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ELECTROSPINNING: THE CHALLENGES IN DEVELOPING NANOMETER-SCALE FIBERS AND THEIR APPLICATIONS IN MATERIALS ENGINEERING

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Abstract: Electrospinning is a material processing technique used to produce nanofibers through the application of an electric field and has an interesting history full of developments over time. From its first applications to the most recent advances, electrospinning has been the subject of intense research and study. Over the years, interest in the technique has grown considerably, reflected in the significant increase in the number of scientific publications on the subject. This exponential growth in the volume of research demonstrates the importance and relevance of this technique in science and industry. There is a wide range of options regarding materials that can be electrospun, such as polymers, metals and ceramics, which are just a few examples of the materials that can be transformed into nanofibers through this process. Such diversity offers several possibilities for different applications, through the prior study and adjustment of electrospinning operational parameters that play a fundamental role in determining the characteristics of the nanofibers produced. Factors such as voltage, flow rate and distance between needle and collector can be regulated to control nanofiber properties such as diameter, morphology and distribution. The applications of the produced nanofibers cover a variety of fields. In medicine, tissue engineering, electronic devices, nanofibers serve as a framework for the new design and improvement of many technologies, such as air and water filtration, flexible electronics, piezoelectric and gas detection sensors, photovoltaic devices, materials composites for adsorption, among other fields.

Keywords: materials processing, nanostructures, polymers, nanofibers.

INTRODUCTION

The promising study of structures and materials based on organization at atomic, molecular and supramolecular scales has, in recent decades, provoked great enthusiasm throughout the scientific community, since this technology at nanometric scales enables modernization and improvement in several areas. of society, such as in medicine, physics, materials engineering, computational electronics, in the energy sector, among other diverse applications. The search for the development of nanotechnology is based on materials presenting enhanced specific properties, compared to a macrometric scale.

In this sense, the focus of the scientific community has turned to the manufacture of nanoscale structures for implementation in a range of devices, such as nanofibers, which are polymeric filaments that can vary from 1 to 500 nm in diameter.

Within the scope of the techniques implemented and described in the scientific literature for the production of polymeric fibers, the "Electrospinning" technique stands out, as, in short, it is an efficient, versatile and simple method (CULLINAN et al., 2012) to obtain fibers with micro and nanometer scale dimensions. The advantages of implementing electrospinning are related to the fact that this technique promotes polymeric nanofibers with properties and morphologies intended by the method for the most diverse applications, such as photovoltaic devices, gas sensors, smart fabrics, among others.

Nanofibers produced by electrospinning are easily processed, and present a better molecular organization of the polymer chains, which contributes to the fibers having greater absorption of radiation in different spectra, in addition to promoting less dissipation energy during the transport of charges in the material or even assume morphologies with high porosity, increasing the sensitivity and response of the device. Finally, in order to obtain nanofibers that contain desired properties, it is necessary to control and study several parameters during the application of the technique, such as solution, process and environmental parameters, where it can be highlighted that the solution parameters act in a most influential during the technique and fiber morphology.

HISTORICAL REVIEW

The term "electrospinning", derived from electrostatic spinning, together with the blow spinning technique, has been mentioned in scientific works as one of the most applied techniques in the production of nanomaterials, due to its simplicity, low cost and versatility.

The technique of producing nano/microfibers through the application of electrostatic forces originated in the 19th century, first by Rayleigh in 1897, and then effectively consolidated by Cooley and Morton, when detailing the method of application of high voltages to produce fine wires and describe the performance of the viscosity and volatility of the precursor polymeric solution, as well as the strength of the electric field used in the quality of the wires produced.

However, it was only in the 20th century that electrospinning had its experimental concepts launched, with the first patent filed by Formhals, who patented the process and the experimental apparatus. After that, Formhals obtained a patent for the production of fibers composed of multiple polymers, in which he described the manufacture of textile threads from cellulose acetate dispersed in a solution containing acetone and ethylene glycol monomethyl ether (2-Methoxyethanol or Methyl glycol). Figure 1 shows the technical drawing of the patent generated by Formhals. Soon, numerous patents involving various polymeric solutions were registered, increasing the popularity of the technique in scientific circles, both due to the enthusiasm in studying the electrospinning process and the properties and purposes of the nanofibers produced.

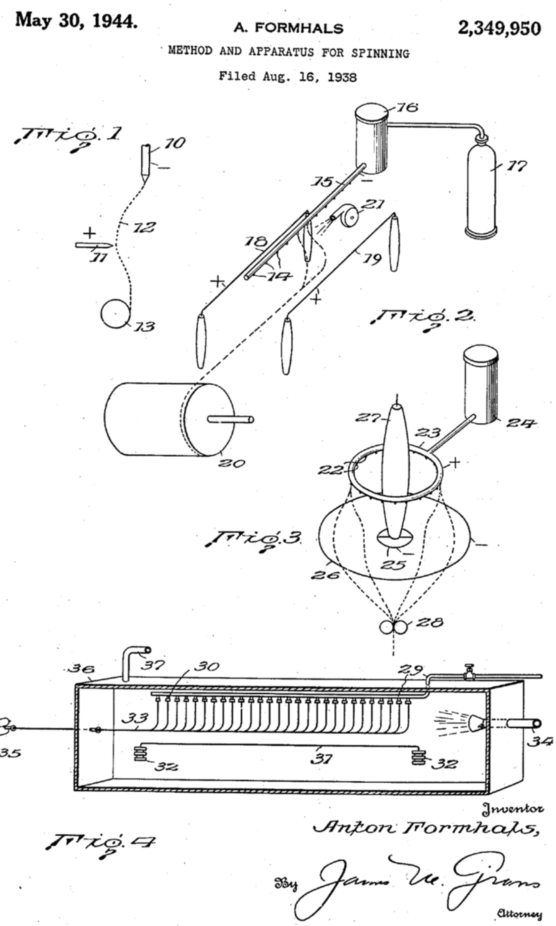

Figure 1 - Technical drawing presented by Formhals for the patent filed in the United States.

Since then, the number of publications has been growing year by year due to the mastery of the technique and thanks to the advent of nanotechnology introduced by Richard Feynman in 1960. Figure 2 shows the increase in the number of publications, based on *Scopus Search,* using the term "electrospinning" for the search.

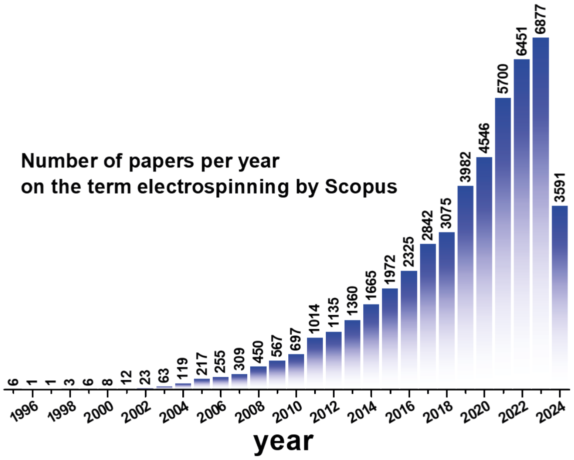

Figure 2 - Number of publications in Scopus involving the term "electrospinning".

MATERIALS USED IN ELECTROSPINNING

A wide variety of materials can be used in electrospinning, including synthetic polymers, natural polymers, and even metal and ceramic composites. The choice of material used in electrospinning directly influences the properties of the resulting fibers. It is important to select a material that is suitable for the desired application, taking into consideration factors such as mechanical strength, flexibility, biocompatibility and other specific properties.

When choosing the material to obtain fibers in electrospinning, its molecular mass and the solvent used must be taken into consideration, as the molecular mass of the polymer directly affects the viscosity of the polymeric solution. Polymers with high molecular mass present more viscous solutions and polymers with low molecular mass present difficulties in producing fibers. The solvent used before electrospinning affects the viscosity of the solution, the evaporation rate during the electrospinning process and the structure of the resulting fibers, different solvents for the same polymer can present different fiber morphologies after electrospinning, in Table 1 the main polymers used in electrospinning, as well as their molecular mass and the main solvents used for each polymer.

Therefore, it is extremely important to select both the polymer and the solvent, taking into consideration their interactions, viscosity and other properties in order to optimize the electrospinning process and obtain fibers with the desired characteristics.

ELECTROSPINNING

The electrospinning technique involves an electro-hydro-dynamic phenomenon that consists of the interaction of surface tension and electrical forces. This technique allows the formation of fibers on a nanometer or micrometer scale using polymeric solutions (solid polymer suitably dissolved in solvent) or molten polymer (HUANG et al., 2003) (polymer heated above its melting point). As a result of its versatility, simplicity and low cost, electrospinning has been widely used in various fields of research.

In the processing of nanofibers, three components are essential, shown in, namely: a high voltage source (Figure 3 a), a capillary tube with a needle (Figure 3 b) and a rotating metallic collector (Figure 3 c). As stated, electrospinning is a process of interaction between electrical forces and surface tension. For this dynamic to work, the solution flows through the needle of the capillary tube, either by gravity or by assistance from an infusion pump.

Immediately after flowing, it is then subjected to an electric field created by a high electrical voltage in the tube. This field induces a charge on the surface of the solution, causing a repulsion of charges, thus generating an electrostatic force opposite to the surface tension (Figure 3 d). As the potential difference increases in intensity, the electric field also increases, as a result of which the surface of the solution at the tip of the capillary tube lengthens, forming a kind of

Polymer	Molecular mass	Solvent	Reference
Poly (vinyl alcohol) (PVA)	130000	Water	(BITTENCOURT et al., 2018; GOIS et al., 2021)
Nylon-66	262.35	Formic acid	(BAIRAGI et al., 2022; KIM et al., 2020)
Nylon-6	13000 - 15000	HFIP, acetic acid, formic acid	(BARAKAT et al., 2009; LALA; THAVASI; RAMAKRISHNA, 2009)
Nylon-4.6	40000	Formic acid	(HUANG et al., 2006; MORI et al., 2021; WANG; JHENG; CHIU, 2013)
Polyethylene terephthalate (PET)	8359	Trifluoroacetic acid, DCM	(ABBAS et al., 2018)
Polystyrene (PS)	192000 - 280000	THF, chloroform, DMF	(AVOSSA et al., 2018; CASPER et al., 2004; UYAR; BESENBACHER, 2008)
Poly (vinylidene fluoride) (PVDF)	275000 - 534000	DMF, DMSO, ACE, THF	(BRAUNGER et al., 2022; CHAMANKAR et al., 2020; GARAIN et al., 2016; YIN et al., 2022)
Poly (methyl methacrylate) (PMMA)	120000 - 500000	Ethyl acetate, Acetone, THF, DMF, DCM, chloroform	(DONG; JONES, 2006; LI et al., 2014; SLEPCHUK; KULISH; SARIBEKOV, 2013)
Polyacrylonitrile (PAN)	150000	DMAc, DMF	(CHOI et al., 2005; KAHRAMAN et al., 2018)
Polycaprolactone (PCL)	67210 - 80000	DCM, DMF	(ČÍKOVÁ et al., 2018; LEE; MOON; JEONG, 2009; NERGİS; ARAL YILMAZ; PALA AVCI, 2023)
poly (vinyl pyrrolidone) (PVP)	360000 - 1300 000	DMF, distilled water/ ethanol	(DING et al., 2011; NERGİS; ARAL YILMAZ; PALA AVCI, 2023; ZHANG et al., 2016)4-ethylenedioxythiophene
Poly (ethylene oxide) (PEO)	300000 - 400000	Water, ethanol	(CHRONAKIS; GRAPENSON; JAKOB, 2006; SONG et al., 2018; YALCINKAYA; YALCINKAYA; JIRSAK, 2015; ZHAO; YALCIN; CAKMAK, 2015)
Polyimide (PI)		DMSO, DMF, NMP, ethanol, chloroform	(LASPRILLA-BOTERO; ÁLVAREZ-LÁINEZ; LAGARON, 2018; XUE et al., 2019b)
Polydiacetylene (PDA)		Ethanol, chloroform	(CHAE et al., 2007; DAVIS et al., 2014)
Thermoplastic polyurethane (TPU)		DMF, THF, ethyl acetate	(ÇAY; AKÇAKOCAKUMBASAR; AKDUMAN, 2015; LI et al., 2020; SHAKER et al., 2023)
Polyvinyl chloride (PVC)	110000	THF, DMF, DMA	(MEDEIROS et al., 2008; PHAM et al., 2021)
Lactic polyacid (PLA)	$2\text{-}4 \times 10^{5}$	Toluene, DMF TFE, HFP	(MEDEIROS et al., 2008)
Poly (p-phenylene sulfide) (PPS)		Insoluble	(YU et al., 2020)

Table 1: Main polymers used in electrospinning, their molecular mass and the main solvents for each polymer.

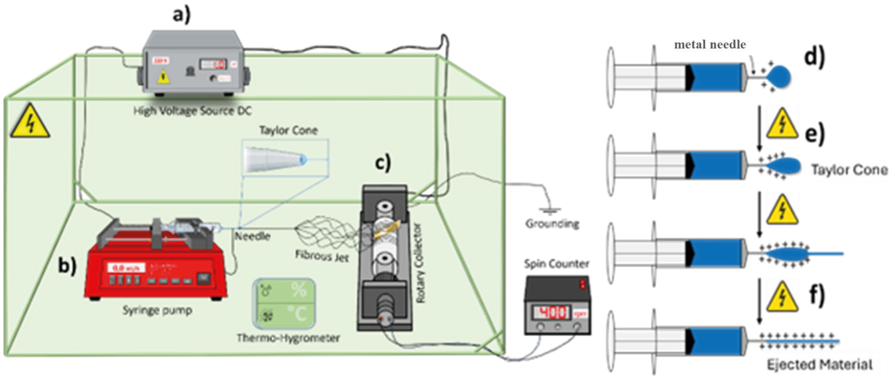

Figure 3: Electrospinning system composed of: a) High voltage source; b) infusion pump with capillary tube and needle; c) rotating collector; d) repulsion forces acting on the polymeric fluid; e) formation of the Taylor cone; f) ejection of the material to be electrospun and formation of nanofibers.

cone, called a Taylor cone (Figure 3 e). When a critical value is reached, the opposing force, the surface tension exceeds the surface tension itself (Figure 3 f), promoting a charged jet that is attracted to the collector and thus forming the fibers. As the jet is expelled into the air, the solvent must be slightly evaporated before reaching the collector.

Different types of polymers have been successfully electrospun to obtain nanofibers, using a potential difference of 5 to 45 kV, in which values below 5 kV cannot break the surface tension of the solution and for values above 30 kV, air ionization occurs, generating ozone gas (O_{3}). The fibers formed by this technique reach diameters of the order of nanometers, resulting in an increased surface-to-volume ratio when compared to continuous films, such as those formed by casting.

PARAMETERS THAT INFLUENCE THE ELECTROSPINNING PROCESS

The electrospinning process, despite using a simple system, suffers several external influences, therefore controlling the parameters that influence the production of nanofibers is always a great challenge, as they are not always independent variables, that is, the change of a single parameter it may affect other parameters, modifying the properties of the nanofibers formed. Below we will show the parameters to be observed for the electrospinning process, namely: i) solution parameters (molecular mass, concentration/viscosity and conductivity); ii) process parameters (applied voltage, solution flow rate and working distance) and iii) environmental parameters (temperature and relative humidity).

SOLUTION PARAMETERS

It is necessary that the polymer solution that will be electrospun follows some parameters, such as: Concentration (solute/solvent), electrical conductivity and surface tension. These will directly influence the morphology and geometry of the nanofibers. Such parameters are related to the physical-chemical properties of polymers, solvents and polymer-solvent interactions.

If the concentration of the solution is below ideal, the effect of electrostatic scattering of the polymer solution, also known as *electrospray, occurs.* But if the concentration is much higher than ideal, the solution inside the needle may become clogged or very high electrical voltages may be required to form the jet and electrospun fibers.

As mentioned previously, the choice of solvent affects several aspects in the production of electrospun fibers. Solvents must, in addition to dissolving the solute, direct the polymer molecules to the collector, so that evaporation occurs along the way. Knowing characteristics such as volatility, boiling point, among others, is of great importance. In a study carried out by Sahoo *et al.*, it was observed that an increase in polymer concentration from 8% to 12% resulted in an increase of 50 nm in fiber diameter, due to the viscosity of the polymer solution.

Another important point within the materials that will be electrospun is the electrical conductivity of the polymeric solution, since it is advantageous to have good conductivity to facilitate the stretching of the fibrous jet, as the Coulomb repulsion present in this interaction will be directly linked to the amount of electrical potential, this being dependent on the amount of electrical charges found in the solution inside the syringe.

The increase in conductivity can be due to the type of solvent used or the addition of salts, ionic surfactants, carbonaceous additives, etc.

However, if this handling occurs too much, there is a risk of excessively increasing the concentration of the solution, which could lead to the needle clogging. This way, the addition of additives to the solution changes both the conductivity and the surface tension of the solution.

This surface tension of the polymeric solution can be defined as the force external to a plane that every material has on its surface per unit of length, that is, the choice of polymer and its respective solvents can change the properties of the solution and thus can also change the surface tension of the material. Increasing or decreasing surface tension requires higher or lower electric fields, respectively.

PROCESSING PARAMETERS

Adjustments of the electrospinning process parameters are essential to obtain nanofibers with the desired morphologies and diameters. One of the main parameters is the voltage applied to the polymeric solution, in addition to other parameters, such as: the distance between the needle and the collector (working distance), the flow rate, the electrospun fiber deposition collectors, as well as, environmental conditions during the execution of electrospinning.

The value of the applied electrical voltage varies from solution to solution, as the formation of fibers on nanometric scales is attributed to the stretching of the polymer chain due to the repulsion of electrical charges, forming a fibrous jet directed to the grounded pole. Each polymer has a critical tension value, which is a threshold that will allow the formation of the Taylor cone and consequently the fibrous jets. However, it is possible to observe two possible scenarios if electrospinning occurs below or above this critical value.

Below this value there will only be the formation of a droplet suspended at the tip of the needle and consequently the beginning of a vertical drip. But if the applied voltage is above the critical value, defects will form in the deposited fibers, due to the high stretching speed of the fibrous jet, causing the Taylor cone to form inside the needle, thus evaporating the solvent very quickly.

Such defects in the deposited fibers will have the appearance of grains, as if they were "lumps", or more technically known as *beads.* Even though it is considered a defect, *beads* also have possible usefulness in different types of applications, whether in drug delivery or even in energy devices.

The working distance between the needle and the collector must have a minimum value to ensure total evaporation of the solvent, and a maximum value so that the electric field is effective in stabilizing the Taylor cone and, consequently, in the formation of fibers. The effect that this distance can cause is directly related to the type of morphology that the fibers can present.

Two other important parameters in electrospinning consist of the flow rate of the polymer solution and the types of collectors where the fibers will be deposited. The flow rate is the rate of material per time that is being released at the tip of the needle, either by means of an infusion pump or simply by the action of gravity, with the latter deposition in the vertical direction. The flow directly affects the morphology of the fibers, influencing both their diameter, shape or even their porosity.

Collectors can directly influence the morphology of the deposited fibers, with the main influencing characteristics being their shape, the material in which the collector is made, the way in which it was grounded and its mode of movement, whether static or not.

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ENVIRONMENTAL PARAMETERS

The manufacturing of electrospun polymer fibers can be influenced by environmental conditions, such as relative humidity, temperature and vacuum conditions.

Air humidity plays an important role in determining the surface and internal morphology of electrospun fibers. In the process of preparing the polymeric solution different solvents are used, depending on the polymer used, and when the solvents are highly volatile, during the electrospinning process they evaporate quickly, absorbing a large amount of heat and thus cooling the surface of the fibers, the which causes them to condense and attract water droplets to the surface of the fibers, leading to solution instability, followed by the occurrence of thermally induced phase separation (TIPS).

When electrospinning is performed at high relative humidity, the solvent evaporates along with the water and diffuses into jets of the polymer, resulting in vapor-induced phase separation (VIPS), forming a polymer-rich phase and a polymer-poor phase. When the solvent is evaporated, the polymer-poor phase turns into voids and the rich phase forms a solid material.

Zaarour *et. all.* (ZAAROUR et al., 2018) presented a method for obtaining macroporous, rough, electrospun PVDF nanofibers with grooves and internal pores. Fibers with a smooth surface and solid interior were obtained at a relative humidity of 5% due to the absence of phase separation. Macroporous fibers with internal pores at relative humidity of 45% and 65% due to the coexistence of TIPS and VIPS.

The mechanism of fiber formation in the presence of high humidity is demonstrated in, where in the 1st step there is evaporation of the solvent and condensation of water droplets on the fiber surface, the water droplets penetrate the fiber in the 2nd step and at the evaporate, the fibers solidify forming pores in the 3rd step, where part of the droplets that penetrated the fibers can form internal pores, therefore electrospinning in high humidity can produce fibers with different surfaces, which we can find porous, rough fibers and the presence grooves.

Figure 4 - Schematic of the electrospinning process in high humidity. Adapted from (ZAAROUR et al., 2018).

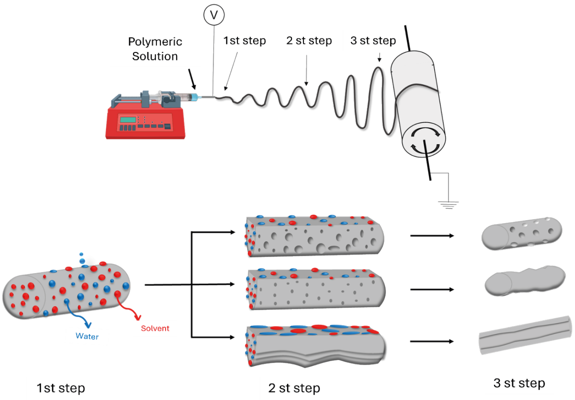

Figure 4 -Schematic of the electrospinning process in high humidity. Adapted from (ZAAROUR et al., 2018).

Temperature also plays an important role in electrospinning, as it affects the viscosity of the polymer solution, where at higher temperatures it can cause a reduction in viscosity, facilitating the flow of the solution through the nozzle. However, it is important to consider that at very high temperatures rapid evaporation of the solvent can occur, resulting in thinner and more unstable fibers. On the other hand, at lower temperatures it can cause an increase in the viscosity of the solution, making electrospinning difficult.

Rangkupan and Reneker (RANGKUPAN; RENEKER, 2003) produced electrospun fibers in a vacuum chamber simulating the space environment, in this context simulating a space environment offers the advantage of allowing a higher electric field to be exerted, since the vacuum has an electrical breakdown higher than the air. The diameter of the fibers was strongly affected by the high applied voltage and radiated heat, 200 kV/m and 350 °C, with diameters varying between 300 nm and 30 μm.

Hur *et. all.* (HUR; KIM, 2006) carried out a study on the influence of vacuum on the electrospinning of poly (ε-caprolactone), in this work it was observed that the fibers obtained in vacuum have better mechanical properties than those produced under atmospheric pressure, the modulus of Young for fibers produced under vacuum is 2.3 MPa and under atmospheric pressure it is 1.7 Mpa.

APPLICATIONS

PIEZOELECTRIC NANOGENERATORS - PENGS/ TRIBOELECTRICS - TENGS

Faced with the unprecedented potential of technologies based on nanogenerators (NGs), several approaches have been academically adopted by researchers, since their respective creations, resulting in an emerging number of scientific works, in general, aiming to obtain strategies capable of optimizing and improving production energetics of PENGs and TENGs.

Among the broad possibilities for improving these devices, the scientific community has focused its efforts mainly on I) Understanding the fundamental theoretical mechanisms responsible for the piezoelectric and triboelectric effects; II) Accessible selection or development of natural and synthetically structured materials (via physical or chemical modifications), respectively, with promising physicochemical properties, such as piezoelectric and triboelectric, objectively to compose the constituent layers of these devices; III) Advantageous and economical processability of layers and devices in general; IV) Improvement of the structural design project for the engineering of PENGs and TENGs and operational modes; V) Exploration of the plurality of multifunctional and scalable applications of these devices.

In the case of PENGs, the piezoelectricity of materials (inorganic, organic, composite and bioinspired) is one of the critical factors that directly influence the electrical response of these devices, thus micro- or nanoscale structuring of materials and manufacturing processes have enabled satisfactory physical properties and adjustable features such as high piezoelectric coefficient, flexibility, good durability, ease in converting minimum mechanical stresses into electricity, as well as improvements in the electromechanical coupling factor and the ability to stretch or integrate into applications. Similarly, from the current status of TENGs, a wide number of strategies have been adopted to improve their electrical production, among these notable scientific efforts, the search for increasing the surface charge density of triboelectric layers stands out, as this is a crucial factor and directly proportional to electrical generation.

However, most strategies for improving PENGs and TENGs require special materials, complicated device structures, as well as manufacturing processes and complex physicochemical modifications, which include high-cost equipment and tools that are difficult to access and maneuver, making them those responsible for the various difficulties in the projection of structural micro/nanopatterns, and consequently, the limitation of these technologies for a wide range of commercial applications.

Electrospinning is a promising technique to produce large-scale tunable micro/ nanostructures, with great potential for use in flexible electronics and NGs. Electrospun nanofibrillar networks exhibit self-polarization, especially in electroactive polymers such as PVDF, due to the high electric field and mechanical stretching during the technique, improving the piezoelectric property, crucial for the electrical generation of PENGs. The technique is also capable of improving the mechanical flexibility of triboelectric materials and providing nanofibers with high surface roughness, which results in a greater effective contact area and surface charge density in the TENGs, optimizing their electrical output. A model of a generic nanogenerator obtained from the electrospinning of the electroactive layer is shown in.

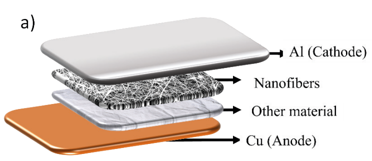

Figure 5: a) Perspective view of a nanogenerator composed of electrospun nanofibers. b) Profile perspective of the device layer by layer.

PHOTOVOLTAICS

Organic Photovoltaic Devices (OPVs) can act as a promising solution for sustainable energy generation. They are semiconductor diodes composed of nanoscale moldable organic materials, which play the roles of both electron donors and acceptors, allowing the conversion of photons into electrical current. They arouse great interest due to their high efficiency, low cost and good stability, enabling the reduction of pollutant emissions and contributing to environmental preservation through sustainable development.

A wide variety of methods for manufacturing organic solar cells (*Organic Solar Cells* - OSCs) have already been researched and adopted with the central aim of reducing costs, increasing flexibility, improving efficiency, preserving the device's durability and being easily reproducible., in addition to being able to morphologically modify and control the characteristics, on a nanometric scale, of the structural components of OSCs (electrodes and active layer), avoiding unfavorable processes for energy conversion, such as the phenomenon of charge recombination.

In this context, the production of OPVs using nanofibers presents a high charge collection efficiency, thanks to the creation of a direct and continuous path for the extraction of electrons within the structure of the solar cell, mitigating the recombination of photogenerated electrons and holes. As nanofibers are three-dimensional and have a high surface area in relation to their volume, they promote improvements in the efficiency of the device, in addition to allowing the nanostructuring of materials in their active layer, or in other layers such as flexible and transparent electrodes that help with the infiltration of sunlight and the versatility of the device, as shown in Figure 6.

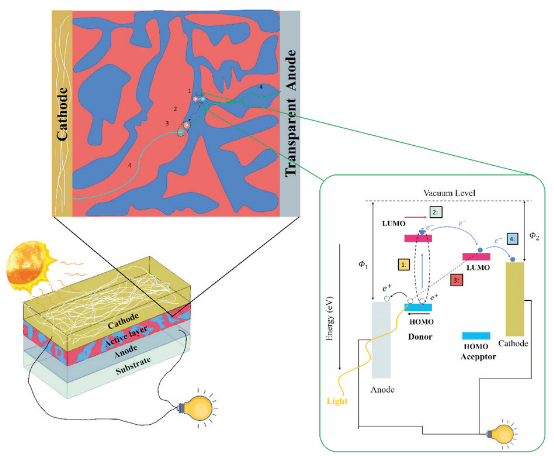

Figure 6 - Composition of an OSC with electrospun layers and the photovoltaic generation mechanism.

SENSORS

The increasing demand for the production and development of sensors capable of quickly detecting different types of gases and devices with smaller sizes has driven research in this area. The direct relationship between polluting gases and mortality, as well as the development of serious diseases, makes the improvement of these devices an emergency need. Gas sensors have diverse applications

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in different sectors of society, some of these sectors are illustrated in.

Figure 7: Gas sensors applied to some sectors.

Every day, countless gases are released into the atmosphere with different levels of toxicity, harming humans, animals and vegetation. In this context, nanofibers have been studied and present potential for innovation. Part of this potential is due to the fact that the fibers are on a nanometric scale, in addition to the creation of composite materials that enable the improvement of gas sensors.

Many nanofiber-based gas detection devices are created to monitor a variety of gases. These include carbon monoxide (CO), a toxic and lethal gas depending on the concentration; hydrogen (H_2), which is not harmful to health, but is highly flammable; carbon dioxide (CO_2), a polluting gas related to global warming that, in high concentrations, can harm life; hydrogen sulfide (H_2S), a toxic gas used in several industries; ammonia (NH_3), a toxic gas that can cause serious health problems; nitrogen dioxide (NO_2), a highly toxic and polluting gas that can be lethal; oxygen (O_2), essential for life, making it necessary to monitor it in many environments; and volatile organic compounds (VOCs), whose exposure can result in different types of reactions, from mild in short-term exposure to severe in prolonged exposure.

One of the main benefits of electrospun nanofibers is their ability to interact more effectively with gas molecules due to their large surface area. This results in faster and more accurate sensor response even for minute gas concentrations, making them ideal for environmental and safety monitoring applications.

Furthermore, electrospun nanofibers provide greater selectivity in gas detection, allowing us to distinguish between different types of chemical substances with greater precision. This is essential in environments where the correct identification of gases present is crucial for making appropriate decisions.

Another important benefit is its durability and stability, ensuring consistent performance over time, even in adverse conditions. This reduces the need for frequent maintenance and increases the reliability of gas detection systems in various applications. The use of electrospun nanofibers in gas sensors offers a unique combination of sensitivity, selectivity, and durability, making them an indispensable tool for safety and environmental monitoring in a variety of industrial and commercial sectors.

ADSORPTION DEVICES

Contamination by pesticides, pharmaceuticals, dyes and especially metals are one of the main sources of pollution in industrial wastewater, coming from production processes such as machine manufacturing, mineral casting, electroplating, and many, many others. Its high toxicity, low biodegradation and easy bioaccumulation affect organisms even at low concentrations, and can enter the human food chain and cause serious diseases, posing significant threats to health.

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The effective removal of these toxic metals from water has been a central topic in the environmental area. Since then, adsorption has recently become one of the most popular methods for separating and removing pollutants. The technique is of great importance in the separation and purification of substances that, for example, in certain quantities resist biological degradation methods or are not effectively removed by other physicochemical processes.

Adsorption is a physical-chemical mass transfer phenomenon, it is widely recognized as a low-cost and operationally simple technique, characterized by its selectivity. This method stands out as a promising approach for treating persistent pollutants. It consists of the accumulation of substances at specific interfaces, where the component in a gaseous or liquid phase (adsorbent) is transferred to the surface of a solid phase (adsorbent), forming adsorbates. And finally, the desorption process, in turn, represents the removal of adsorbed substances from the surface of the adsorbent.

The effectiveness of adsorption is influenced by the surface area of the adsorbent per unit of solid mass, and porous adsorbents are commonly used. This phenomenon can occur at two distinct interfaces: solution/solid and gas/solid, and can be classified as chemical adsorption (chemisorption) or physical adsorption (physisorption), depending on the forces involved and the associated energy. adsorption processes are beyond the scope of this work.

In this context, the use of membranes made with electrospun micro and nanostructures, more specifically PVDF, becomes a viable alternative for application in adsorption, as their use significantly improves the ability to remove pollutants, due to their ease of incorporating materials into nanometric scale, in addition to offering a high surface area. Furthermore, its fibrous structure, which is often porous, allows rapid diffusion of contaminants to adsorption sites, resulting in reduced contact times and increased removal efficiency.

The PVDF nanoscale blankets can interact with metal ions through different adsorption mechanisms, such as ion exchange, complexation or chemical bonding, exchanging in different media, this allows the effective removal of metals such as pharmaceuticals, pesticides, among others, by example of contaminated water. Furthermore, PVDF nanofiber multilayers have also shown to be effective in removing pollutants in different fluids due to electrostatic molecular interactions, largely due to their ability to interact with a wide range of inorganic and organic molecules and different functional groups in their structure. In addition, it is clear to be matrices for magnetic micro- and nanoparticles and other additives from a physical mixture in their synthesis, which will interact during the adsorption process. This is especially important given the growing concern about the presence of these contaminants in water resources and their potential toxicity for aquatic organisms and humans, among others.

However, it is important to highlight that, although PVDF nanofibers present great potential for contaminant removal applications, challenges and continuous research are being carried out to optimize these materials and processes, mobilizing a considerable amount of publications and also aiming to remove more efficient and economical removal of environmental contaminants.

CONCLUSION

This work highlighted the importance of electrospun nanofibers, which have been consolidated mainly as a simple and versatile technique, efficient in producing fibers on both the micrometric and nanometric scales. These nanofibers have shown remarkable properties that involve a large surface area, the possibility of carrying charges, among others. The analysis of the literature presented here strongly suggests that nanofibers are one of the most adaptable materials in academia, as it allows the development of different types of fiber, since different polymers can be used and the creation of composites.

Given the diverse possibilities for manufacturing electrospun nanofibers, they can be used in various applications, such as smart materials, piezoelectrics, in solar cells, in the area of health and the environment, among others, depending only on their obtaining conditions and the additive used. It is also clear that, given the countless applications that electrospun nanofibers can have, examining all influencing parameters in the electrospinning process is essential. In summary, nanofibers play a crucial role in current scientific advances involving the production of flexible materials and devices, enabling significant opportunities for innovation.

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