into a size of 1 x 2 cm. The top and bottom electrodes, made of aluminum foil, are cut into shapes that match the dimensions of the active layer. Next, the chitosan film is sandwiched between the two electrodes, creating the PENG sensor. To ensure proper insulation and avoid short circuits, the device was encapsulated in polyamide.

## 3.4 Results and discussion:

Frequency sensitivity and pressure sensitivity are key parameters for evaluating the performance of piezoelectric nanogenerators. Optimizing these two parameters can enhance the energy conversion efficiency, frequency response range, and adaptability of the nanogenerator. Frequency sensitivity refers to the degree of response of the piezoelectric nanogenerator to changes in external mechanical vibration frequency. In the piezoelectric nanogenerator, mechanical energy is converted into electrical energy through the piezoelectric effect. The magnitude of frequency sensitivity directly affects the performance of the nanogenerator under different frequency vibrations. Higher frequency sensitivity means that the nanogenerator can better respond to vibrations of different frequencies, thereby achieving more efficient energy conversion. In practical applications, optimizing frequency sensitivity can enable the nanogenerator to achieve maximum energy conversion efficiency within a specific frequency range, thereby improving energy harvesting and utilization efficiency.

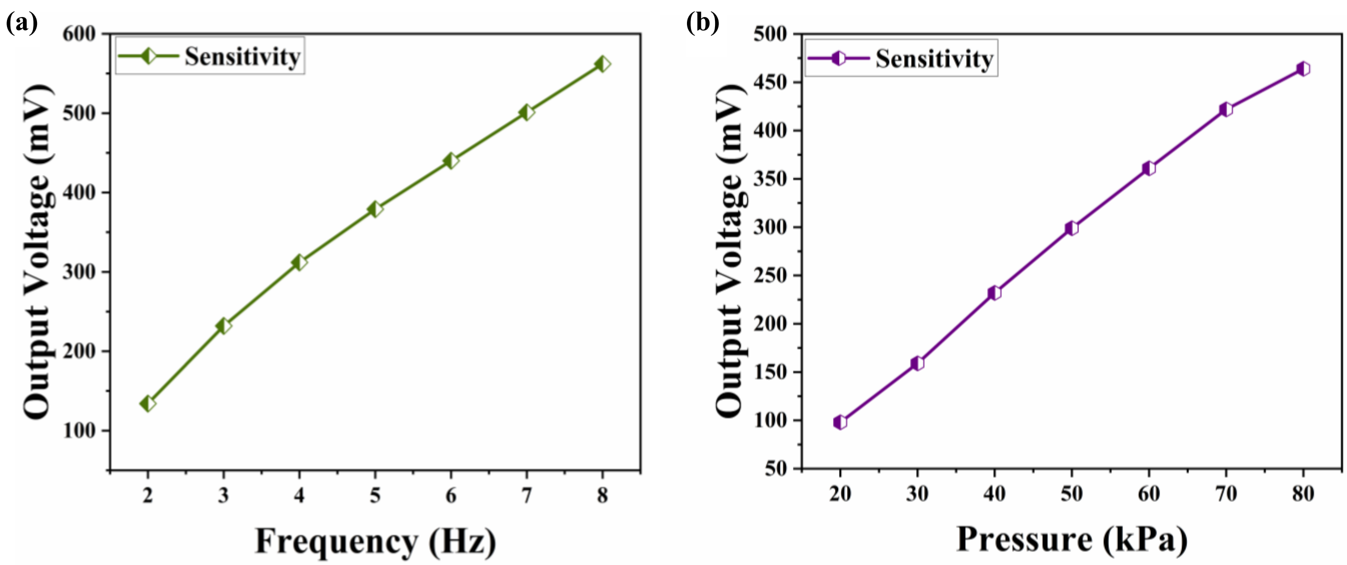


**Figure 3:** (a)(b) Frequency and pressure sensitivities of the PENG under different pressures at a constant frequency of 8 Hz, and different frequencies at a constant pressure of 60 kPa, respectively.

Pressure sensitivity, on the other hand, refers to the degree of response and energy conversion efficiency of the piezoelectric nanogenerator to external pressure changes. Pressure sensitivity determines the sensitivity of the piezoelectric material to external pressure variations, i.e., the material's ability to generate charge separation and potential difference. Higher pressure sensitivity means that, under a given pressure, the nanogenerator can generate a greater amount of charge and voltage, thereby improving energy conversion efficiency. Optimizing pressure sensitivity can increase the power output and energy harvesting efficiency of the piezoelectric nanogenerator, enhancing its potential applications in self-powering and energy harvesting domains. Therefore, the optimization of these two parameters is of great significance for improving the performance of piezoelectric nanogenerators and promoting their applications in various fields.

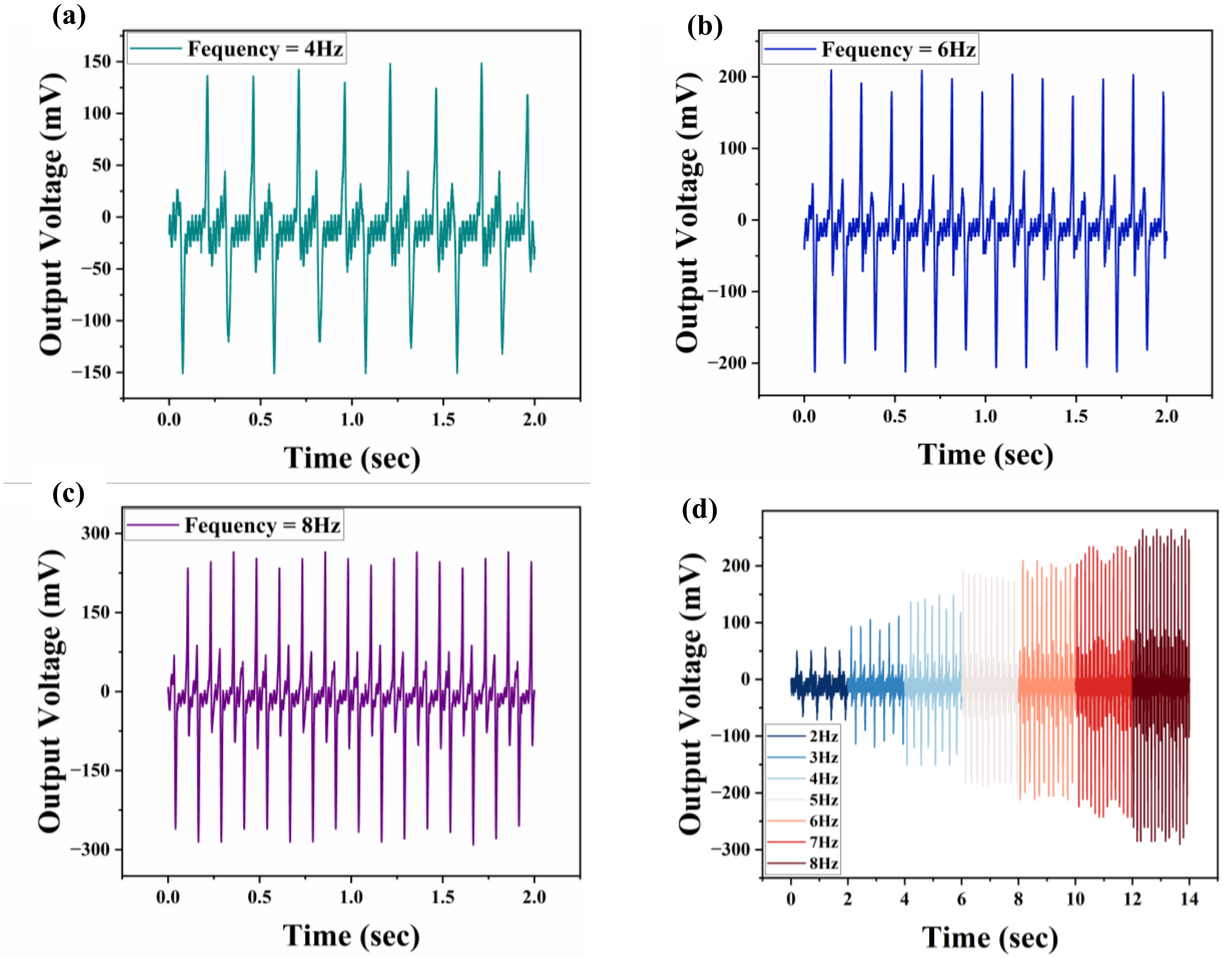


**Figure 4:** (a) (b) and (c) temporal response characteristics of the chitosan-alginate based piezoelectric nanogenerator showing different output voltages at different frequencies under a constant pressure (d) cyclic increment of the self-powered touch sensor.

The piezoelectric characteristics of the A-PENG device were evaluated by measuring the output voltage under different frequencies pressures. Figure 3(a) demonstrates the output response characteristics of the sensor under different frequencies ranging from 2 Hz to 8 Hz at a constant pressure of 80 kPa. The frequency sensitivity ($S_f$) of the pressure sensor is the ratio of the change in the output voltage to the change in the applied pressure which is obtained as 71 ± 0.2 mV/ Hz and calculated using the following equation (1)

$$S_f = \frac{\Delta Output\ voltage}{\Delta Frequency} \quad \ldots\ldots\ldots\ldots\ldots (1)$$

Similarly, Figure 3b shows the pressure sensitivity ($S_P$) of the sensor under different pressures ranging from 20 kPa to 80 kPa at a constant frequency of 8 Hz. The $S_P$ of the A-PENG was obtained as 6 ± 0.2 mV/Hz and was calculated using the following equation (2)

$$S_P = \frac{\Delta Output\ voltage}{\Delta Pressure} \text{..............} (2)$$

Finally, the results of frequency sensitivity and pressure sensitivity reflect the sensitivity of the A-PENG (piezoelectric nanogenerator) to external vibration frequency and pressure, demonstrating its ability to respond effectively to low-frequency vibrations and subtle pressure changes. This highlights the A-PENG's excellent responsiveness, energy harvesting rate, and energy conversion efficiency. These characteristics make it well-suited for real-time applications such as smart sensors and environmental monitoring.

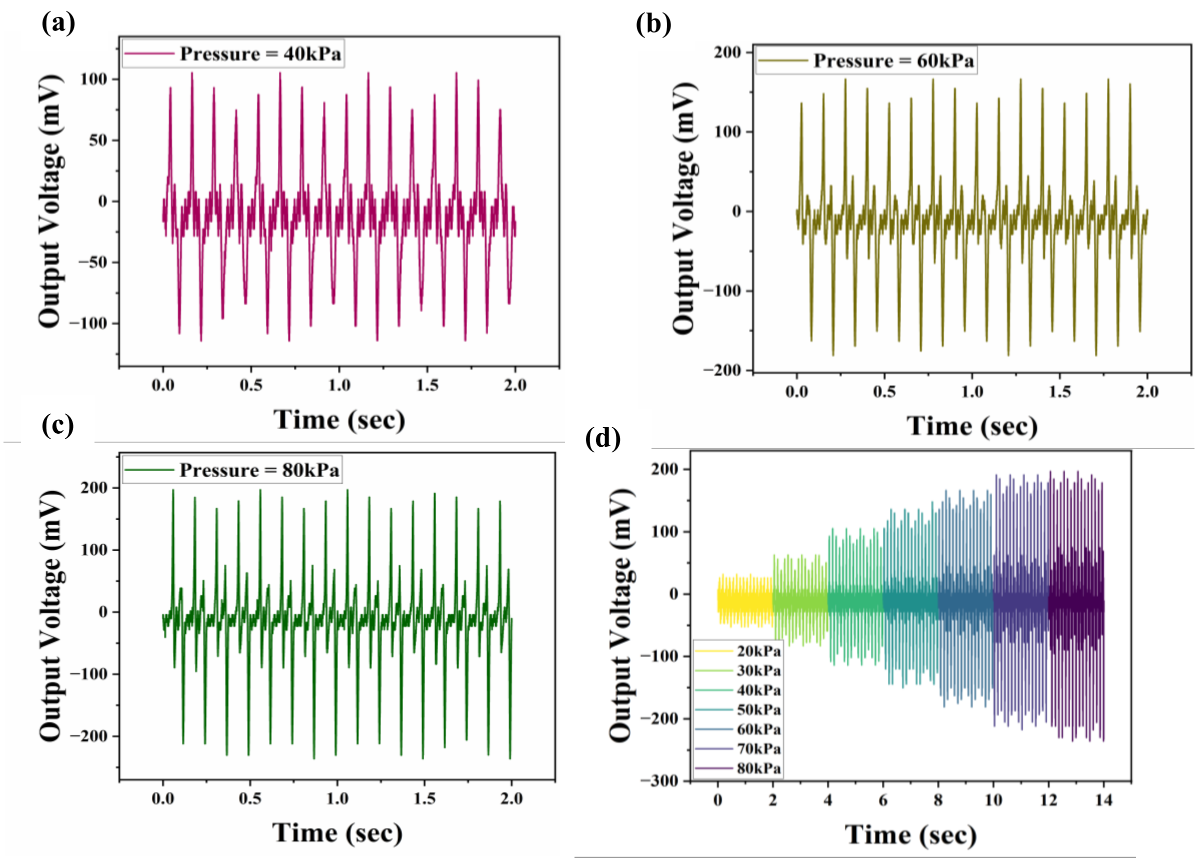


**Figure 5:** (a) (b) and (c) output response characteristics of the chitosan-alginate-graphene based piezoelectric nanogenerator showing different output voltages under different pressures at a constant pressure of 40kPa. (d) cyclic increment of the self-powered touch sensor.

The as fabricated flexible and self-powered dynamic touch sensor exhibit excellent response under different pressures varying from low, medium, and high pressures and different frequencies. Figure 4a shows the output response characteristics of the sensor at a pressure of 40ka at a frequency of 4Hz and the results suggest that the device exhibit a very high output voltage of 300mV peak to peak. Similarly, the figure 4b shows the output response characteristics of the sensor at a pressure of 40ka at a frequency of 6Hz and the results suggest that the device exhibit a very high output voltage of 400mV peak to peak. Next, the figure 4c shows the output response characteristics of the sensor at a pressure of 40ka at an applied frequency of 8Hz and the results suggest that the device exhibit a very high output voltage of 600mV peak-peak with a very less noise. Next, the output response of the sensor under cyclic increment of frequencies varying from 2Hz to the 8Hz clearly demonstrate the linear increase in the output voltage as shown in figure 4d. The output voltage of a self-powered piezoelectric nanogenerator based on chitosan-alginate-graphene exhibits a linear increase with a linear increase in frequency due to several factors. Mainly, the inherent piezoelectric properties of the chitosan-alginate-graphene nanocomposite result in an electric potential being generated in response to mechanical deformation. As the frequency of the applied force increases, the rate of deformation also increases, leading to a linearly increased output voltage. Next, the rapid oscillation at higher frequencies enhances the charge separation process within the nanocomposite, resulting in a greater output voltage. Additionally, the incorporation of graphene improves the electrical conductivity of the nanocomposite, facilitating efficient charge transfer and contributing to the linear increase in output voltage with frequency. Lastly, the resonance phenomenon plays a role, as the nanogenerator operates closer to or at its resonant frequency, leading to maximum deformation and charge separation. These factors collectively contribute to the linear relationship between output voltage and frequency in self-powered piezoelectric nanogenerators based on chitosan-alginate-graphene, enabling their utilization in various energy harvesting applications. Figure 5a shows the output response characteristics of the sensor at a pressure of 40ka and the results suggest that the device exhibit a very high output voltage of 200mV peak-peak at a constant frequency of 4 Hz. Similarly, Figure 5b shows the output response characteristics of the sensor at a pressure of 60ka and the results suggest that the device exhibit a very high output voltage of

350mV peak-peak at a constant frequency of 4 Hz. Next, the device is tested under a high pressure of 80kPa at a constant frequency of 4 Hz which provide an output voltage of 500mV peak-peak with a much lower noise voltage levels as shown in figure 5c. Figure 5d shows the cyclic increment of the sensor under the different pressures varying from 20kPa to 80kPa in steps of 10kPa with an output voltage ranging from 100mV to 500mV respectively. Cyclic increment is a highly advantageous feature for self-powered chitosan-alginate-based touch sensors. Mainly, it enhances the sensitivity of the sensor by incrementally amplifying the output signal in response to touch inputs. This amplification enables the sensor to detect even subtle touches with greater precision and accuracy. Additionally, cyclic increment expands the dynamic range of the sensor, allowing it to accurately capture a wide spectrum of touch intensities, from gentle to stronger interactions. Moreover, it improves the signal-to-noise ratio by amplifying the touch signal relative to background noise, resulting in more reliable touch detection, and reduced false positives or negatives. The fine-grained sensing capabilities of cyclic increment enable the sensor to capture precise variations in touch intensity, facilitating accurate and nuanced touch-based interactions. Further, cyclic increment optimizes energy usage, contributing to the overall energy efficiency of the touch sensor system. In conclusion, the incorporation of cyclic increment in self-powered chitosan-alginate-based touch sensors significantly improves sensitivity, dynamic range, signal-to-noise ratio, fine-grained sensing, and energy efficiency, enhancing the overall performance and user experience of the touch sensor.

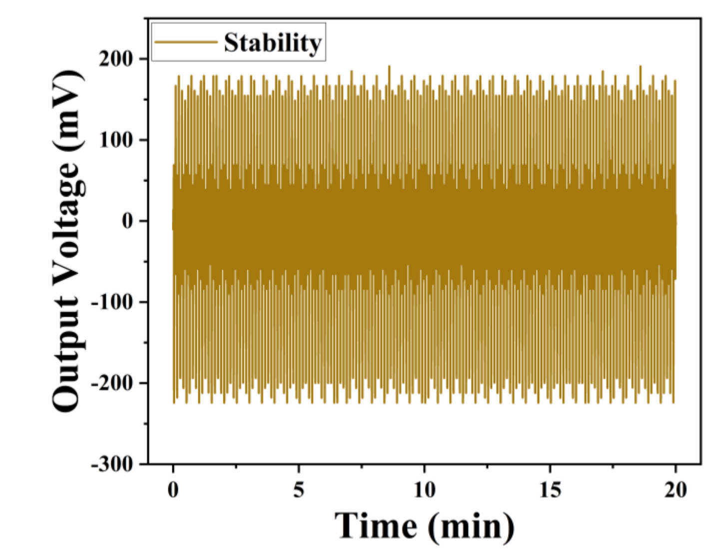

**Figure 6:** Stability response characteristics of the self-powered touch sensor for various repeated cycles.

Cyclic stability refers to the ability of a sensor to maintain consistent performance over multiple cycles of operation. This characteristic plays a crucial role in ensuring the reliability, durability, and consistent performance of touch sensors, making them suitable for a wide range of applications. Cyclic stability is a critical factor in the design and development of chitosan-alginate-based self-powered touch sensors. Its importance lies in ensuring long-term reliability, durability, consistent performance, and compatibility with different environmental conditions and usage scenarios. By maintaining stable performance over multiple cycles, these touch sensors offer accurate and reliable touch detection, enhancing user experience and overall functionality. As technology advances, further research and development efforts in improving cyclic stability will contribute to the continuous evolution and widespread adoption of touch sensors based on chitosan-alginate. Figure 6 shows the cyclic stability of the touch sensor under different repeated number of cycles greater than 2.5 x $10^3$ cycles further demonstrating its excellent long term cyclic stability. The outstanding cyclic stability of chitosan-alginate-based touch sensors can be attributed to several key factors. Firstly, the inherent mechanical strength of chitosan and alginate contributes to the sensor's ability to withstand repetitive touch inputs without structural deformation or failure. Additionally, the chemical crosslinking of chitosan and alginate creates a robust network that enhances the stability and integrity of the sensor during cyclic operations. Moreover, the uniformity of the film coating, achieved through precise fabrication techniques, ensures consistent thickness and distribution of the polymer material, minimizing variations in sensitivity and response. The design and integration of electrodes also play a crucial role, providing stable electrical connections throughout cyclic operations. Furthermore, the compatibility of chitosan and alginate with other sensor materials fosters strong adhesion and interface bonding, reducing the risk of delamination or detachment. Lastly, extensive optimization of the chitosan-alginate formulation and processing parameters ensures the sensor's longevity and reliable performance over numerous cycles. Collectively, these factors contribute to the exceptional cyclic stability of chitosan-alginate-based touch sensors, enabling their long-term reliability and consistent functionality during repetitive touch interactions.

## 4. Conclusion:

In conclusion, the chitosan-alginate-graphene based self-powered piezoelectric nanogenerator touch sensor holds great potential for e-skin applications. Its unique combination of materials offers advantages such as mechanical flexibility, piezoelectric properties, self-powering capability, and enhanced sensitivity. These attributes make it well-suited for integrating into electronic skin (e-skin) technologies, which aim to replicate the sense of touch in artificial systems. The chitosan-alginate-graphene nanocomposite enables the touch sensor to detect and convert mechanical stimuli into electrical signals, making it suitable for various touch-sensitive applications. Its self-powered nature eliminates the need for external power sources, allowing for more autonomous and versatile operation. Additionally, the linear increase in output voltage with frequency further enhances its touch detection capabilities, enabling accurate and responsive sensing of different touch intensities. Furthermore, the touch sensor's compatibility with flexible and stretchable substrates makes it highly suitable for e-skin applications, where conformability and wearability are crucial. Its robust mechanical properties and excellent cyclic stability ensure long-term reliability and durability under repetitive touch interactions. The potential applications of chitosan-alginate-graphene based self-powered piezoelectric nanogenerator touch sensors in e-skin technology are vast. They can be utilized in prosthetics, robotics, human-machine interfaces, and virtual reality systems to provide a more immersive and interactive user experience. Moreover, their integration into wearable devices and smart textiles can enable advanced haptic feedback, biometric sensing, and touch-based control interfaces. While there are still challenges to overcome, such as scalability and cost-effectiveness, the advancements in chitosan-alginate-graphene based touch sensors pave the way for exciting developments in e-skin applications. Continued research and innovation in this field will further enhance the capabilities and integration of these touch sensors into next-generation e-skin technologies, bringing us closer to realizing the full potential of touch-sensitive artificial systems.

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