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ULVAN FROM *ULVA NEMATOIDEA* AS A NOVEL ACTIVE SURFACE MATERIAL FOR TRIBOELECTRIC NANOGENERATORS

Fernando G. Torres * and Adrian Urtecho

Department of Mechanical Engineering, Pontificia Universidad Católica del Perú. Av. Universitaria 1801, 15088, Lima, Peru

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ABSTRACT

Marine algae represent an underutilized biomass resource. Biopolymers can be extracted from different types of algae. Alginates and carrageenans are among the most common biopolymers extracted from brown and red algae. They find applications in the food and biomaterials industries, among others. However, other available marine algae are not commercially exploited. For instance, green algae from the Ulvaceae family remain largely unexploited and have no industrial applications. In particular, Ulva species can serve as a promising source for the extraction of a biopolymer known as ulvan. This work reports the development of triboelectric nanogenerators (TENGs) for energy harvesting applications using ulvan extracted from the green algae *Ulva nematoidea*. Ulvan was extracted via an alkaline method. The extracted ulvan was dissolved in water, poured into petri dishes, and dried to form thin films. TENGs were prepared using Ulvan-Kapton® and Ulvan-Polytetrafluoroethylene (PTFE) triboelectric pairs. The Ulvan-Kapton® TENG showed a maximum voltage of 2.12 V and a short-circuit current of 1.6 µA while the Ulvan-PTFE TENG showed a maximum voltage of 43.60 V and a short-circuit current of 5.6 µA. This performance is similar to the performance of other TENGs fabricated from commercial biopolymers. This suggest that ulvan extracted from *Ulva nematoidea* has potential applications as active surface of TENGs for the development of sustainable energy harvesting devices. This work shows that bio-based materials from green algae can serve as a potential alternative for renewable energy generation. Further research will allow to enhance mechanical properties, electrical performance, and durability of ulvan-based TENGs to improve their practical applicability.

1. INTRODUCTION

Biomass derived from macroalgae is recognized as a source of valuable biopolymers with applications in the biomedical, nutraceutical, cosmeceutical, and pharmaceutical industries, among others. Algae are classified into brown (Phaeophyceae), red (Rhodophyta), and green (Chlorophyta) algae. The difference between them is the presence of different types of chlorophyll and pigments (Osório et al., 2020). Marine algae contain high amounts of biopolymers in the form of carbohydrates (~60%) and proteins (10–47%) (Kraan, 2013). Biomass from the oceans have become an attractive alternative for the extraction of biopolymers. For instance, brown and red algae have been used to extract commercially important biopolymers such as alginate, carrageenan, and agar, among others.

Green algae belonging to genus Ulva (family: *Ulvaceae*) are mainly used as food and remain unexploited for large scale industries. Most research have been focused on their applications as food and pharmaceutical supplements, due to their antioxidant/radical scavenger and anti-inflammatory activity (Le et al., 2019; Matloub et al., 2018). However, Ulva sp. can be a source of biopolymers such as ulvan. Ulvan is a sulfated polysaccharide mainly composed of rhamnose, xylose and uronic acids. The structure of this polysaccharide is dependent to the species, season of collection and processing (Rodríguez-Iglesias et al., 2024). It has been reported that ulvan comprise from 9% to 36% of the dry weight biomass of the cells of Ulva sp. (Kidgell et al., 2019). Ulvan yield ranges from 8% to 29% of the dry weight of algae (Lahaye & Robic, 2007).

The presence of Ulva has been associated to ecological disasters such as green tides and eutrophication. These processes could result in hypoxic conditions (due to algal respiration) and severely compromise the survival of aquatic vertebrates (Wilhelm, 2009). It has been proposed that sustainable harvesting of Ulva sp. could be an alternative to mitigate their negative effects (Torres & De-la-Torre, 2022). Previous work (Torres & De-la-Torre, 2022) showed that green algae can be used for the development for sus-

* Corresponding author:
Fernando G. Torres
email: fgtorres@pucp.pe

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tainable energy materials. The biopolymer ulvan, extracted from this family of algae, has been studied for energy-related applications (Gonzales et al., 2024). They can be used as solid and gel electrolytes, and even as electrodes in energy storage applications (Torres et al., 2024).

The use of low-power devices, such as sensors, Wi-Fi modules, and Internet of the things (IoT) devices, have seen significant growth in recent years. These devices require a reliable energy source to operate effectively. Batteries have long been the main energy source for these devices. However, a significant drawback with batteries is the environmental pollution that occurs when they are improperly disposed of, as they can contaminate large water bodies and soil (Melchor-Martínez et al., 2021; Mrozik et al., 2021). Recently, more sustainable solutions have emerged to address this issue, including piezoelectric nanogenerators (Bairagi et al., 2020), triboelectric nanogenerators (Zhu et al., 2024) and bio-based batteries (Liu et al., 2021).

Triboelectric nanogenerators (TENGs) take advantage of the contact electrification phenomenon to harvest mechanical energy. In this process, two surfaces from two different materials are put in contact and separated alternatively. Contact electrification occur when these two surfaces touch, and electrical charges flow from one surface to the other. The active surfaces of most TENGs are made from dielectric synthetic polymers such as polytetrafluoroethylene (PTFE) and polyethylene terephthalate (PET), due to their ability to give and receive electrons by contact electrification. TENGs from synthetic polymers could pose potential ecological problems due to the generation of electronic waste. By contrast, a TENG made from biopolymers could become an alternative energy source of small electronic devices with a limited impact on the environment.

Synthetic polymers have been extensively used as materials for triboelectric surfaces. In recent years, most new TENGs have been constructed using synthetic polymers. For instance, Tung et al. (2025) developed a TENG utilizing a polymer composite film composed of polyhexamethylene guanidine hydrochloride (PHMG), polyvinyl alcohol (PVA), and glutaraldehyde (GA) as a crosslinking agent. The device demonstrated a peak-to-peak open-circuit voltage of 664.5 V and a short-circuit current of 116.8 μA. Zhao et al. (2025) employed a poly(vinylidene fluoride-hexafluoropropylene) / molybdenum disulfide (MoS2) as a triboelectric layer in a TENG; the fabricated device exhibited an open-circuit voltage of 208 V, a short-circuit current of 31 μA, and a peak power density of 1.42 W/m² at 50 MΩ. Yang et al. (2024) developed a TENG using a two-dimensional graphitic carbon nitride incorporated poly(vinylidene fluoride) (g-C3N4/PVDF) as a tribonegative layer and nylon-11 nanofibers as a positive layer. This device achieved an open-circuit voltage of 339 V, a short-circuit current of 14.5 μA, and a power density of 0.94 W/m². You et al. used polyurethanes (PU) on polyethylene terephthalate fabric (PET-F) to create a film for a TENG device. This configuration achieved a peak-to-peak voltage of 352 V and a maximum power density of 18 mW/cm². These examples highlight the widespread use of synthetic polymers in TENG development and their promising electrical performance. However, despite their ability to generate high voltage outputs, the non-biodegradability of synthetic polymers raises environmental concerns, potentially limiting their long-term sustainability.

These environmental concerns have triggered the development of energy harvesting devices using a variety of biopolymers. Small generators such as TENGs have been developed using different biopolymers (Table 1). Chen et al. (2021) developed a chitosan/montmorillonite/lignin (CML) composite film as a tribopositive layer in a TENG. The device featured an open circuit voltage of 262 V and an instantaneous output power of 429 mW/m^2. The authors demonstrated that CML-TENG maintains better performance at high temperatures compared to chitosan-only based devices. Petchnui et al. (2024) developed a TENG using a nanocomposite based on natural rubber (NRL) and chitin nanofibers (ChNF) obtained from shrimp shells biowaste. The TENG with a triboelectric layer composed exclusively of NRL exhibited low output voltages, around 2.56 ± 0.8 V. In contrast, incorporating 0.2% by weight of ChNF significantly enhanced performance, achieving an open-circuit voltage of 106.04 V. Cellulose has also been used as a triboelectric material for TENG. Zhang et al. (2021) fabricated an eco-friendly TENG using cellulose. The device had an open-circuit voltage of 29 V and a short-circuit current of 0.6 μA. Somseemee et al. (2024) developed a TENG using Natural rubber filled with cellulose nanocrystals. The device achieved an open circuit voltage of 80.3 V a short-circuit current of 7.4 μA. Other biopolymer used in TENGs is starch. Ansori et al. (2023) developed a cassava starch/PVA-TiO_2 nanocomposite film as a triboelectric film in a TENG. The device achieved an open circuit voltage of 180 V and a short-circuit current of 13.7 μA.

Most studies on biopolymers for TENG applications have focused on red and brown algae, particularly alginate and carrageenan. While these materials have demonstrated potential for energy harvesting, they exhibit limitations such as complex processing, and low triboelectric performance. For example, Pang et al. (2018) fabricated a TENG using calcium alginate, but its low output voltage (33 V) and short-circuit current (150 nA) suggest that improvements in material properties are needed. Similarly, Li et al. (2023) incorporated silver nanowires into an alginate-based TENG to enhance conductivity, but this increases production costs and environmental impact. The resulting device reached an output voltage of 53 V and a power of 4 μW. Kang et al. (2022) developed a TENG using carrageenan, a biopolymer extracted from red algae. The developed device had a peak-to-peak output voltage of 30 V and an output power of 0.15 mW·m^{-2}. These studies remark the need for alternative biopolymers that balance sustainability, mechanical integrity, and triboelectric efficiency.

Unlike alginate and carrageenan, which have found commercial applications, ulvan remains largely unexploited despite its potential as a sustainable biopolymer. Previous research has primarily investigated it for its bioactive properties, but its role in energy harvesting remains almost completely unexplored. Few studies have investigated the use of green algae as a material for energy devices. For example, Noman et al. used ground Ulva lactuca algae as a triboelectric layer in a TENG. This device achieved a

maximum output voltage of 875 V, an output current of 52 μA, and a power density of 272.72 μW/cm² (Noman et al., 2024). However, biopolymers extracted from green algae, such as ulvan, remain largely understudied. Due to its sulfated polysaccharide structure, ulvan may possess favorable triboelectric properties. However, research on ulvan-based TENGs is currently lacking, a gap this work seeks to address.

In this paper, the extraction of Ulvan from *Ulva nematoidea* and its application in the development of a mechanical energy harvesting device (TENG) is reported. Such device can convert low frequency mechanical vibrations into electricity for small portable low-power electronic devices. The extracted ulvan was used to fabricate films to be used as triboelectric surface in this TENG. The films were characterized by Scanning Electron Microscopy (SEM), Fourier-transform infrared spectroscopy (FTIR), Differential Scanning Calorimetry (DSC) and tensile tests. TENG's electrical output confirmed the suitability of ulvan as a potential material for energy harvesting devices.

1.1 Highlights

- Ulvan was extracted from *Ulva nematoidea* using an alkaline method.
- Ulvan films were used as a tribopositive triboelectric surface for energy harvesting devices.
- Ulvan-based TENGs achieved an open-circuit voltage of 43.60 V and a short-circuit current of 5.6 μA.

2. MATERIALS AND METHODS

2.1 Materials

Fresh green algae *Ulva nematoidea* were collected in Lima, Peru. All the reagents used in the present study were analytical grade and purchased from Sigma-Aldrich and Himedia Laboratories LLC.

2.2 Extraction of Ulvan

Ulvan was extracted using an alkaline extraction method (Peasura et al., 2015; Tabarsa et al., 2018). The extraction was conducted in two major steps, pre-treatment and extraction (Figure 1).

For the pre-treatment step, green algae were washed with abundant distilled water to remove impurities. After that, they were dried in an oven at 40°C for 72 h. Then, the dried samples were powdered and stored at 4°C. The obtained biomass was treated with ethanol to remove soluble materials, using 34 g of dry algae biomass per 500 mL of ethanol under constant stirring for 24 h. The supernatants were discarded, and the biomass was dried in an oven at 40°C for 48 h.

After the pre-treatment, ulvan was extracted using 0.1 M NaOH (pH 13) under constant stirring at 80°C for 6 h, with a biomass to solvent ratio of 1:35 (w/v). The supernatants were separated by centrifugation (10,000 rpm for 10 min) and discarded. Then the ulvan solution was concentrated by evaporation until 50% of its initial volume and precipitated by slowly adding the concentrated in 2 volumes of cold ethanol. The ulvan precipitate was recovered by centrifugation (10,000 rpm for 10 min). After that, ulvan was repeatedly washed with ethanol to remove impurities or any reagents, and then, dried in an oven at 40°C for 72 h. The dried Ulvan was stored in a desiccator for further use.

2.3 Preparation of triboelectric surfaces and Triboelectric Nanogenerators (TENG)

Ulvan-based films were used as triboelectric surfaces. To prepare ulvan films, a solution of ulvan (1% w/v) in distilled water was stirred at 60°C for 3 h. Then, 10% of glycerol was added to the ulvan solution. Finally, the solutions were poured onto Petri dishes and dried in an oven at 40°C for 48 h.

TABLE 1: Open circuit voltage and short circuit current of different TENGs.

Biopolymer-based TENGs				
Biopolymer	**Open Circuit Voltage (V)**	**Short-circuit current (μA)**	**Power Output**	**Ref.**
Chitosan	262	-	429 mW/m²	(Chen et al., 2024)
Chitin	106.04	-	-	(Petchnui et al., 2024)
Alginate	33	0.15	9.5 μW	(Pang et al., 2018)
Alginate	53	-	4 μW	(Li et al., 2023)
κ-Carrageenan/Agar	-	-	0.15 mW/m²	(Kang et al., 2022)
Bacterial Cellulose	29	0.6	3 μW	(Zhang et al., 2021)
Cellulose	80.3	7.4	1.32 W/m²@ 9 MΩ.	(Somseemee et al.,2024)
Starch	180	13.7	-	(Ansori et al., 2023)
Grounded Ulva algae/ PET	875	52	272.72 μW/cm²	(Noman et al., 2024)
Synthetic Polymer-based TENGs				
Polymer	**Open Circuit Voltage (V)**	**Short-circuit current (μA)**	**Power Output**	**Ref.**
PHMG-GA-PVA	664.5	116.8	-	(Tung et al., 2025)
PVDF-HFP	208	31	1.42 W/m²	(Zhao et al., 2025)
A g-C3N4/PVDF	339	14.5	0.94W/m²	(Yang et al., 2024)
PU-CD4/PET-F	352	-	18 mW/cm²	(You et al., 2024)

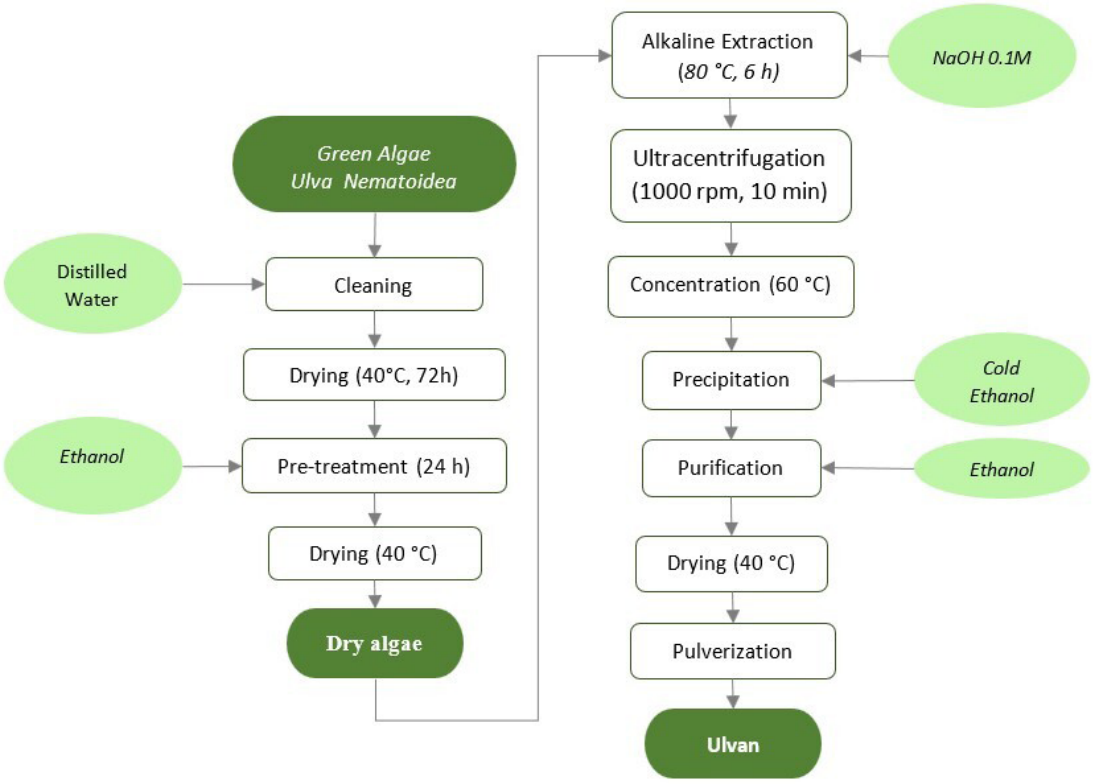

FIGURE 1: Scheme of the alkaline process used in this study to extract ulvan.

TENGs were fabricated using two different triboelectric surfaces, in contact-separation mode. Two types of TENGs were prepared: ulvan-Kapton® and ulvan-PTFE TENGs. Kaptop® feature a tribopositive behavior, i.e. it is prone to give away electrons. On the other hand, PTFE has a tribonegative behavior because is an electron-accepting material. The interaction between the selected triboelectric surfaces and the ulvan film was used to evaluate the triboelectric behavior of the ulvan based active surface. Ethylene-vinyl acetate (EVA) sleeves were used as support for the two surfaces of each TENG. Copper films were used as electrodes (current collectors). These copper films were glued to the polymeric films and attached to the EVA sleeves using a methacrylate adhesive. The Ulvan, Kapton®, PTFE and copper films were cut in 4cm x 4cm squares and mounted in the EVA sleeve as shown in Figure 2a.

2.4 Characterization Techniques

2.4.1 Scanning electron microscopy (SEM)

A Thermo Fisher (Massachusetts, USA) Axia ChemiSEM Scanning Electron Microscopy (SEM) equipped with an energy-dispersive X-ray spectroscopy detector (EDX), was used to observe the morphology of the ulvan films. Tests were carried out in low vacuum with a voltage of 20 kV and a working distance of ~10 mm.

2.4.2 Fourier transform infrared (FTIR) spectroscopy

Ulvan films were characterized using FTIR spectroscopy to identify the functional groups. FTIR spectra was obtained using a Spectrum Two Perking Elmer (Connecticut, USA) spectroscope, equipped with a universal attenuated total reflectance (ATR) accessory. Film samples were cut in 1cm x 1cm squares and inserted in the ATR. Samples were recorded in the 500–4000 cm^{-1} spectral range with a resolution of 4 cm^{-1} and 64 scans. Perkin Elmer Spectrum 10 software was used to acquire the spectra.

2.4.3 Differential Scanning Calorimetry (DSC)

DSC tests were performed using a Perkin Elmer (Connecticut, USA) DSC4000 calorimeter. DSC was calibrated using Indium and Zinc as reference materials. Nitrogen was used as purging gas with a flow rate of 20 mL/min. 10 mg of samples were loaded in aluminum pans and heated from 0°C to 180°C, at a heating rate of 10°C/min. An empty aluminum pan was used as reference. Perkin Elmer Pyris software was used to record the thermograms.

2.4.4 Electric performance of the TENGs

The electrical performance of the TENGs was evaluated using a DPO2022 Tektronix (Oregon, USA) oscilloscope. The instrument was calibrated with a self-calibration function. A 10 MΩ probe was used to perform the measurements. TENGs were manually operated through alternating motions(contact-separation). The generated voltage signal was measured directly with the oscilloscope. Additionally, the rectified voltage was also measured. Voltage data were recorded over a 10-second interval. The short-circuit current was measured using an SR570 Stanford current preamplifier paired with a circuit containing an equivalent resistance. The resistance was selected based on the research of Abid et al. (Abid et al., 2024). According to their study, the optimal load resistance is determined from the

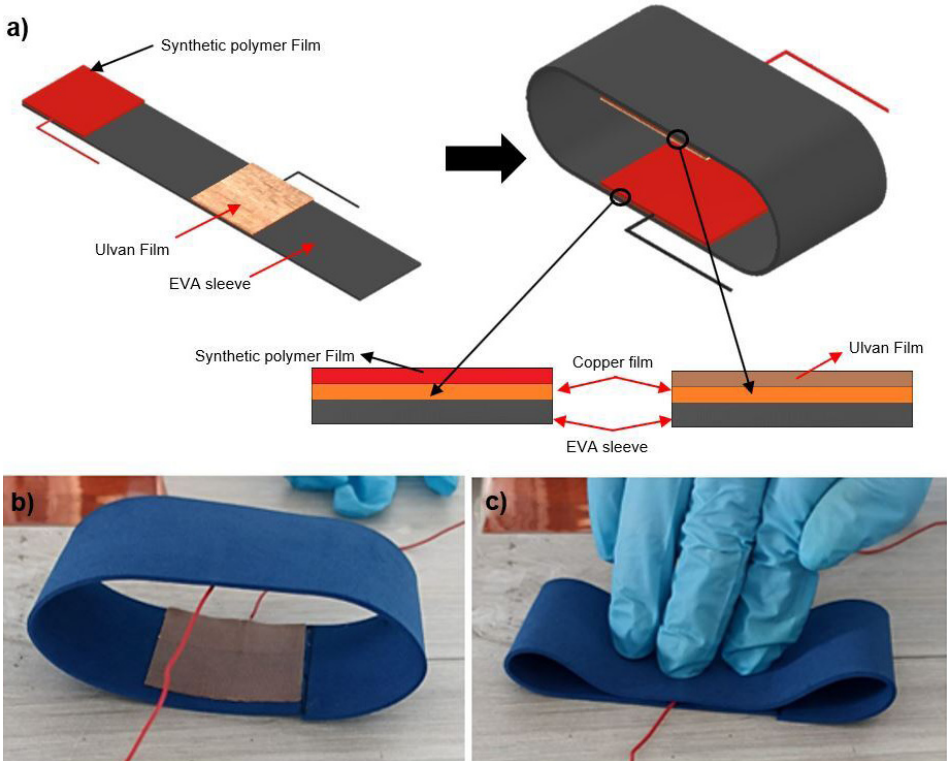

FIGURE 2: (a) Schematic illustration of a TENG fabricated using an EVA sleeve as support. The two polymeric films (ulvan – PTFE / ulvan-Kapton®) are attached to copper films connected by a copper wire. These assemblies are mounted on the EVA sleeves and arranged in opposite positions to form a closed loop. An electrical current is generated when the films are alternately brought into contact (c) and separated (b).

TENG's current curve, which is obtained by testing the device across a range of resistive loads. In order to investigate differences in the maximum value of open circuit voltage and short-circuit current in each TENG (ulvan+PTEF and ulvan+Kaptop®), the results were analyzed using a one-way analysis of variance (ANOVA) followed by Bonferroni post-hoc analysis at a family significance level of 0.05.

2.4.5 Mechanical properties

Mechanical properties were evaluated using a bench top tensile testing machine ESM Mark-10 (New York, USA), equipped with a 10N (±0.5%) load-cell. Films were cut into 1 cm x 7 cm rectangular strips with an average thickness of 72 µm, measured using a micrometer Mitutoyo (Kanagawa, Japan) MDC-25PX, and tested at a grip separation speed of 10 mm/min. 5 repetitions were carried out. Young's modulus, ultimate tensile strength (UTS) and maximum strain were recorded.

3. RESULTS AND DISCUSSION

Ulvan is a sulfated polysaccharide characterized by a backbone composed of α- and β-(1,4)-linked monosaccharides, including rhamnose, xylose, glucuronic acid, and iduronic acid, which form repeating disaccharide units. The primary repeating disaccharides in ulvan are aldo-biuronic acids. These disaccharides are formed from uronic acids (either glucuronic or iduronic acid) that are linked through a (1,4) glycosidic bond to rhamnose units. Disaccharides of the aldo-biuronic type are referred to as ulvanobiuronic acids and are classified into two categories: A and B. The A type, ulvanobiuronic acid 3-sulfate (A3s), consists of β-D-glucuronic acid linked to α-L-rhamnose 3-sulfate via a (1,4) bond, while the B type, ulvanobiuronic acid 3-sulfate (B3s), comprises α-L-iduronic acid linked to α-L-rhamnose 3-sulfate through a (1,4) bond. Additionally, disaccharides of the aldobiose type are present in smaller proportions. These aldobiose-type disaccharides are termed U-type ulvanobiosas. There are two variants of ulvanobiosas: U3s, which consists of β-D-xylose linked to α-L-rhamnose 3-sulfate via a (1,4) bond, and U2's,3s, which consists of β-D-xylose 2-sulfate linked to α-L-rhamnose 3-sulfate through a (1,4) bond (Gonzales et al., 2024; Lahaye & Robic, 2007). Ulvan does not exhibit an ordered conformation. Molecular models indicate that the A3s and B3s disaccharide units adopt stable helix-like conformations when hydrogen bond interactions occur between the oxygen atoms of the sulfate groups on rhamnose and the hydroxyl or carboxylic groups located on the preceding uronic acids (Lahaye & Robic, 2007). Ulvan can be extracted from a variety of green algae species. They have a polysaccharide content in the range of 8.2% to 27.5% (Kidgell et al., 2019). In this study, ulvan was extracted from *Ulva Nematoidea* algae using an alkaline method. The yield of the extracted ulvan was 15.12% based on the dry algae-to-ulvan ratio.

The extracted ulvan was used to prepare films by casting. Pure ulvan films were too rigid and difficult to handle. Glycerol had to be used as a plasticizer. SEM was used to

carry out the morphological characterization of the ulvan films. Figure 3a and 3b show a non-smooth texture. White regions (arrows) were identified by EDX as sodium, calcium and potassium oxide. Figure 3c and 3d show the EDX spectra of points 1 and 2 (Figure 3a), respectively. The EDX spectrum of point 1 has no carbon signal as only sodium and sulfur oxide are present. The EDX spectrum of point 2 shows carbon, oxygen, sodium, and sulfur signals. The SEM and EDX results show that the films prepared had a rough, non-homogeneous morphology with the presence of salt inclusions. The sodium signal can be attributed to the extraction process that uses sodium hydroxide. The sulfur signal confirms that ulvan is a sulfated polysaccharide.

The presence of sulfate groups together with other functional groups were studied with FTIR. In order to assess the effect of glycerol, FTIR tests were carried out on pure ulvan and ulvan-glycerol films (Figure 4). The spectra are similar, and the same peaks are observed. The broad absorption band between 3000-3500 cm^{-1}, with a peak around 3355 cm^{-1}, correspond to the stretching vibration of the O-H group (Peasura et al., 2015). The peaks at 2938 cm^{-1} are characteristic of stretching vibrations of C-H bonds in methyl groups. The peaks observed at 1599 cm^{-1} and 1415 cm^{-1} are related to the asymmetric and symmetric stretching vibration of the carboxyl group (-COO-) (Guidara et al., 2020). The peak found at 1030 cm^{-1} is associated with C-O stretching vibrations in C-O-C bonds found in rhamnose and glucuronic units (Chen et al., 2021). The peak near 1225 cm^{-1} is related to the stretching vibration of the ester-sulfate group (S=O) which is characteristic of sulfated polysaccharides (Gonzales et al., 2024).

Figure 5 shows a representative DSC thermogram of an ulvan-glycerol film. An endothermic stepwise change is observed, consistent with a glass transition process. The glass transition temperature (Tg) was measured at the inflection point of the curve. The glass transition temperature had a value of 135.69°C, and the related specific heat capacity (ΔCp) was 0.625 J/g°C. These values agree with previous reports. Morelli and Chiellini (Morelli & Chiellini, 2010) measured the Tg of ulvan extracted from U. armoricana. They reported a Tg of 132.60°C, associated to a ΔCp of 0.496 a J/g°C. Ghazy et al. (Ghazy et al., 2024) carried out a Density Functional Theory (DFT) simulation and calculated a Tg of 165.88°C for ulvan extracted from Ulva lactuca.

The ulvan-glycerol films were then used as triboelectric surfaces. Two different dielectric materials are usually needed to fabricate a contact-separation mode TENG. In this case we have evaluated the electric performance of an ulvan-PTFE and ulvan-Kapton® TENGs. The triboelectric behavior of the ulvan based active surface was assessed evaluating the interaction between these selected triboelectric surfaces and the ulvan film. Kapton® and PTFE were chosen to determine if ulvan featured a tribopositive or tribonegative behavior. The best electric performance of

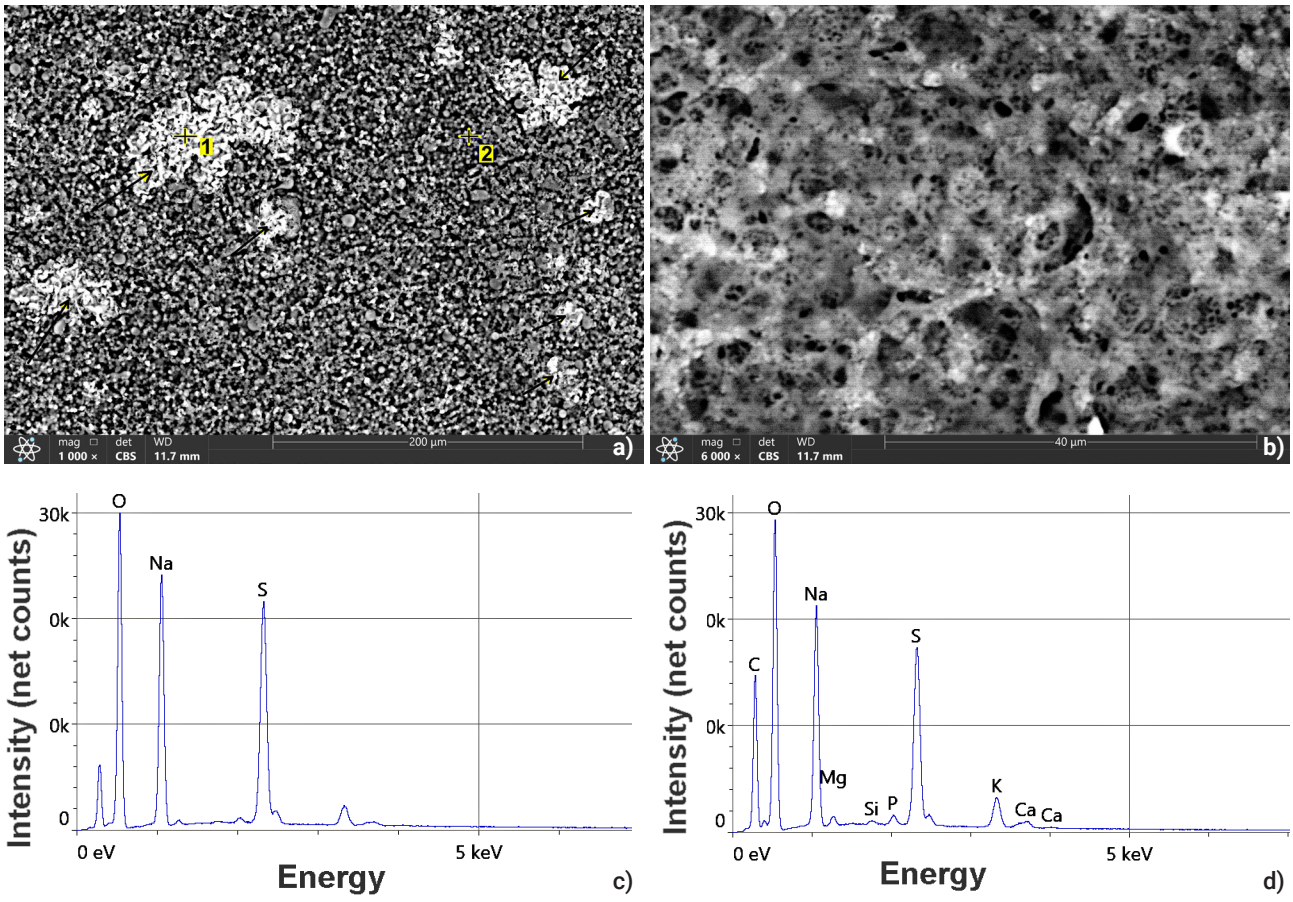

FIGURE 3: SEM micrographs of ulvan-based films at 1000x (a) and 6000x (b). EDX spectra of the point 1 (c) and 2 (d).

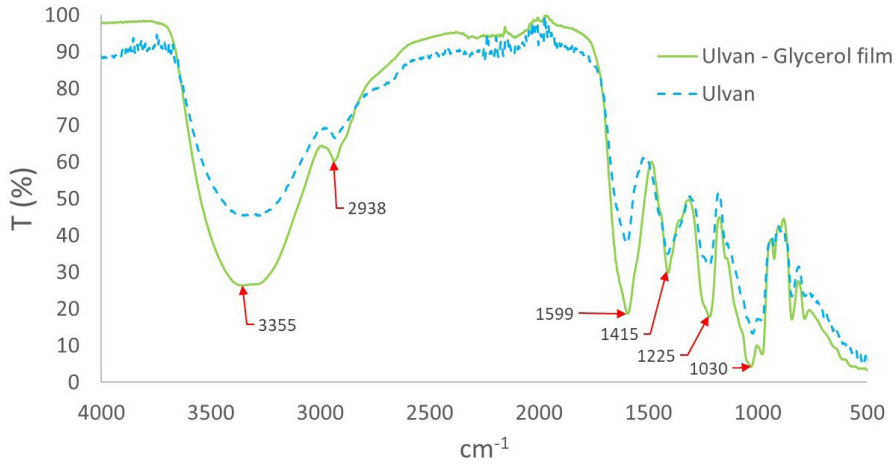

FIGURE 4: Representative FTIR spectra of a pure ulvan and a glycerol-ulvan film.

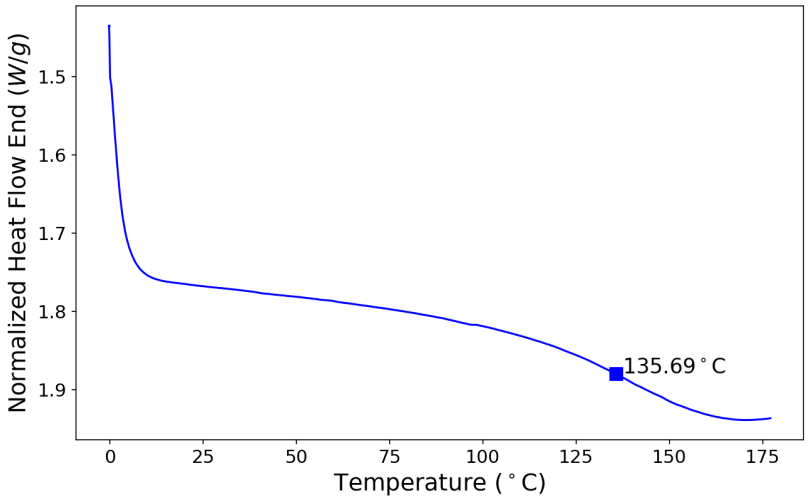

FIGURE 5: Representative DSC thermogram of an ulvan-glycerol film.

a TENG is achieved when a tribopositive material is working with a tribonegative material.

Figure 2 shows how these TENGs work. The triboelectric surfaces are manually pressed together, applying a force of approximately 10 N. Upon contact, free electrons transfer from one material to the other, generating surface charges. When the materials are separated, some electrons return to their original position producing a voltage differential. The voltage signal of the TENGs was analyzed using an oscilloscope. Figure 6 shows representatives signals of ulvan-PTFE and ulvan-Kapton® TENGs. When measuring the open circuit voltage of TENGs, the voltage signal features two peaks (Figure 6a, 6c): one positive and the other negative, corresponding to the contact (positive) and separated (negative) states. This type of mechanical vibration is directly transformed into alternative current (AC). A diode bridge was used to rectify the voltage signal to have a direct current (DC) circuit. The rectified signal (Figure 6b, 6d) shows only positive peaks, with the highest values occurring in the contact state.

The short circuit current was assessed using a preamplifier paired with a field resistance ranging from 3.1 MΩ to 20 MΩ. Figure 7 shows the short circuit current measured across the different resistance used. The maximum short circuit current measured for the ulvan-Kapton® samples was 1.6 μA. The maximum short circuit current measured for the Ulvan-PTFE samples was 5.6 μA. Table 2 lists the maximum open circuit voltage and short circuit current achieved. These results show that the selection of polymeric materials is of utmost importance. Ulvan-Kapton® TENGs featured the lowest voltage value. Ulvan-Kapton® samples featured a maximum voltage of 2.12 V and a short-circuit current of 1.6 μA at 9.3 MΩ and a power density of 0.0281 W/m^2. On the other hand, ulvan-PTFE TENGs showed maximum voltage of 43.60 V, a short-circuit current of 5.6 μA at 9.3 MΩ and a power density of 0.176 W/m^2.

The difference between the fabricated TENGs could be explained in terms of the dielectric properties of the materials. In fact, Kapton® is prone to give away electrons (tribopositive), whereas PTFE is prone to receive electrons (tribonegative). The fact that ulvan-PTFE TENGs feature higher voltages compared to ulvan-Kapton® TENGs, suggests that ulvan is also prone to give electrons (tribopos-

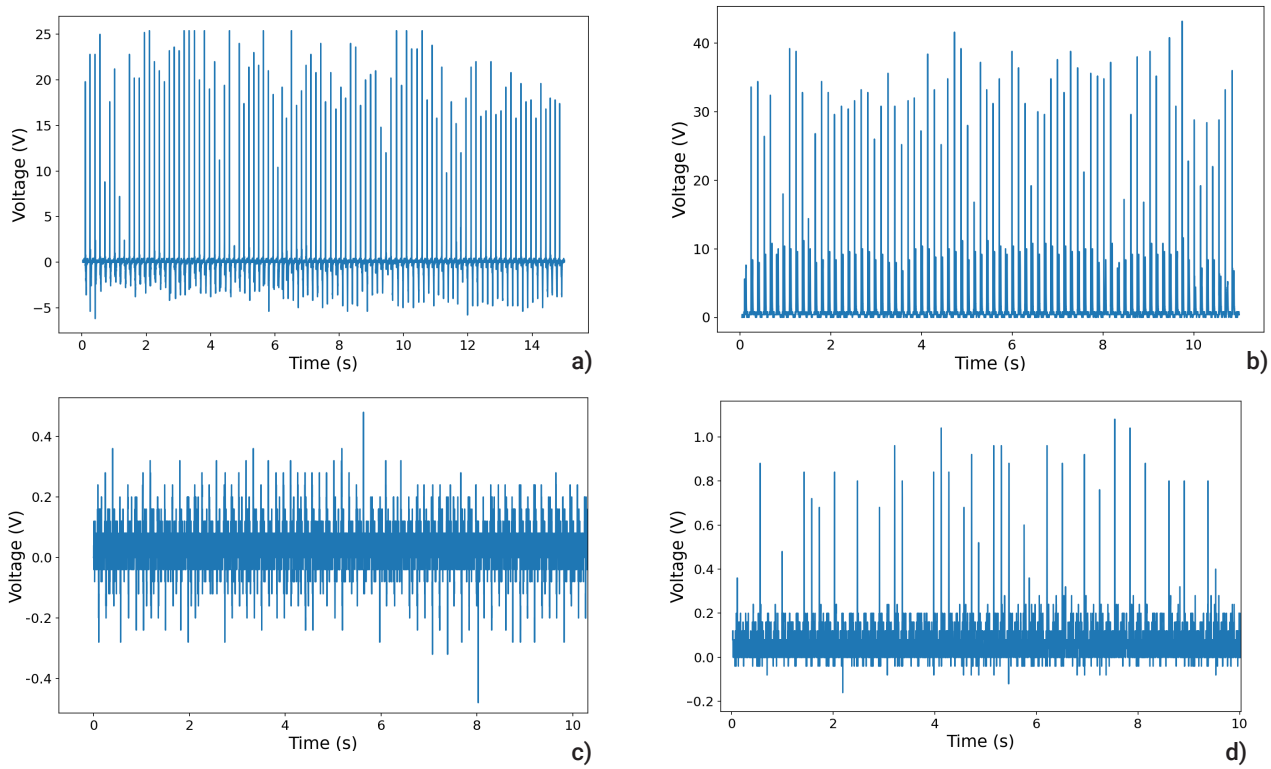

FIGURE 6: Voltage signals from Ulvan-PTFE TENGs in an open circuit mode (a) and a rectified circuit (b). Voltage signals from Ulvan-Kapton® TENGs in an open circuit mode (c) and a rectified circuit (d).

itive). A material that donates electrons works best when paired with a material that accepts electrons to maximize the voltage. For synthetic polymers, there is established knowledge regarding which material combination works better. There are published lists that ranks materials according to their tendency to gain or lose electrons (Khandelwal et al., 2021; Zou et al., 2020a). The currently existing triboelectric series are primarily qualitative, ordered by the polarity of charge production (Zou et al., 2020b). However, this type of information remains scarce for biopolymers.

The voltage and current values that characterize the output performance of both synthetic polymer-based and biopolymer-based TENGs are shown in Table1. Biopolymer-based TENGs exhibit a voltage range of 29 to 262 V and a short-circuit current of 0.15 to 13.7 µA. In contrast, synthetic polymer-based TENGs achieve a voltage output ranging from 208 to 664.5 V and a current output of 14 to 116.8 µA. Ulvan-based TENGs perform similarly to the algae-based TENGs shown in Table 1; however, their performance remains significantly lower than that of synthetic

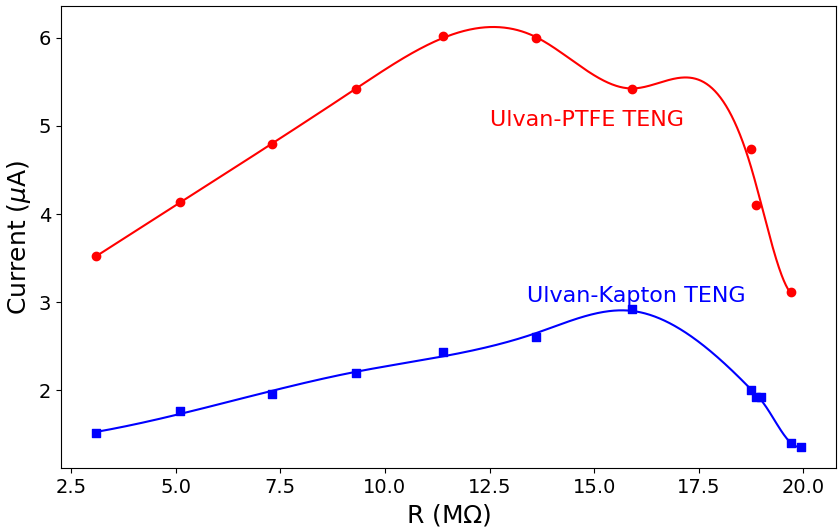

FIGURE 7: Representative curves of the short circuit current values measured across a range of resistive loads (3.1 - 20 MΩ).

TABLE 2: Open circuit voltage and short circuit current of the TENGs prepared in this study (maximum rectified values).

Triboelectric Layers	Open Circuit Voltage (V)	Short-circuit Current (μA) @ 9.3 MΩ	Power Density (W/m²)
Ulvan + PTFE	43.60 ± 1.395 [a]	5.6 ± 0.264 [a]	0.176 ± 0.059 [a]
Ulvan + Kapton	1.92 ± 0.171 [b]	1.60 ± .0643 [b]	0.0281 ± 0.0016 [b]

[a, b] *Values are mean ± SD. Letters indicate significantly different groups (Student-Newman-Keuls)*

polymers. This output disparity can be attributed to the intrinsic properties of each polymer type, one of which is the dielectric constant. Synthetic polymers typically possess a higher dielectric constant and lower dielectric loss compared to biopolymers. The dielectric constant is indicative of a material's capacity to store energy; a higher dielectric constant allows for greater energy storage within the material (Urtecho et al., 2024). While synthetic polymers currently outperform biopolymers in TENG applications, sustainable energy harvesting remains a priority. Innovations in material engineering, including chemical modification, surface modification, and the development of high-performance nanocomposites, could lead to significant enhancements in the performance of biopolymers as triboelectric materials, thereby narrowing the performance gap with synthetic polymers.

Additionally, tensile tests were used to assess the flexibility and resistance of the ulvan films to be used in flexible TENGs. A representative strain-stress curve is observed in Figure 8. The test revealed that ulvan-glycerol films exhibit a max strain of 23.67%, with an ultimate tensile strength of 1.85 MPa. The elastic region was observed up to a deformation level of 1.7% strain with a yield stress of 0.28 MPa and a Young's modulus of 0.247 MPa. These films showed low tensile strength, high deformation, and poor shape recovery, with most of the deformation being plastic. This behavior may be associated with the conformation of the ulvan chains and their interactions with glycerol, which was used as a plasticizer. Plasticizers reduce intermolecular forces along polymer chains, enhancing flexibility and chain mobility (Vieira et al., 2011).

The results showed that it is possible to successfully develop a TENG that can generate energy for low power devices using a material obtained from a green alga. Ulvan-based films behaved as a tribopositive material as was prone to give away electrons. Future work will be focused on improving the ulvan triboelectric behavior by preparing composite and nanocomposite films with high dielectric constant. This strategy has been used with other biopolymers and should be explored for ulvan.

4. FUTURE PERSPECTIVES

TENGs present a promising solution for harvesting mechanical energy, addressing the critical demand for renewable and sustainable energy sources. Biopolymer-based TENGs represent a viable pathway for eco-friendly energy harvesting. Although they encounter challenges related to energy generation efficiency and durability when compared to synthetic polymers, ongoing advancements in materials science and engineering hold the potential to improve the properties of biopolymer-based TENGs. It is essential to explore new strategies aimed at enhancing the characteristics of the biopolymers employed as triboelectric layers to develop high-efficiency biodegradable TENGs. Some effective strategies for improving the triboelectric layers include chemical functionalization, surface engineering, and the development of nanocomposites.

Scaling up production represents a significant challenge for biopolymer-based TENGs. To date, only laboratory prototypes have been developed, and transitioning this technology to large-scale production remains a considerable challenge. This process involves several obsta-

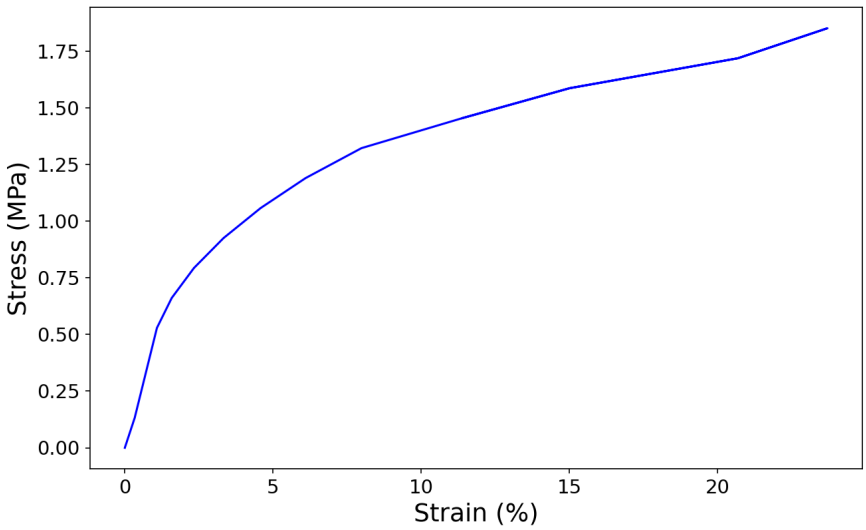

FIGURE 8: Representative Stress-Strain curve of an ulvan film.

cles, including the large-scale extraction of biopolymers, the development of efficient manufacturing techniques for triboelectric surfaces, and the establishment of a scalable production process for biopolymer-based TENGs.

Another significant challenge for future research is evaluating the environmental impact of biopolymer-based TENGs. Utilizing natural materials, such as algae and other biodegradable substances, for biopolymer development presents a sustainable alternative; however, large-scale implementation may lead to unforeseen environmental consequences. A comprehensive life-cycle assessment (LCA) is essential to ascertain the impact of this technology should a large-scale industry emerge from these advancements. Furthermore, the establishment of environmental policies and regulatory frameworks is crucial to ensure the safe, reliable, and scalable integration of these devices as replacements for traditional batteries in Internet of Things (IoT) sensor networks and other applications that require sustainability.

Governments and international organizations could establish funding programs and tax incentives to encourage the development of biopolymer-based energy harvesting devices, such as ulvan-based TENGs. This support can accelerate innovation and facilitate the commercialization of sustainable energy solutions. For instance, the European Commission has proposed actions to unlock the potential of algae in the EU, which could indirectly support ulvan-based technologies. Policies should encourage the incorporation of ulvan-based TENGs into circular economy frameworks. This includes supporting recycling programs and the development of biodegradable electronics to minimize environmental impact. To transition from laboratory research to large-scale production, policies should provide grants and infrastructure support for pilot projects. This assistance can help address challenges related to mass production, cost reduction, and industrial application of ulvan-based TENGs. The ULVA FARM project, funded by the European Maritime and Fisheries Fund, exemplifies how targeted support can lead to successful large-scale cultivation of Ulva species, which could be pivotal for ulvan extraction.

One example of a policy framework related to natural materials is the legislation governing algae. The European Union has established various laws and policies concerning the collection, cultivation, processing, and marketing of algae. This legislation pertains to products intended for human consumption, animal feed, pharmaceuticals, cosmetics, fertilizers, raw materials for the chemical industry, bioremediation, and algae-based fuels (Leinemann & Mabilia, 2019). However, algae possess significant untapped potential for broader applications. Developing new policies and regulatory frameworks could facilitate the expansion of algae-based biopolymers and other sustainable materials, while also promoting the use of natural resources in environmentally friendly technologies.

In summary, although biopolymer-based TENGs encounter several challenges before they can be considered viable alternatives, they possess significant potential. With further research aimed at overcoming these obstacles, this technology could facilitate a transition toward sustainable energy harvesting.

5. CONCLUSIONS

The increasing demand for sustainable energy solutions has driven the exploration of bio-based materials for energy harvesting applications. One significant challenge in this field is the environmental impact of synthetic polymers commonly used in TENGs. This study addressed this issue by investigating ulvan, a biopolymer extracted from *Ulva nematoidea*, as a novel active surface material for TENGs. The research focused on the extraction and processing of ulvan to develop films that were integrated into TENG devices for energy harvesting.

The results demonstrate that ulvan can function as a tribopositive material, particularly when paired with tribonegative materials like PTFE. The ulvan-PTFE TENG exhibited a maximum open-circuit voltage of 43.60 V and a short-circuit current of 5.6 µA, comparable to other biopolymer-based TENGs. In contrast, Ulvan-Kapton® TENG showed a low output compared to the TENGs found in the literature. While the performance remains lower than synthetic polymer-based TENGs, it presents a viable alternative for environmentally friendly energy solutions. Additionally, material characterization techniques, including SEM, FTIR, DSC, and mechanical testing, confirmed the structural integrity, thermal behavior, and flexibility of ulvan films. SEM and FTIR results demonstrated the presence of sulfate groups on ulvan. DSC shown ulvan-based films feature a glass transition temperature of 135.69°C.

The benefits of this research extend beyond energy harvesting applications. Utilizing ulvan from *Ulva nematoidea* provides a sustainable approach to mitigating green tides and eutrophication by promoting the use of these algae. Moreover, the development of ulvan-based TENGs aligns with global sustainability goals. Future research should focus on enhancing the mechanical and electrical properties of ulvan films through chemical modifications, doping, or optimization of the triboelectric layer structure.

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