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REVIEW ARTICLE

Electrospinning of Nanofibers and Their Applications in Herbal Industry-A Review

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ABSTRACT

Nanofiber innovation is an energizing territory pulling in the consideration of numerous analysts as a potential answer for the present difficulties in the biomedical field, for example, wound care, organ repair. Nanofibers are alluring in this field for a few reasons. In the first place, surface area on nanofibers is significantly higher contrasted with mass materials, which takes into account upgraded bond of cells. Second, nanofibers can be created into complex full scale structures. The capacity to create nanofibers permits reestablished endeavors in creating progressive structures that copy those in creatures and human. Over that, an extensive variety of polymers can be created into nanofibers to suit distinctive applications. Nanofibers are most normally created through electrospinning, which is equipped for being scaled-up for large scale manufacturing. This audit investigated two mainstream zones of biomedical nanofiber advancement: tissue regeneration and drug delivery.

KEYWORDS

Electrospinning, Nanofibers, Polymers, Feed rate, Solution conductivity, Wound dressing, Drug delivery

INTRODUCTION

Technological advances over the last few decades have resulted in the realization of several competing processes for fabricating nanometer-size objects electrospinning has emerged as a popular nanotechnology since the late 1990 s owing to the ease of fabricating nanofibers from a wide selection of materials. [1] Electrospinning has gained much attention in the last decade not only due to its versatility in spinning a wide variety of polymeric fibers but also due to its consistency in producing fibers in the submicron range.[2] It is possible to produce nanofibers with diameters ranging between a few nanometers to a few hundrednanometer.[3]

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The process of spinning fibers with the help of electrostatic forces is known as electrospinning. In electrospinning, the spinning of fibers is achieved primarily by the tensile forces created in the axial direction of the flow of the polymer by the induced charges in the presence of an electric field. Fibers with diameters below 100 nm are generally classified as nanofibers. These fibers, with smaller pores and higher surface area than regular fibers, have enormous applications in nanocatalysis, tissue scaffolds, protective clothing, filtration, and optical electronics.[3]

The electrospinning process uses a high voltage electric field to produce electrically charged jets from polymer solution or melts, which on drying by means of evaporation of the solvent produce nanofibers.[2]

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Electrospinning is a versatile and efficient method to produce continuous nanofibers from submicron diameters down to nanometer diameters by using a high potential electric field. It is possible to produce nanofibers with diameters ranging between a few nanometers to a few hundred nanometer.[3]

In addition, electrospun Nanofibers with various morphologies and structures such as core-shell, hollow, yarn, and porous structures can be obtained by modifying process parameters including applied voltage, feed rate, collector type, tip-to-collector distance, nozzle design, and calcination treatment.[4]

Electrospinning shares characteristics of both electrospraying and conventional solution dry spinning of fibers. The process does not require the use of coagulation chemistry or high temperatures to produce solid threads from solution. This makes the process particularly suited to the production of fibers using large and complex molecules.[5]

A number of processing techniques such as drawing, template synthesis, phase separation, self-assemble, electrospinning, etc. have been used to prepare polymer nanofibers in recent years.[6]

History

In 1934, Formhals patented his first invention relating to the process and the apparatus for producing artificial filaments using electric charges.[6]

Though the method of producing artificial threads using an electric field had been experimented with for a long time, it had not gained importance until Formhals's invention due to some technical difficulties in earlier spinning methods, such as fiber drying and collection.[3]

The first spinning method adopted by Formhals had some technical disadvantages. It was difficult to completely dry the fibers after spinning due to the short distance between the spinning and collection zones, which resulted in a less aggregated web structure.[3]

In 1960's, jet forming process were studied fundamentally by Taylor. He studied the cone shape of the polymer droplet at the needle tip when an electric field was applied, leading to the name as 'Taylor cone'.[7]

First observed by Raleigh in 1897. Origins by first patents by Cooley and Morton. Zeleny studied further on electrospraying in 1914. Formhals patented the process in 1934. Between 1934 and 1944, patents were published by Formhals. About 50 patents were taken on electrospinning between 1944 and 2004.

Taylor laid the groundwork by his work on electrically driven jets Vonnegut and Neubauer produced 0.1 mm diameter streams from highly electrified uniform droplets in 1952.In 1966, Simons patented an apparatus for production of nonwovens with different patterns using electrical spinning. Baumgarten built an apparatus to electrospin acrylic fibers having diameter range between 0.05-1.1 micron in 1971.

Electrospinning process gained more popularity in 1980's due to interest in nanotechnology and increase in use of ultrafine fibers and fibers in submicron and nanometer scale. In 1981, Larrondo and Manley investigated electrospinning process using melting polymer. Reneker and Chun proved the probability of electrospinning using different kind of polymer solution

A high number of research activity is going on in this area, especially after the relevance of electrospun nanofibers in applications including tissue engineering, energy storage, composite materials, etc. was shown, Studies and work is also focused on upscaling and on extending the application areas of electrospun fibers and fibrous materials. Companies such as Donaldson Company and Freudenberg are using electrospinning process in their air filtration products since the last two decades.[7]

Electrospinning Theory and Process

Electrospinning technique can be considered as a variant of the electrostatic spraying (electrospraying) process, as both techniques use high voltage to induce the formation of liquid jets. Small droplets or particles are formed as a result of the break-up of the electrified jet in electrospraying, whereas a solid fiber is formed as the electrified jet is stretched in electrospinning. Electrospinning makes use of electrostatic forces to stretch the solution or melt as it solidifies. The fiber mat is collected as a distribution of continuous nanofibers.

A typical electrospinning set-up, as shown in Figure, consists of mainly three components:

1) A capillary tube with pipette or needle of small diameter

2) A high voltage supplier

3) A metal collecting screen.[7]

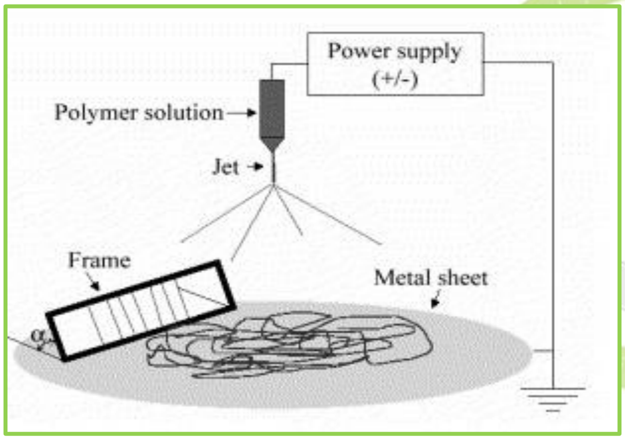

Figure 1: Electrospinning set up

Polymer solution or the melt that has to be spun is forced through a syringe pump to form a pendant drop of the polymer at the tip of the capillary. High voltage potential is applied to the polymer solution inside the syringe through an immersed electrode, thereby inducing free charges into the polymer solution. These charged ions move in response to the applied electric field towards the electrode of opposite polarity, thereby transferring tensile forces to the polymer liquid.[5]

At the tip of the capillary, the pendant hemispherical polymer drop takes a cone like projection in the presence of an electric field. And, when the applied potential reaches a critical value required to overcome the surface tension of the liquid, a jet of liquid is ejected from the cone tip. After the initiation from the cone, the jet undergoes a chaotic motion or bending instability and is field directed towards the oppositively charged collector, which collects the charged fibers. As the jet travels through the atmosphere, the solvent evaporates, leaving behind a dry fiber on the collecting device. For low viscosity solutions, the jet breaks up into droplets, while for high viscosity solutions it travels to the collector as fiber jets.[3]

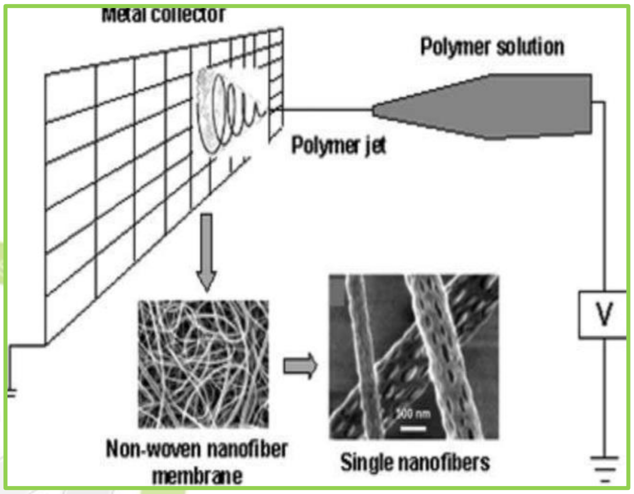

Figure 2: Schematic diagram for the electrospinning process

Jet Initiation

The behavior of electrically driven jets, the shape of the jet originating surface, and the jet instability are some of the critical areas in the electrospinning process that require further research.

Taylor showed that a conical shaped surface referred to as the Taylor cone with an angle of 49.3° is formed when a critical potential is reached to disturb the equilibrium of the droplet at the tip of the capillary, that is, the initiating surface. When a high potential is applied to the solution, electrical forces and the surface tension help in creating a protrusion wherein the charges accumulate. The high charge per unit area at the protrusion pulls the solution further to form a conical shape, which on further increase in the potential initiates the electrospinning process by jetting.

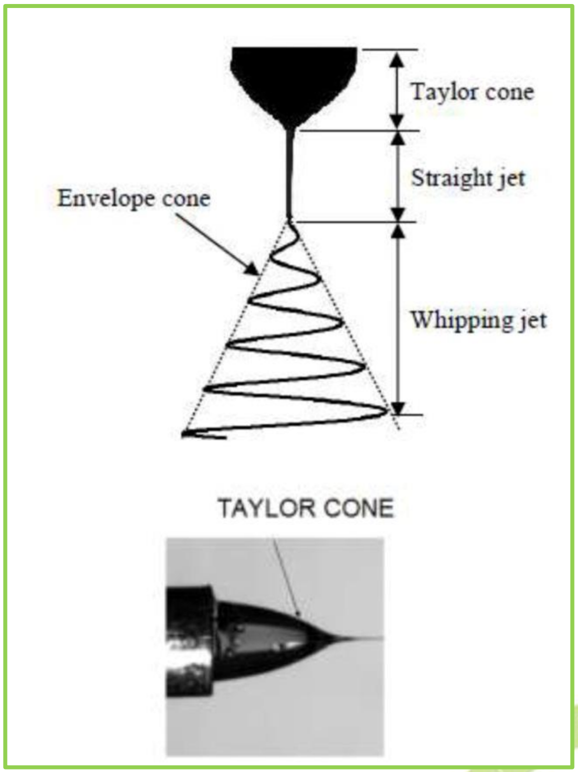

Figure 3: Taylor cone

Bending Instability

The jet ejected from the apex of the cone continues to thin down along the path of its travel towards the collector, and the jetting mode has been termed as electrohydrodynamic cone-jet. The charges in the jet accelerate the polymer solution in the direction of the electric field towards the collector, thereby closing the electrical circuit. The jet while moving towards the collector undergoes a chaotic motion or bending instability due to the repulsive forces originating from the charged ions within the electrospinning jet. The bending instability was originally thought to be occurring by a single jet splitting into multiple thin fiber filaments due to radial charge repulsion, which was termed as splaying.

Electrospinning Technology and Equipment: Current Scenario

- There has been a substantial amount of research carried out on the fundamental aspects of electrospinning. The major issue that is yet to be resolved is the scaling-up of the process for commercialization. Academic and research communities should join hands in taking the lab-scale technology to the commercial level.
- A succinct summary on nanofiber research that is of use to the fiber and textile industry has been provided by Shastri and Ramkumar.
- Electrospinning apparatus is simple in construction, and there have been no significant developments in the equipment design in the last decade. Research groups have improvised the basic electrospinning setup to suit their experimental needs and conditions.
- A new parallel plate setup for effectively controlling the operating variables to quantify the electrohydrodynamics of the process was designed.
- The parallel plate design is expected to overcome the problem of a nonuniform electric field experienced in the point-plate configuration.
- Jaeger et al. have used a two electrode setup by placing an additional ring electrode in front of the capillary to reduce the effect of the electrostatic field at the tip and to avoid corona discharges.
- It has been stipulated that by using the two electrode setup, a more stable field can be established between the ring electrode and the collector, thereby avoiding the effect of changing shape at the capillary tip over the electric field.
- Productivity enhancement for commercializing the electrospinning process is under active research, with emphasis on multiple spinneret designs and alternative experimental setup for feed charging. However, there is still a debate on the potential of scaling up this technology for commercialization. This is an important issue, which government agencies, academia, and industry should pay attention to for further growth and development of the field.

- There are only a few technology companies engaged in research and development on nanofibers. There is hardly any information available in the public domain on the mass production of nanofibers for different applications.
- Espin Technologies, a nanofiber technology company, is involved in developing a proprietary high speed device that could effectively overcome the traditional drawbacks of low output and high production cost.
- Donaldson filtration has its own patented process setup for making tens of thousands of square meters of electrospun nanofiber filter media.
- From the available published literature and the current state of understanding of the electrospinning process, it is likely that commercial scaling up of the electrospinning process can only be achieved by more fundamental understanding of the process and better control of the instability behavior of the jets that determine the diameter of the fibers. In addition, there needs to be an active participation between government agencies, industry, and academia for scaling-up the process.[2,3]

Spinning of Polymeric Nanofibers

Research activity on the electrospinning of nanofibers has been successful in spinning submicron range fibers from different polymeric solutions and melts.

Polymers with attractive chemical, mechanical, and electrical properties like high conductivity, high chemical resistance, and high tensile strength have been spun into ultrafine fibers by the electrospinning process, and their application potential in areas like filtration, optical fibers, drug delivery system, tissue scaffolds, and protective textiles have been examined.

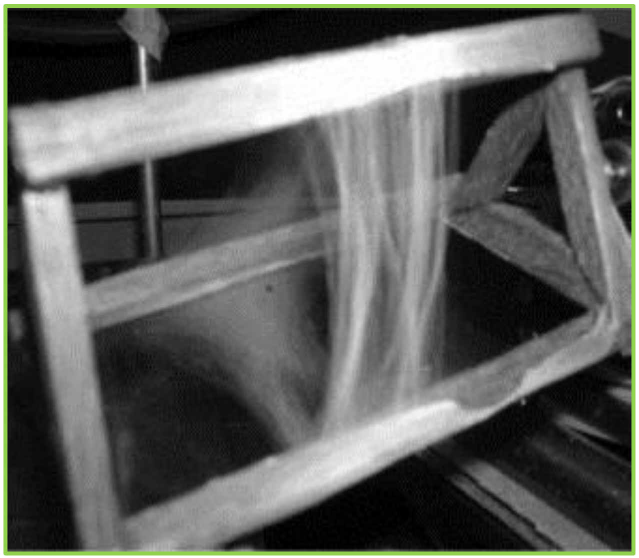

Figure 4: Continuous spun nanofibers deposited on a rotating multi-frame structure

Structure and Morphology of Polymeric Nanofibers

- In recent times, nanofibers have attracted the attention of researchers due to their pronounced micro and nano structural characteristics that enable the development of advanced materials that have sophisticated applications.
- More importantly, high surface area, small pore size, and the possibility of producing three dimensional structures have increased the interest in nanofibers morphology of nanofibers as a function of process parameters and material characteristics.
- The production of nanofibers by the electrospinning process is influenced both by the electrostatic forces and the viscoelastic behavior of the polymer.
- Process parameters(solution feed rate, applied voltage, nozzle-collector distance) and material properties (solution concentration, viscosity, surface tension, conductivity, and solvent vapor pressure) influence the structure and properties of electrospun nanofibers.[2,3]

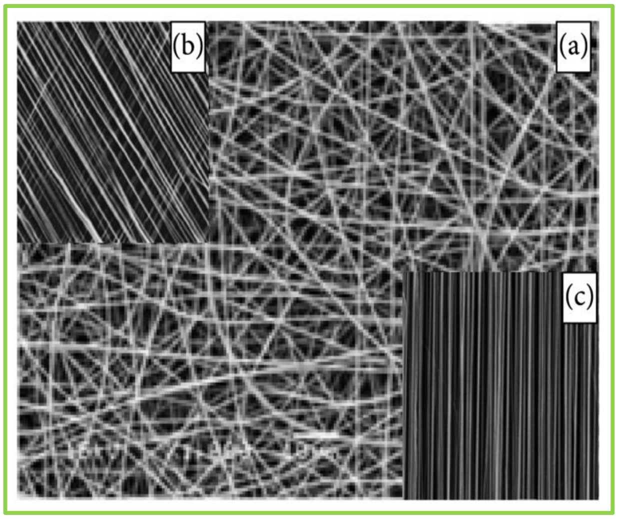

Figure 5: Scanning electron micrographs of electrospun (a) random NFs, (b) aligned fibers at an angle, and (c) aligned fibers

Polymer

- Polymers consist of a long chain of molecules with repeating unit called monomers that are mostly covalently bounded to one another. Example of a polymer would be polyethylene which consist of repeating units of $[-CH_2CH_2-]n$. such single unit is also called as monomer.
- The monomer must either have reactive functional groups such as amino groups ($-NH_2$) or have double bonds which may react under suitable to provide the covalent linkage between the repeating units. Such strong linkages forms the back bone of the polymer chain. Polymers exhibit several properties that are attractive for many applications. Most of the polymers are inexpensive as they contain simple elements and they are relatively easy to synthesize.
- Polymers with their low density can easily be moulded into complex shapes, which are strong and relatively inert.
- They have found applications in many areas such as clothing, food packaging, medical devices and aircrafts. Natural polymers such as silk, collagen and agarose have found usage in many tissue engineering applications.[9]

Ideal Targets in Electrospinning of a Polymer into Nano Fiber

1. Diameter of a fiber must be consistent and controllable.
2. Fiber surface must be defect free and defect controllable.
3. Continuous single nano fiber must be collectable.

Electrospun Polymers and Literature

Table 1: Various solvents used according to the polymer

S. No	Polymer	Solvent
1	Cellulose acetate	Acetone
2	Acrylic resin	DMF
3	Polyethylene oxide Poly vinyl alcohol Cellulose acetate	Water/chloroform Water Acetone
4	Polythene oxide(PEO)	Water
5	Polyethylene terephthalate	Mixture of dichloro methane and trifluoroacetic acid
6	Polyaniline	Chloroform
7	Polysterene	Tetrahydrofuran (THF)
8	Polyethylene oxide Polyurethane Polyvinyl chloride	Isopropyl alcohol DMF THF,DMF
9	Silk like polymer	Formic acid

Properties of Nanofibers

As briefly discussed in the introductory section of the article, a major upsurge in research on nanofibers has taken place most recently due to its high surface area and nanostructure surface morphologies that enable a myriad of advanced applications. Nanofibers have been reported to have marked differences in their thermal and mechanical properties compared to regular fibers and bulk polymers.[2,3]

Thermal Properties

There are a few published reports on the thermal properties of nanostructured materials. Thermal analysis has been carried out on a number of electrospun polymeric materials to understand the relationship between nanostructure and thermal properties. DSC studies have indicated that electrospun PLLA fibers have lower crystallinity, glass transition temperature (Tg), and melting temperature (Tm) than semicrystalline PLLA resins.57 Zong et al. attributed the decrease in the Tg to the large surface to volume ratio of nano- fibers with air as the plasticizer. The high evaporation rate followed by rapid solidification at the final stages of electrospinning is expected to be the reason for the low crystallinity. The Tg and the peak crystallization temperature (Tc) of the electrospun polyethylene terephthalate (PET) and polyethylene naphthalate (PEN) decreased significantly, while the heat of crystalline melting increased. The decrease in Tg and Tm, and the increase in the heat of melting were attributed to the increase in the segmental mobility. The melting temperature of the PET and PEN electrospun fibers remained almost constant, without any significant variations compared to that of regular fiber forms. PEO nanofibers have shown a lower melting temperature and heat of fusion than the PEO powder, which is attributed to the poor crystallinity of the electrospun fibers. The crystallinity of the PLLA fibers was observed to be completely retarded by electrospinning, and the WAXD patterns of the electrospun PLLA fibers confirmed highly oriented fibers. This decrease in crystallinity has been shown to be a general phenomenon and has been observed in poly (meta-phenylene isophthalamide), poly (glycolide), and polyacrylonitrile. Deitzel et al. inferred that PEO nanofibers retained the same crystal structure as PEO powders, while there is a clear indication of reduced crystalline order in nanofibers. Bognitzki et al. concluded with the help of a DSC thermogram that the degree of crystallinity of electrospun PLLA fibers was in the order of 40%.Thermal degradation of PET and PEN before and after electrospinning was analyzed by Kim and Lee using the TGA thermogram, and they found that on electrospinning the intrinsic viscosities of both PET and PEN reduced significantly. The thermal degradation and hence the decrease in intrinsic viscosities (i.e., decrease of molecular weight) were postulated to be the reasons for the decrease in Tg and Tc caused by reduced entanglements.[2,3]

Mechanical Properties

- Electrospun fibers have nanostructured surface morphologies with tiny pores that influence mechanical properties like tensile strength, Young's modulus, etc.
- Nanofiber reinforced polymer composites have shown more highly enhanced mechanical properties than the un- filled or carbon/glass fiber filled composites.
- Young's modulus of a nanofiber composite has been found to be 10-fold greater than the pure Styrene-Butadiene rubber. [2,3]

Material Properties

- NFs exhibit numerous fantastic properties in several fields such as optics, electricity, mechanics, thermotics, magnetics, and chemistry due to their surface effect, small-size effect, interface effect, and quantum size effect.
- The most direct impact of quantum size effect is the blue shift of the boundary of the absorption spectrum. Thus, photon-generated charge carriers transfer to the surface more easily and the small-size effect gives rise to a high extinction coefficient that all ultimately lead to high quantum efficiency.

- The NFs prepared by electrospinning have a high surface area-to-volume ratio (SVR), high porosity, and a unique web structure that are crucial to energy conversion and storage.[4]

A. Surface Area-to-Volume Ratio

- NFs with higher SVR show enhanced dye adsorption and faster charge transport. Therefore, electrospun NFs can be used as solar energy conversion materials for energy devices such as dye-sensitized solar cells and hydrogen generators.
- High SVR also enables NFs to form a nonwoven structure thereby producing good ionic conductivity.
- Electrospun NFs can be used as separator materials in fuel cells and batteries.[4]

B. Porosity

- The high porosity of nanofiber structures is necessary for their application in hydrogen storage. For example, when electrospun graphite nanofiber structures with small pores are used as hydrogen storage materials, hydrogen molecules can enter and aggregate between layers of graphite through pores on the NFs surface leading to a high storage capacity
- It is these unique properties that make electrospun nanofiber materials more attractive to be used in many areas like environmental modification, energy, medicine, and water filtration.[4]

Critical Parameters of Electrospinning

The characteristics of electrospun nanofibers depend on a number of parameters. These parameters are commonly divided into three categories:

1. Solution parameters (such as solution concentration and/or viscosity, solution surface tension, and solution conductivity)
2. process parameters (such as feed rate, applied voltage, and tip to collector distance)
3. ambient conditions (like ambient temperature and humidity

1. Solution Parameters

A. Solution Concentration

- Solution concentration is one of the factors that determine the diameter of fibers. It has been found that fibers with a smaller diameter can be obtained by reducing the concentration of the polymer solution, when the solution concentration is decreased to the entanglement concentration (Ce), beaded fibers are produced.
- An increase in concentration above Ce prevents the formation of beaded fibers and when the increase is up to 2–2.5 times Ce smooth fibers are obtained. When the concentration is too high, helix-shaped microribbons are formed.[3]

B. Solution Conductivity

- Polymers are mostly conductive, with a few exceptions of dielectric materials, and the charged ions in the polymer solution are highly influential in jet formation. The ions increase the charge carrying capacity of the jet, thereby subjecting it to higher tension with the applied electric field.
- The effect of ions by adding ionic salt on the morphology and diameter of electrospun fibers. It was found that PDLA fibers with the addition of ionic salts like KH_2PO_4, NaH_2PO_4, and NaCl produced beadless fibers with relatively smaller diameters ranging from 200 to 1000 nm.[2]

C. Volatility of Solvent

- As electrospinning involves rapid solvent evaporation and phase separations due to jet thinning, solvent vapor pressure critically determines the evaporation rate and the drying time.
- Solvent volatility plays a major role in the formation of nanostructures by influencing the phase separation process.
- The influence of vapour pressure was evident when PS fibers spun with different

THF/DMF combinations resulted in micro and nanostructure morphologies at higher solvent volatility and a much-diminished microstructure at lower solvent volatility.[2,3]

2. Process Parameters

A. Feed Rate

- The feed rate of the solution is a crucial factor that influences the diameter and morphology of fibers in the electrospinning process. As the feed rate of the solution increases, the charge density will decrease.
- A high charge density may lead to the electrospinning jet undergoing secondary bending instabilities, which contributes to the formation of fibers with smaller diameter.Thus, with an increase of the feed rate, there is a corresponding increase in the diameter of the fibers.[4]

B. Applied Voltage

- The applied voltage to the solution is also an important parameter because fiber formation only occurs when the applied voltage surpasses the threshold voltage (about ~1 KV/cm, dependent on the gel solution).
- In most cases, applied voltage affects fiber diameter, but the level of significance varies with other parameters such as the polymer solution concentration and the distance between the tip and the collector.
- An increase in the applied voltage increases the electrostatic force on the solution, which favors the stretching of the jet, ultimately leading to reduction in the fiber diameter.
- It has been found that changing the applied voltage will change the shape of the initial drop thereby resulting in a change in the structure and morphology of the fibers.[4]

C. Tip to Collector Distance

- Both the diameters and the morphology of the nanofibers can be also controlled by the distance between the tip and the collector.
- A minimum distance that enables enough time for solvent evaporation before the fibers reach the collector is required in the process of electrospinning.
- Longer distance has yielded thinner fibers. Beads would produce when the distance was too far or too close.[4]

3. Ambient Parameters

Ambient parameters such as humidity and temperature also effect the fiber diameter and morphology. Increased temperature leads to yield of fibers with decreased diameter, while lower humidity may dry the solvent completely. Also, increased humidity results in appearance of small pores on the fiber surface.[7]

Advantages

- A unique advantage of electrospinning is that complex hierarchical structures can be obtained via controlled calcinations.
- Wet-chemistry methods such as polyol method, hydrothermal method, and sol-gel synthesis have also been adopted to synthesize NWs. Of these, hydrothermal method has been viewed as one of the efficient fabrication methods of inorganic nanomaterials. Specifically, TiO2 NWs produced by this method have advantages of fine and controllable crystal form and good dispersibility.
- NWs synthesized via the hydrothermal method typically have a lower aspect ratio, which is crucial to charge transfer in energy devices such as LIBs and hydrogen generators.
- In addition, the disadvantages of hydrothermal method such as relatively long production cycle, rigid temperature, and pressure conditions make electrospinning more attractive.
- Considering the lengthy and complex procedures in the milling of NWs prepared by sol-gel, sol-gel is inferior to electrospinning.

- Generally speaking, electrospinning is a comprehensive, simple, and advantageous approach for fabrication of NWs or NFs.[4]

Disadvantages

- The variety of polymers used in electrospinning is limited and the structure and performance of NFs are not well researched.
- The performance and range of application of electrospun inorganic NFs have been limited due to their friability after calcination, although inorganic NFs have a potential application in many fields such as energy devices, high temperature filtration, biological tissue engineering, and efficient catalysis
- Electrospinning has been implemented at industrial level; however, in terms of producing fibers for the application of filters electrospinning is inferior to traditional methods due to its higher cost to produce fibers with large diameter.
- Furthermore, it remains a challenge to fabricate NFs with diameters less than 10 nm by electrospinning.[4]

Future of Electrospinning

1. Techniques such as uv cutting, chemical fragmentation and ion etching have been developed to address the preference for short fiber in noninvasive surgical and solar energy application.
2. Owing to high surface area of nano fiber, intresting properties and improved device performance can be expected.[1]

Applications

Nanofibers promise diverse applications including biotechnology, drug delivery, wound healing, tissue engineering, microelectronics, environmental protection, energy harvest and storage due to their very large surface area to volume ratio, flexibility in surface functionalities and superior mechanical performan

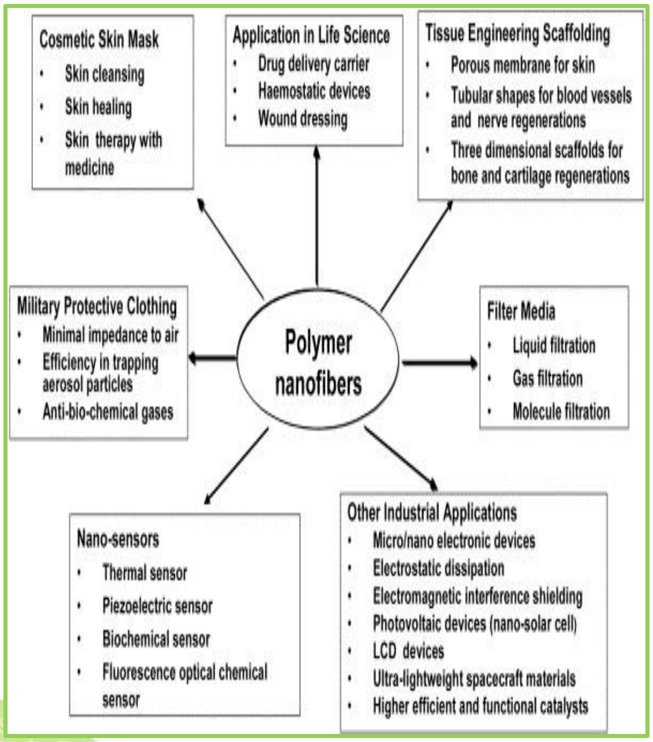

Figure 6: Various applications of nanofibers

Carbon and Graphitic Nanofibers

- Carbon nanofibers are finding enormous applications in unconventional energy sources and storage cells due to their enhanced conductivity and high aspect ratio.
- Their mechanical properties enable them to be used as fillers in composites that find applications in synthetic and rubber industries.[2,3]

Tissue Scaffolds

- Nanofibers fabricated by electrospinning are morphological mimics of fibrous components of the native extracellular matrix, making nanofibrous scaffolds ideal for three-dimensional cell culture and tissue engineering applications. [8]
- Nanofibers with high surface area and porosity have enormous scope for applications in engineering mechanically stable and biologically functional tissue scaffolds.
- The tissue scaffolding material must be selected carefully to ensure its biocompatibility with the body cells. The

biocompatibility depends on the surface chemistry of the scaffolds, which is influenced by the material properties.

- Biological signals from growth factors, extracellular matrix (ECM), and the surrounding cells regulate the biological functions, and the ECM molecules surround the cells to give the necessary mechanical support.
- Natural polymers of type I and type III collagen are the primary structural elements of the ECM that supports tissue reconstruction. The high surface to volume ratio of the nano- fiber provides more room for the cell attachment than the regular fibers.
- The high porosity of the electrospun nanofiber scaffolds provides enough space for the cell accommodation and an easy passage for the nutrient intake and metabolic waste exchange
- Culturing aortic muscle cells on these electrospun collagen microfibrils produced scaffolds with densely populated smooth muscle cells. The muscle cells were seen deeply meshed within the electrospun collagen Uniform fibers with diameter ranging from 100 to 150 nm were produced.
- Nanofiber mats due to their high functional characteristics find application as drug carriers for the drug delivery system. Controlled delivery of drugs at a defined rate over a definite period of treatment is possible with biocompatible delivery matrices of either biodegradable or non-biodegradable polymers.[2,3]

Catalytic Nanofibers

- Chemical reactions employing enzyme catalysts are important in chemical processes due to their high selectivity and mild reaction conditions. Immobilized enzymes are used largely due to easiness of catalyst separation, enzyme stability, and their availability for continuous operations. The efficiency of these immobilized enzymes depends mainly on the pore structure and diffusion limitations of the substrate material.
- Nanomaterials are of recent interest as catalyst substrates due to their large surface area per unit mass and the feasibility for high catalyst loading.
- Fibrous catalysts offer advantages, such as feasibility of adapting to any geometry and low resistance to the flow of liquids and gases.
- The activity of the catalyst supported on a substrate depends on its large active surface area. Nonporous substrates can be coated with a high surface area material like nanofibers to increase the surface area, thereby enhancing reactivity.
- Carbon nanofiber supports loaded with iron particles have shown high conversion of hydrocarbons in comparison with active carbon and -alumina.[2,3]

Filtration

- Polymeric nanofibers have been used in air filtration applications for more than a decade. Due to poor mechanical properties of thin nanowebs, they were laid over a substrate suitable enough to be made into a filtration medium.

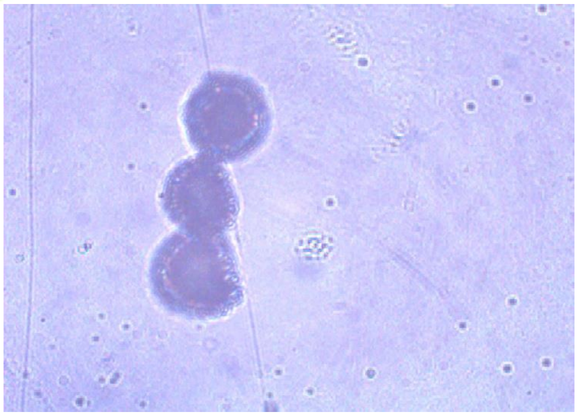

Figure 7: Lycopodium club moss spores (diameter about 60micrometers) captured on an electrospun polyvinyl alcohol fiber.[2,3,5]

- The small fiber diameters causes slip flows at fiber surface, causing an increase in the interception and inertial impaction efficiencies of these composite filter media. The enhanced filtration efficiency at the same pressure is possible with fibers having diameter having less than 0.5 micron.

- The potential for using nanofiber webs as a filtering medium is highly promising.

Electrical and Optical Application

- Conductive nanofibers find use in applications such as sensors, actuators, batteries, etc. There are studies to impart sensing capability to nanofibers.
- Electrical conductivity is an important property for sensing devices. Conductive polymers are interesting with this respect. Insulating polymers were also used, but ions or nano fillers were added to improve conductivity.
- Several approaches have been used to impart nanofibers sensing capability. A polymeric sensing material can be used to electrospin nanofibers, sensing molecules can be incorporated into nanofibers, sensing material can be applied on the nanofiber surface by coating/grafting.[7]

Tissue Engineering

- Tissue engineering is among the most promising and mostly studied application areas. The purpose of tissue engineering is to repair, replace, maintain or enhance the function of a particular tissue or organ, with the basic principle shown in Figure 8.
- Electrospun nanofibers were suggested to be used in soft tissue prostheses such as blood vessel, vascular, breast and also to be deposited on hard tissue protheses as porous film. Design of scaffolds that mimic the structure and biological functions of natural extracellular matrix is an important challenge in tissue engineering.
- Electrospun nanofibrous scaffolds have exhibited great performance in cell attachment, proliferation and penetration both in vivo and in vitro trials. There is a wide range of material choices for preparation of electrospun scaffolds for tissue engineering applications and they may be in natural and synthetic polymer categories.

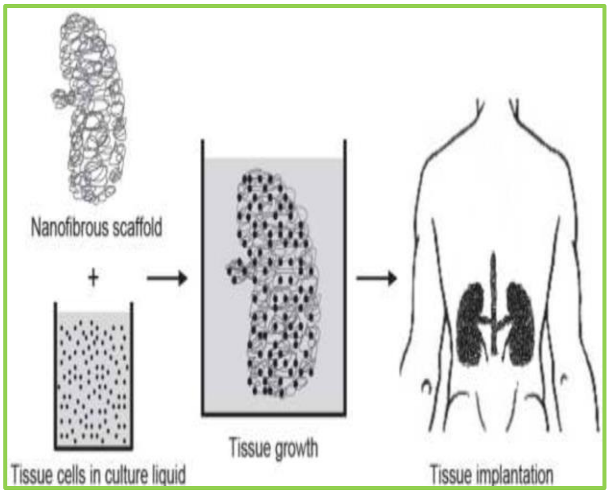

Figure 8: Tissue engineering

- Electrospun fibrous scaffolds prepared from natural polymers, for example from collagen, alginate, silk protein, hyaluronic acid, fibrinogen, chitosan, starch, are mostly preferred. Among synthetic polymers, poly (-caprolactone) (PCL), poly(lactic acid) (PLA), poly(glycolic acid) (PGA) and their copolymers are extensively used for biomedical applications due to their biocompatibility and biodegradability
- Biodegradable scaffolds are used as temporary templates for cell seeding, invasion, proliferation and differentiation prior to the regeneration of biologically functional tissue or natural extracellular matrix (ECM)[7]

Tissue Template

- For the treatment of tissues or organs in malfunction in a human body, one of the challenges to the field of tissue engineering/biomaterials is the design of ideal scaffolds/synthetic matrices that can mimic the structure and biological functions of the natural extracellurlar matrix (ECM).
- Human cells can attach and organize well around fibers with diameters smaller than those of the cells. In this regard, nanoscale fibrous scaffolds can provide an optimal template for cells to seed, migrate, and grow. A successful regeneration of biological tissues and organs calls for the development of fibrous structures with fiber

architectures beneficial for cell deposition and cell proliferation.

- Recently, people have started to pay attention to making such scaffolds with synthetic biopolymers and/or biodegradable polymer nanofibers. It is believed that converting biopolymers into fibers and networks that mimic native structures will ultimately enhance the utility of these materials as large diameter fibers do not mimic the morphological characteristics of the native fibrils.[6]

Wound Dressing

- Electrospun nanofiber mat is also a good candidate for wound dressing due to the highly porous structure and well interconnected pores for exuding fluid from the pores, high specific surface area to inhibit the exogenous microorganism invasions. An open wound healing test using electrospun collagen nanofiber showed that early stage healing was faster than normal cotton gauze.
- Electrospun nanofibers also exhibited many advantages as potential drug delivery carrier, as drug loading is very easy with electrospinning. [7]
- Polymer nanofibers can also be used for the treatment of wounds or burns of a human skin, as well as designed for haemostatic devices with some unique characteristics. With the aid of electric field, fine fibers of biodegradable polymers can be directly sprayed/spun onto the injured location of skin to form a fibrous mat dressing which can let wounds heal by encouraging the formation of normal skin growth and eliminate the formation of scar tissue which would occur in a traditional treatment.
- Non-woven nanofibrous membrane mats for wound dressing usually have pore sizes ranging from 500 nm to 1 µm, small enough to protect the wound from bacterial penetration via aerosol particle capturing mechanisms. High surface area of 5–100 m^2/g is extremely efficient for fluid absorption and dermal delivery.[7]

Figure 9: Wound dressing using nanofiber

Electrospun Chitosan Based Nanofiber Mats Loaded With Garcinia Mangostana Extracts

Introduction

Chitosan is a copolymer of N-acetyl-d-glucosamine (Glc-NAc) and d-glucosamine (GlcN) that is created by soluble deacetylation of chitin. Chitosan is biodegradable, biocompatible, and non-lethal; consequently, it has been utilized as a material for utilize in biomedical applications. Chitosan has been competitor as an injury dressing material due to the exceptional properties as expansion, cell reinforcement, antibacterial, enacts macrophages and hemostasis. Chitosan nanofibers have been effectively produced from the electrospinning of unadulterated chitosan, chitosan subsidiaries and chitosan mixes with different polymers

Materials

Chitosan and ethylene diamine tetra acetic acid (EDTA), Polyvinyl alcohol (PVA), G. mangostana, Normal human foreskin fibroblast (NHF) cells, Dimethyl sulfoxide (DMSO) Dulbecco’s modified Eagle’s medium (DMEM), fetal bovine serum (FBS), Trypsin–EDTA, and penicillin–streptomycin.

Preparation of GM Extracts

The structures of GM were cut into little pieces and dried in a hot air stove at 50◦C for 24 h. The dried examples were processed into powder by blender. Dried powder was independently macerated with 70% CH3)2CO at room temperature until the point that the extraction was depleted. CH3)2CO separate was joined and sifted through a Whatman no. 1 channel paper under suction. The filtrate was focused on water shower and vanishes dissolvable in revolving evaporator to get the dry unrefined concentrates.

Result

In the investigation, GM separates were joined into CS-EDTA/PVA nanofiber mats utilizing the electrospinning procedure. The fiber mats gave reasonable elasticity and swelling properties. These mats are non-dangerous and -mangostin is quickly discharged, which holds the cancer prevention agent and antibacterial movement, and quickens the injury recuperating process. These biodegradable, biocompatible and antibacterial electrospun nanofiber mats have promising potential for use as viable injury dressings.[10]

New Chitosan/Poly(Ethylene Oxide)/Thyme Nanofiber Prepared By Electrospinning Method For Antimicrobial Wound Dressing

Introduction

Chitosan is a characteristic polysaccharide that is non-poisonous, biocompatible, mucoadhesive, and financially savvy, which makes it alluring for different biomedical and pharmaceutical applications

Chitosan is a notable biopolymer that demonstrating a wide range of antibacterial action against both Gram-negative and Gram-positive microscopic organisms

Antimicrobial properties are imperative for twisted dressings to give a hindrance against the development of undesirable microorganisms

Material and Method

Acetic acid, tween 80 and nutrient agar cultivation environment were prepared from Merck. Medium molecular weight chitosan and PEO with 900000 Mw

Three different bacteria including Escherichia coli (E.coli) and Pseudomonas aeruginosa (P.aeruginosa) as gram-negative bacteria, and Staphylococcus aureus (S.aureus) as a gram-positive bacteria were used.

Electrospinning process was performed with an electrospinning apparatus model ES1000.

Preparation of Chitosan/Peo/Thyme Extract Solution

Arrangement of chitosan/PEO was set up by gradually including 0.27 g of chitosan powder with medium sub-atomic weight and 0.04 g PEO on the fitting volume of half acidic corrosive. At that point, 0.25 mL tween 80 was added to this arrangement as an emulsifier. This arrangement was mixed on an attractive stirrer at 300 rpm for 12 h at 37ºC to yield a homogeneous arrangement. At long last, Shirazian thyme remove was added to the chitosan/PEO answer for get arrangements containing 0.5, 1, 2 and 3% of thyme extricate.

Result

Chitosan-based nanofibers mixing with PEO were manufactured by utilization of electrospinning technique and were effectively connected as wound dressing. Since thyme leaf remove has distinctive organic and pharmacological properties, for example, high antibacterial action, henceforth, it was presented in the readied nanofibers framework as a characteristic antibacterial specialist to enhance the mending impacts of chitosan based nanofibers.

Filtering electron microscopy (SEM) and FT-IR were utilized as a part of request to examine the morphology and structure of arranged nanofibers.

New arranged nanofiber composite indicated high security and great antibacterial exercises versus three write under investigation microscopic organisms.

Also, UV-Vis consider uncovered that thyme extricate discharges decently from the nanofiber framework amid the 10 days that can be result in a superior and more powerful twisted recuperating. In total, one might say that the new presented chitosan/PEO/thyme nanofiber demonstrates great mending action and can be connected as another perfect injury dressing arrangement that reason speedier and better twisted recuperating.[11]

Drug Delivery

- Delivery of drug/pharmaceuticals to patients in the most physiologically acceptable manner has always been an important concern in medicine. In general, the smaller the dimensions of the drug and the coating material required to encapsulate the drug, the better the drug to be absorbed by human being. Drug delivery with polymer nanofibers is based on the principle that dissolution rate of a particulate drug increases with increasing surface area of both the drug and the corresponding carrier if needed.
- Bioabsorbable nanofiber membranes of poly(lactic acid) targeted for the prevention of surgery-induced adhesions, ware also used for loading an antibiotic drug Mefoxin. As the drug and carrier materials can be mixed together for electrospinning of nanofibers, the likely modes of the drug in the resulting nanostructed products are:

(1) drug as particles attached to the surface of the carrier which is in the form of nanofibers

(2) both drug and carrier are nanofiber-form, hence the end product will be the two kinds of nanofibers interlaced together

(3) the blend of drug and carrier materials integrated into one kind of fibers containing both components

(4) the carrier material is electrospun into a tubular form in which the drug particles are encapsulated.

The modes (3) and (4) may be preferred. However, as the drug delivery in the form of nanofibers is still in the early stage exploration, a real delivery mode after production and efficiency have yet to be determined in the future.[6]

Cosmetics

- The current skin care masks applied as topical creams, lotions or ointments may include dusts or liquid sprays which may be more likely than fibrous materials to migrate into sensitive areas of the body such as the nose and eyes where the skin mask is being applied to the face.
- Electrospun polymer nanofibers have been attempted as a cosmetic skin care mask for the treatment of skin healing, skin cleansing, or other therapeutical or medical properties with or without various additives .
- This nanofibrous skin mask with very small interstices and high surface area can facilitate far greater utilization and speed up the rate of transfer of the additives to the skin for the fullest potential of the additive.
- The cosmetic skin mask from the electrospun nanofibers can be applied gently and painlessly for healing or care treatment to the skin.[6]

Protective Clothing

- Electrospun nanofiber membranes are considered as potential clothing applications due to their lightweight, large surface area, high porosity (breathable nature), great filtration efficiency, etc.,which are also desirable characteristics of protective clothing. Electrospun nanofibers laid down in a layer with high porosity but small pore size provide resistance to the chemical harm agents in aerosol form.[7]
- The protective clothing in military is mostly expected to help maximize the survivability, sustainability, and combat effectiveness of the individual soldier system against extreme weather conditions, ballistics, and NBC (nuclear, biological, and chemical) warfare .
- In peace ages, breathing apparatus and protective clothing with the particular

function of against chemical warfare agents such as sarin, soman, tabun and mustard gas from inhalation and absorption through the skin become special concern for combatants in conflicts and civilian populations in terrorist attacks.

- Current protective clothing containing charcoal absorbents has its limitations in terms of water permeability, extra weight-imposed to the article of clothing. As such, a lightweight and breathable fabric, which is permeable to both air and water vapor, insoluble in all solvents and highly reactive with nerve gases and other deadly chemical agents, is desirable. Because of their great surface area, nanofiber fabrics are capable of the neutralization of chemical agents.[6]

Electrical and Optical Application

- Conductive nanofibers are expected to be used in the fabrication of tiny electronic devices or machines such as Schottky junctions, sensors and actuators. Due to the well-known fact that the rate of electrochemical reactions is proportional to the surface area of the electrode, conductive nanofibrous membranes are also quite suitable for using as porous electrode in developing high performance battery .
- Conductive (in terms of electrical, ionic and photoelectric) membranes also have potential for applications including electrostatic dissipation, corrosion protection, electromagnetic interference shielding, photovoltaic device, etc.[6]

Energy Harvest and Storage Applications

- Polymeric conductive membranes are also considered to have potential use in electromagnetic interference shielding, photovoltaic device, electrostatic dissipation, production of tiny electronic devices, sensors, actuators, etc
- Nanofibrous materials were found to have higher energy conversion and storage efficiency than their bulk counterparts. Electrospun anofibers have shown great application potential in dye-sensitized solar cells.
- In fuel cells, electrospun nanofibers have been prepared as alternative catalyst to the Pt nanoparticle catalyst, which is the main component in the fuel cell. They have high catalytic efficiency and good durability.
- As for mechanical energy harvesters, different piezo electric materials can be made into nanofibrous structure by electrospinning and these electrospun nanofibers proved to have energy scavenging capability.
- Carbon nanofibrous mats produced by electrospinning are used in supercapacitors and they offer high capacitive behavior.
- Nanofiber mats of various polymers were studied as lithium battery separator in lithium ion batteries. Electrospun PAN mat displayed high ion conductivity and electrochemical stability.[4,7]

Other Functional Application

- Nanofibers from polymers with piezoelectric effect such as polyvinylidene flouride will make the resultant nanofibrous devices piezoelectric.
- Electrospun polymer nanofibers could also be used in developing functional sensors with the high surface area of nanofibers facilitating the sensitivity. Poly(lactic acid co glycolic acid) (PLAGA) nanofiber films were employed as a new sensing interface for developing chemical and biochemical sensor applications .
- Highly sensitive optical sensors based on fluorescent electrospun polymer nanofiber films were also recently reported.
- Nanoscale tubes made from various materials including carbon, ceramics, metals, and polymers are important in many industry fields. Ultrafine fibers prepared from electrospinning can be used as templates to develop the various nanotubes . In general, the tube material is coated on the nanofiber template, and the nanotube is

formed once the template is removed through thermal degradation or solvent extraction. For this purpose, the template nanofiber must be stable during the coating and be degradable or extractable without destructing the coating layer.[6]

Encapsulation of R-(+)-Limonene in Edible Electrospun Nanofiber

Introduction

Unstable substances with antimicrobial highlights, for example, limonene, are of incredible enthusiasm for the dynamic bundling industry and their effective exemplification and controlled discharge speak to a noteworthy test, considering their high risk towards natural variables.

Electrospinning, has gotten extraordinary consideration in practical nourishment and dynamic sustenance bundling frameworks. This straightforward procedure empowers the generation of nanofibrous polymeric layers, utilizing electric fields to turn polymer strands with breadths going from hundreds to many nanometers. Due to their submicron-scale distance across and substantial surface region, electrospun strands are perfect for sensors, biomolecules and cells immobilization and controlled discharge, filtration and tissue building applications.

Material

A food grade preparation of pullulan, β-CD and R-(+)-limonene, double distilled water, Sodium chloride, potassium chloride and potassium nitrate

Electrospinning Solution Preparation

A polymer arrangement was set up by dissolving pullulan dry powder in water (20 wt %) at room temperature under 4 hour mixing. After this, the pullulan arrangement was blended with a measure of dry free β-CD and with 10% wt % (AC/β-CD), containing more than 90 wt % of the dynamic compound D-limonene. The arrangement was emulsified utilizing an Ultra Turrax T25 IKA blender running at 10.000 rpm for 5 min. It must be seen that on adding cyclodextrins the framework swings to a water-in-water emulsion as a result of the thermodynamic uncompatibility of the two polymers: cyclodextrin rich fluid beads are scattered inside a watery pullulan rich stage.

Electrospinning Process

Plastic syringes (10 mL) with a metallic needle were loaded with the polymeric emulsions and put in a syringe pump. Pump was set as 0.5 mL/h. The needle was connected to a Spellman SL150 high voltage control supply and a grounded thwart secured copper plate, situated before the needle. The generation of a solitary layer was ceased at 15 min, the film were expelled from the gatherer and dried.

Result

The framework is steady amid months without critical misfortune when kept in generally dry conditions, even at high temperatures (up to 260°C)

The arrival of the unstable from the layers is activated by relative mugginess changes, occurring at aw ≥ 0.9. [9]

Gallic Acid Loaded Cellulose Acetate Electrospun Nanofibers: Thermal Properties, Mechanical Properties and Drug Release Behaviour

Introduction

Gallic corrosive (3,4,5-trihydroxybe-nzoic corrosive) is a characteristic phenolic mixes generally found in gallnuts, sumac, witch hazel, grapes, oak bark, and green tea. It has a few organic exercises includ-ing cancer prevention agent, antityrosinase, antimicrobial, against inflammatory and anticancer exercises. Because of its promising cancer prevention agent action, gallic corrosive is included different skincare items as normal natural concentrates. Gallic corrosive is likewise utilized as a standard substance in numerous cell reinforcement measures.

Material

Cellulose acetate, Acetone and *N*, *N*-dimethylacetamide (DMAc), Gallic acid

Fiber mat preparation by electrospinning method

An underlying measured measure of CA powder was broken up in 2:1 v/v $CH_3)_2CO$/DMAc to acquire a 17% w/w CA solution

Gallic corrosive stacked CA arrangements were set up by dissolving a similar measure of CA powder and gallic corrosive in the measure of 2.5 - 10 wt% in view of the heaviness of CA powder, individually, in the $CH_3)_2CO$/DMA blend.

Gallic corrosive stacked electrospun cellulose acetic acid derivation (CA) fiber mats were set up by electrospinning procedure under a settled electric field of 12 kV/12.5 cm.

17% w/v CA arrangement in 2:1 v/v $CH_3)_2CO$/N,N-dimethylacetamide was utilized as the base turning arrangement, into which gallic corrosive in a measure of 2.5% - 10% w/w (in view of the heaviness of CA) was added to set up the gallic corrosive turning arrangements.

Conclusion

The electrospun filaments from these arrangements were observed to be cross-sectionally round with smooth surface for low gallic corrosive stacking content however watched the totaled gallic corrosive chip on the surface of fiber for high gallic corrosive stacking content.

The normal distances across were running in the vicinity of 537 and 1057 nm which found to increment with expanding gallic corrosive stacking content

The dissolving conduct of these electrospun fiber mats was relied upon the gallic corrosive stacking content which diminished with expanding gallic corrosive substance.

The mechanical properties as far as the rigidity and the level of prolongation ate break of these electrospun fiber mats was assessed in correlation with that of the comparing as-cast films. It was watched that the as-cast films displayed more prominent rigidity than the electrospun fiber mats, while the level of stretching ate break of the electrospun fiber mats was around 10× as much as that of the as-cast films.

The discharge qualities of gallic corrosive from the gallic corrosive stacked electrospun CA fiber mats and the comparing as-cast films were tried in the phosphate support medium at room temperature, by the aggregate drenching strategy.

The stacking substance of gallic corrosive was essentially influenced to the discharge conduct because of the distinctive fiber morphology. In examination with the measures of gallic corrosive discharged from the medication stacked electrospun CA fiber tangles, those of the gallic corrosive discharged from the comparing as-cast films were much lower[12]

CONCLUSION

Nanoscience is one of the few growing scientific fields of this decade that is enjoying broad based support from the government and industries. The ability to manipulate individual molecules and understand their characteristics at atomic levels has made this field very promising. Electronics and semiconductor industries have been harnessing the potential of nanotechnology to a major extent. Other fields, such as biomedical, polymer, and fiber science, are yet to realize the full potential of nanotechnology. To enable the fullest exploitation of nanotechnology in fiber and polymer science disciplines, a timely and in-depth review of research on nanofibers is essential. Government agencies and nongovernmental agencies have given high priority to both fundamental and applied nanoscience research activities. The support for research activities in nanotechnology is growing internationally. As elaborated in this overview article, nanofibers have applications in many different fields, such as protective textiles, filtration, drug delivery, etc. The production of nanofibers is still in the laboratory level, and it is extremely important to make efforts for scaled-up commercialization. A thorough investigation on the scaling up of nanofiber technology is necessary for the growth and development of this field. The overview presented in this article has focused on nanofibers, experimental method to produce them, and their applications in important fields.

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