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Baršausko str. 59,
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KAUNAS UNIVERSITY OF TECHNOLOGY

Advanced Electrospun Materials: Bridging Nanotechnology and Sustainability

assoc. prof. Erika Adomavičiūtė

Faculty of Mechanical Engineering and Design

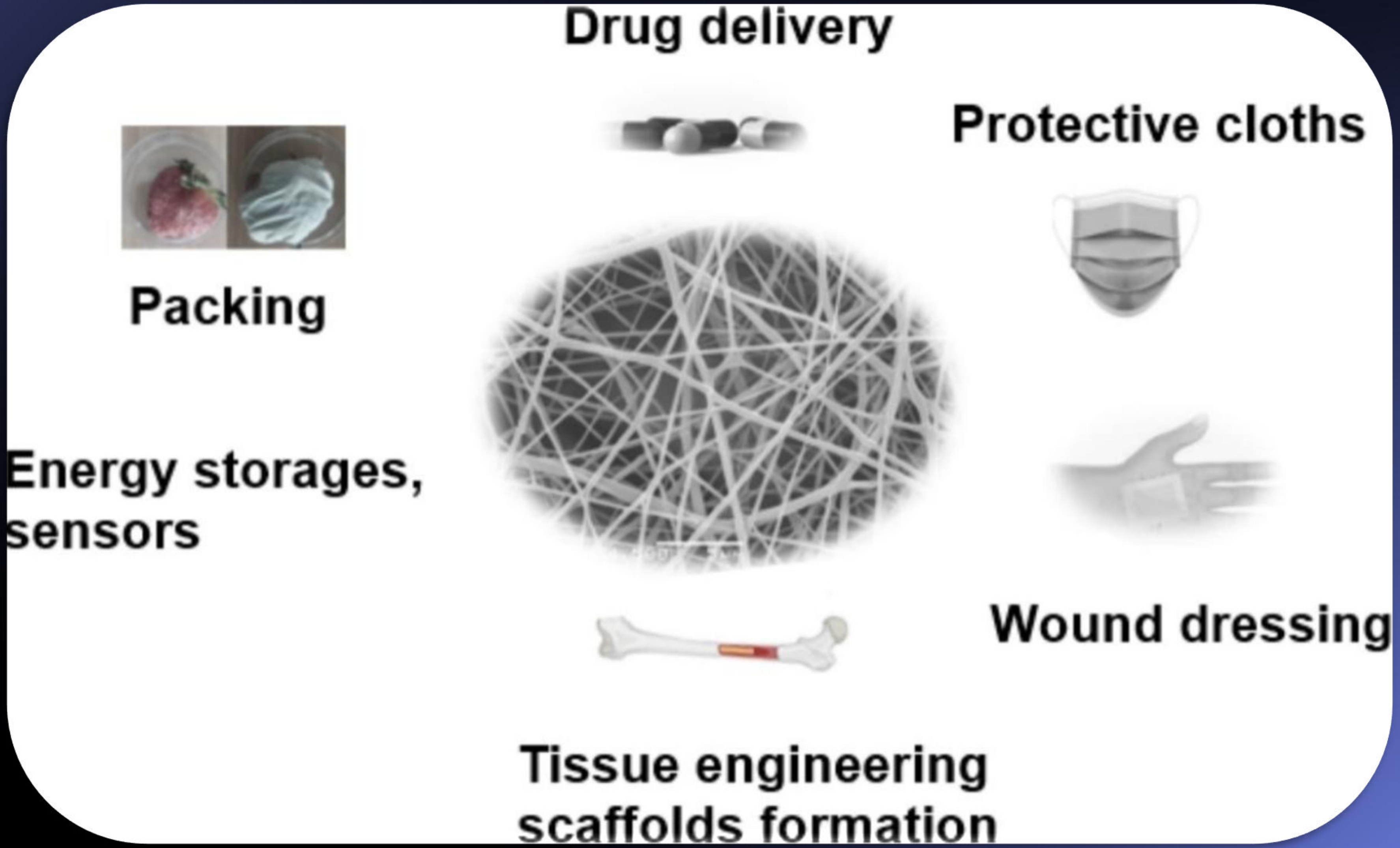
Content of presentation

- Overview of electrospinning technology
- Importance of electrospun mats for nano-microfibers in modern materials science – application areas
- Growing demand for sustainable materials

Introduction

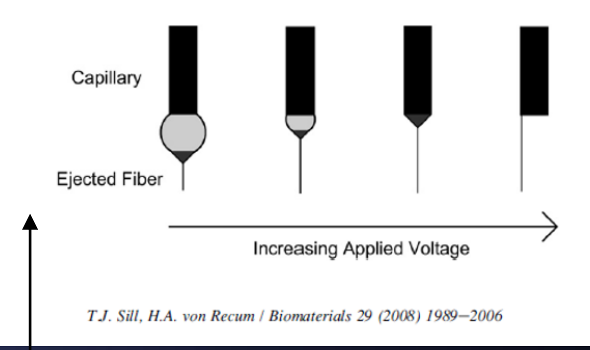
Electrospinning is a versatile and highly efficient technique for the fabrication of nano-microfibers producing nonwoven materials for applications in different fields including:

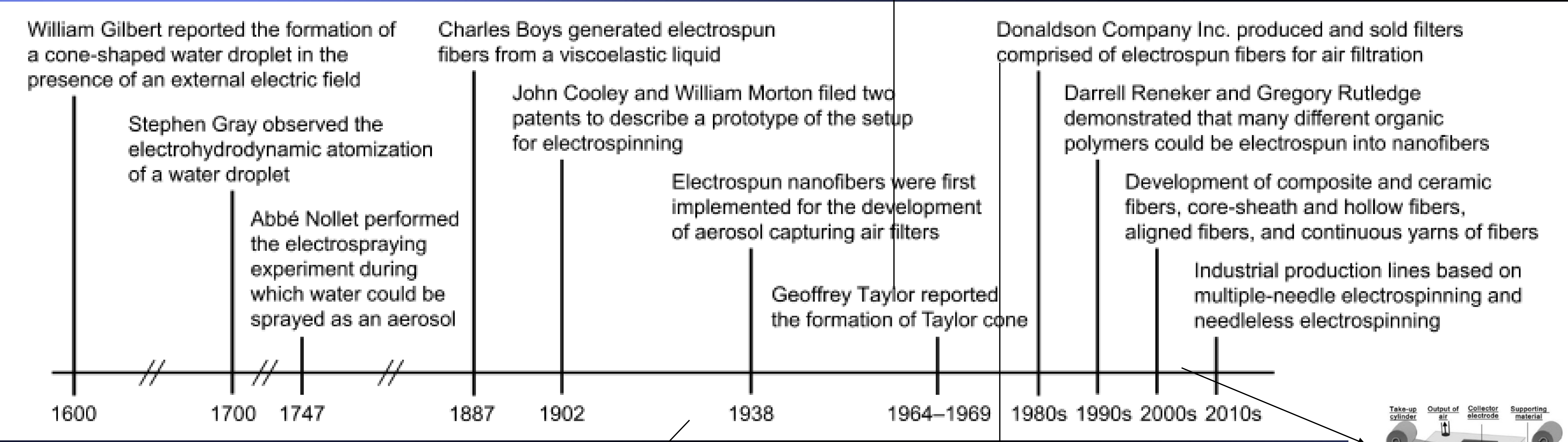
- biomedicine,
- tissue engineering,
- environmental science,
- energy storage,
- sensors,
- electronics,
- textiles,
- optical applications,
- and advanced material sciences

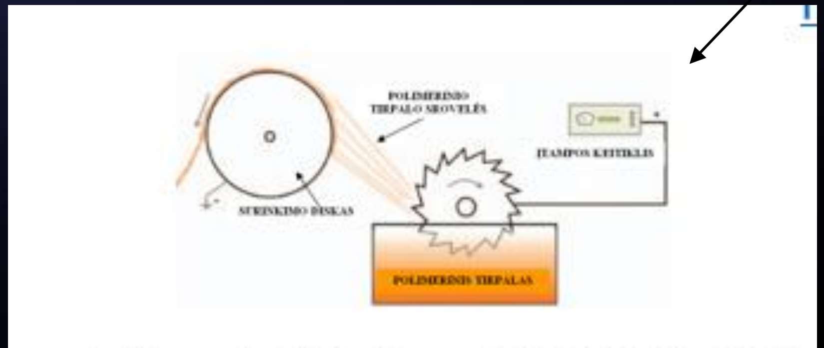


E. Adomaviciute , V. Valeika, V. Jankauskaite, European polymers j., 2026, https://doi.org/10.1016/j.eurpolymj.2025.114402

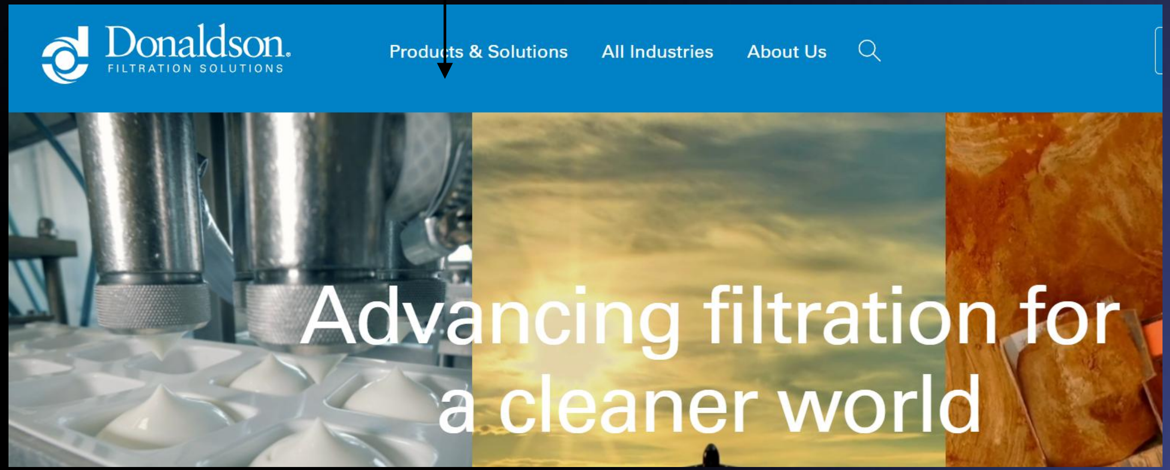
History of electrospinning

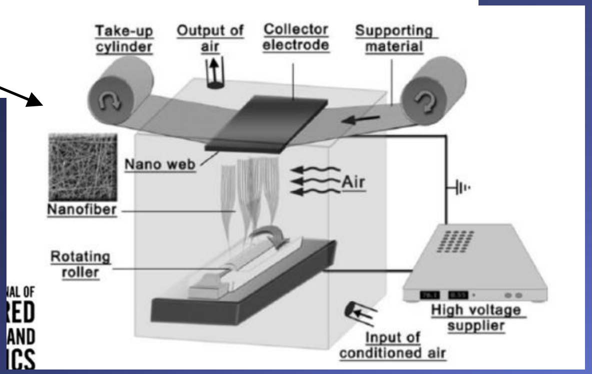






A. Formals U.S. Patent 1.975.504 in 1934





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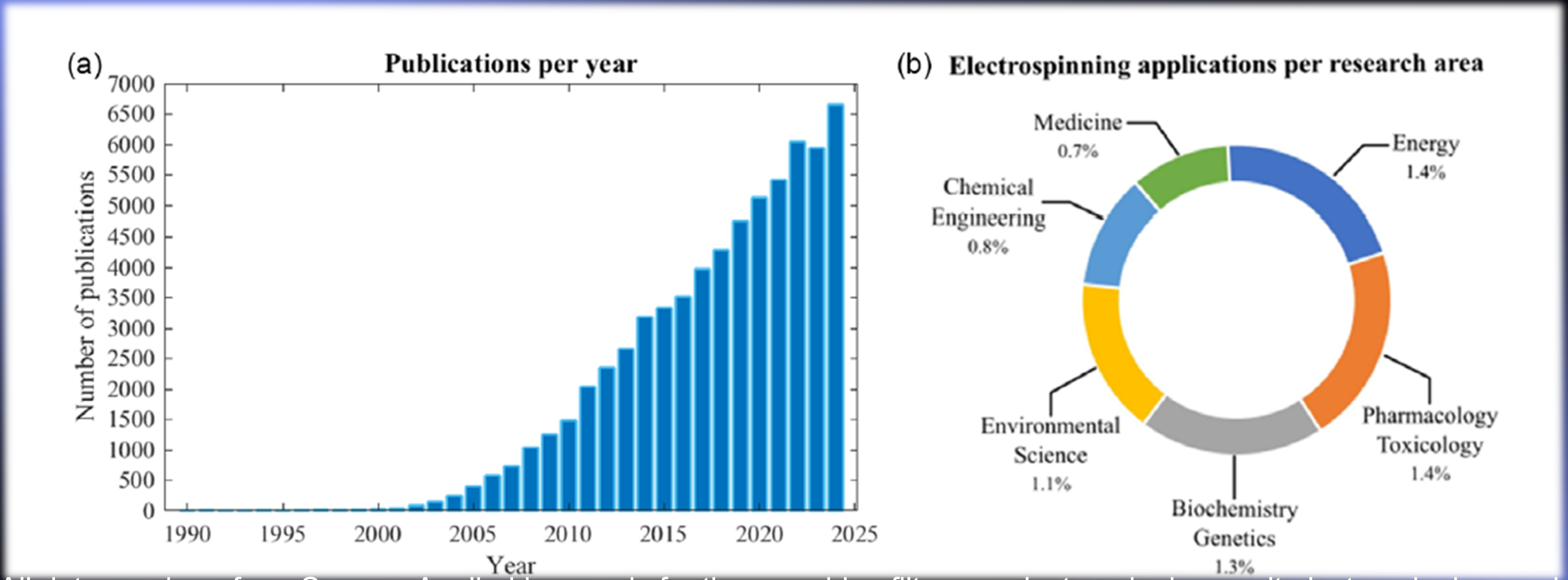
https://pubs.acs.org/doi/pdf/10.1021/acs.chemrev.8b00593

Electrospinning relevant in research publications

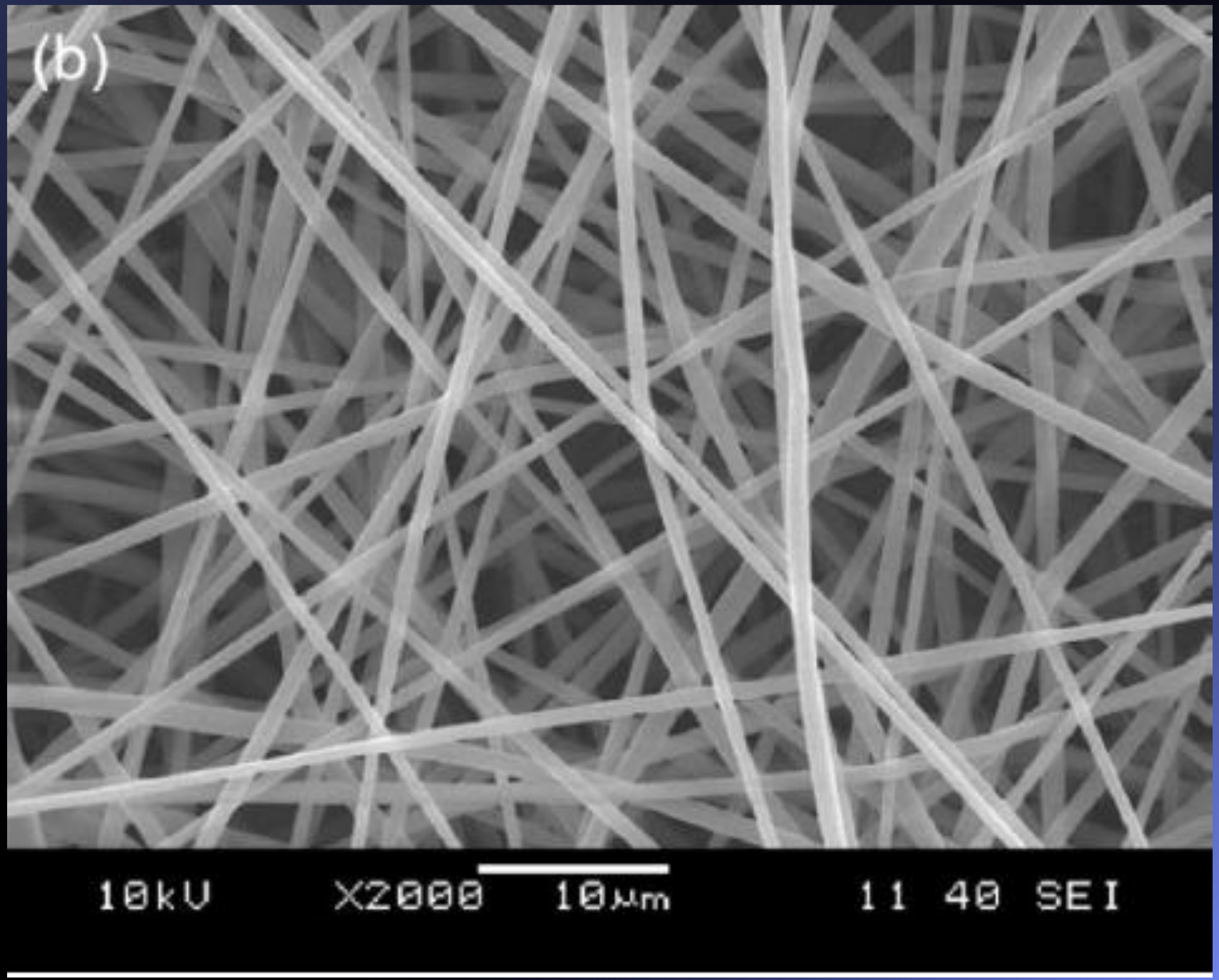


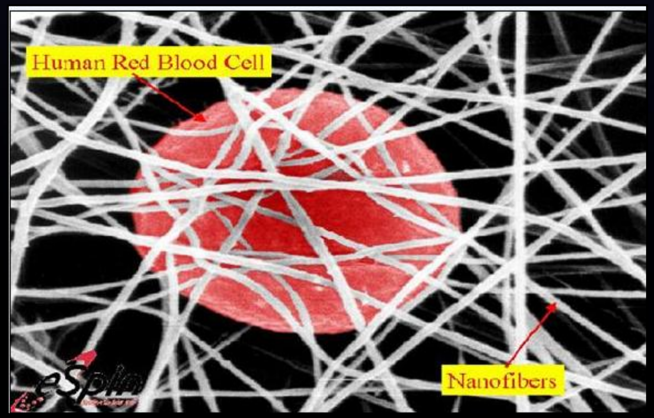
All data used are from Scopus. Applied keywords for the searching filter are electrospinning, melt electrospinning, and melt electrowriting. a) Number of total publications related to electrospinning since 1990. b) Research areas in which the application of electrospinning have expanded the most over last 10 years compared to the first decade of this century.

2401353. https://doi.org/10.1002/adem.202401353

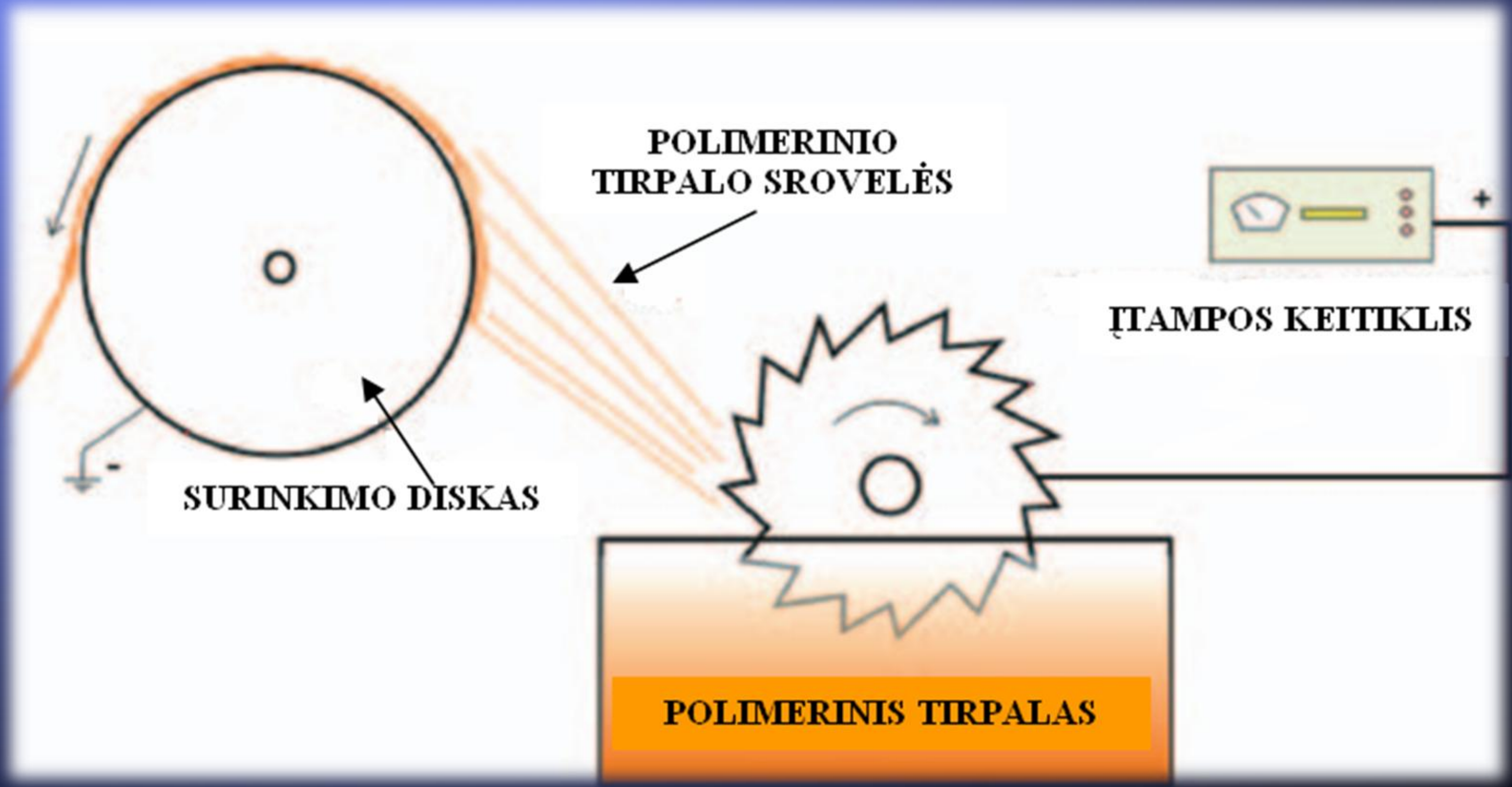
Why electrospun material are so widely investigated?

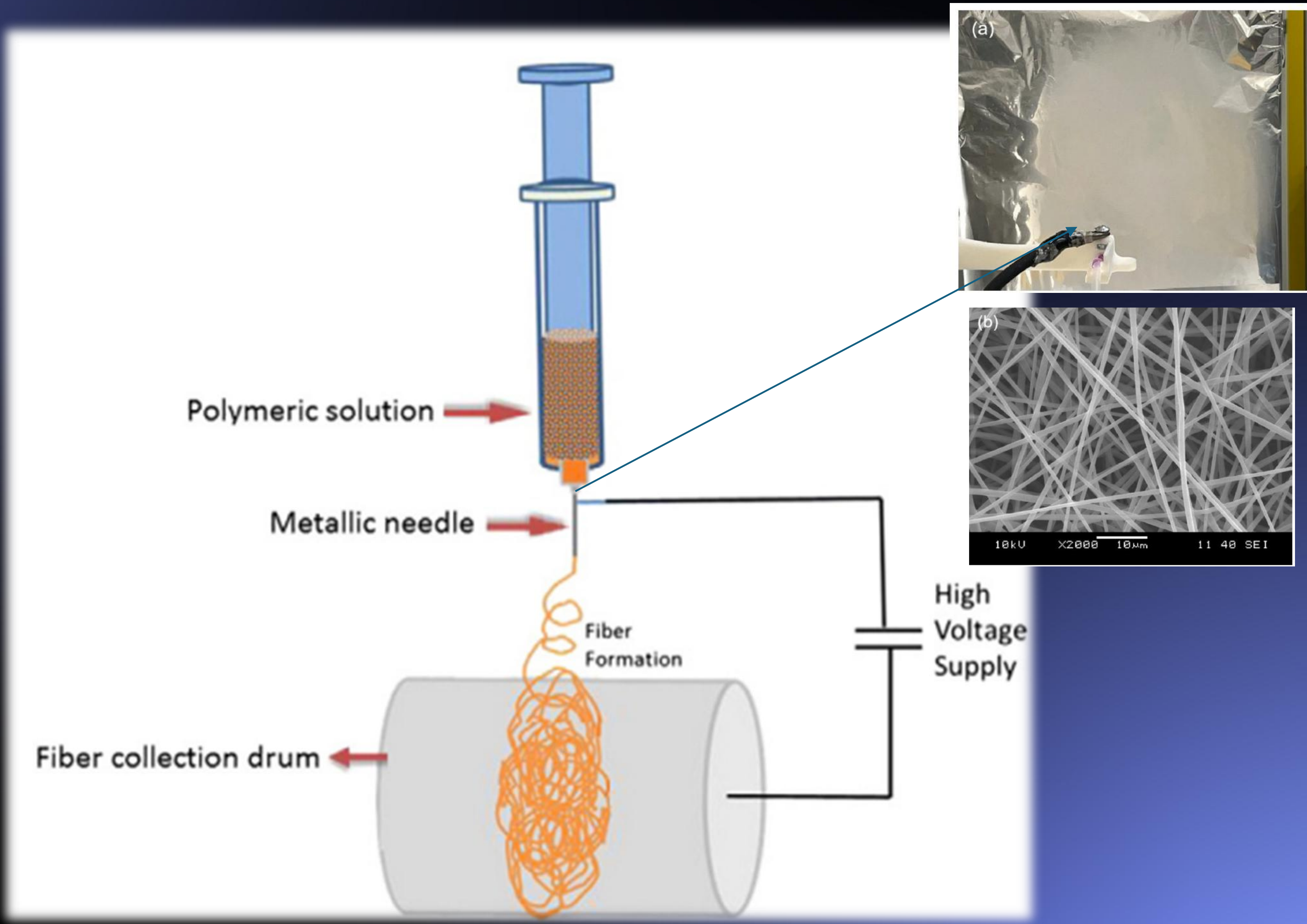
- High surface-area-to-volume ratios;
- Diameter of fibers are in nano range;
- High and controlled porosity;
- **Ability** to electrospin different type of polymers.



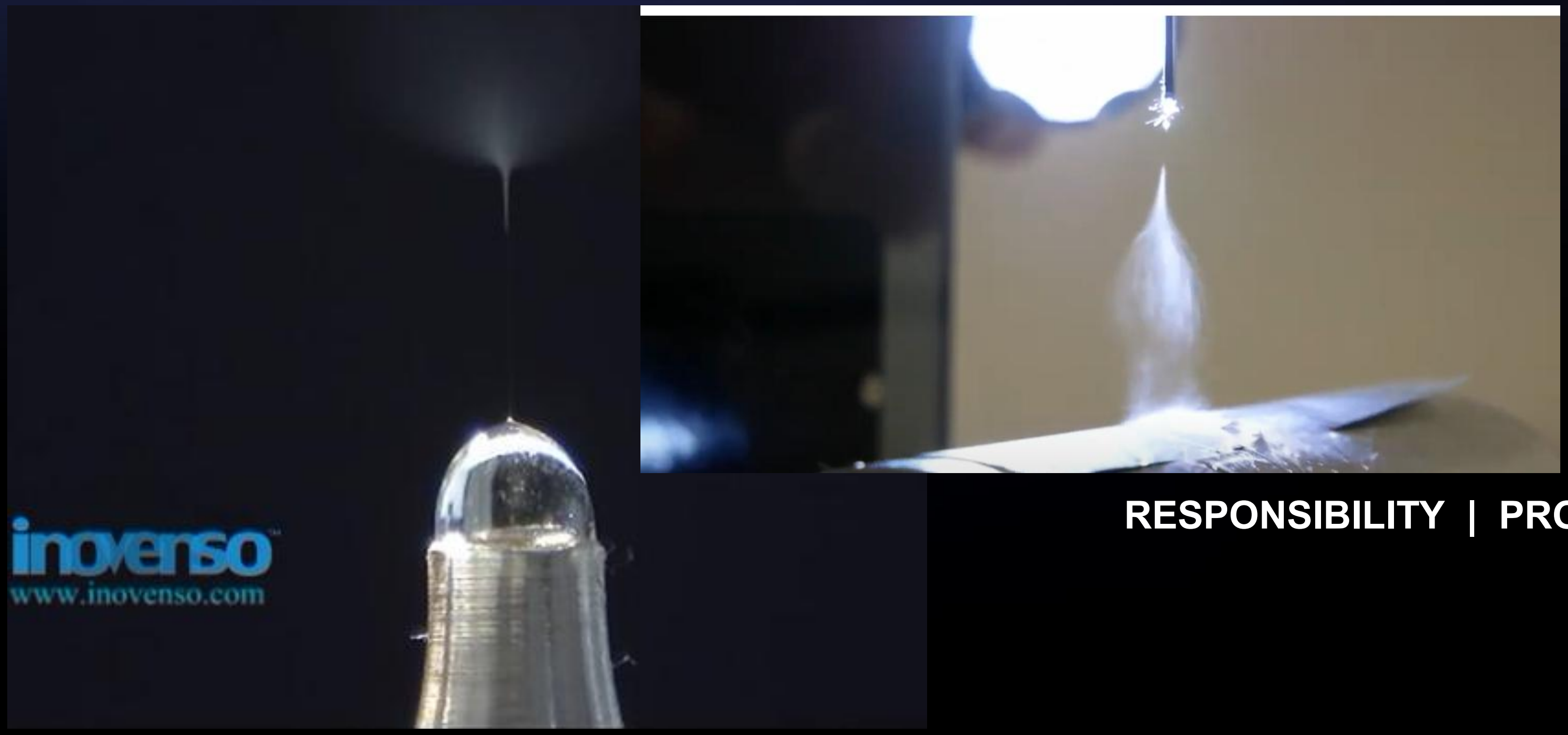


Electrospinning

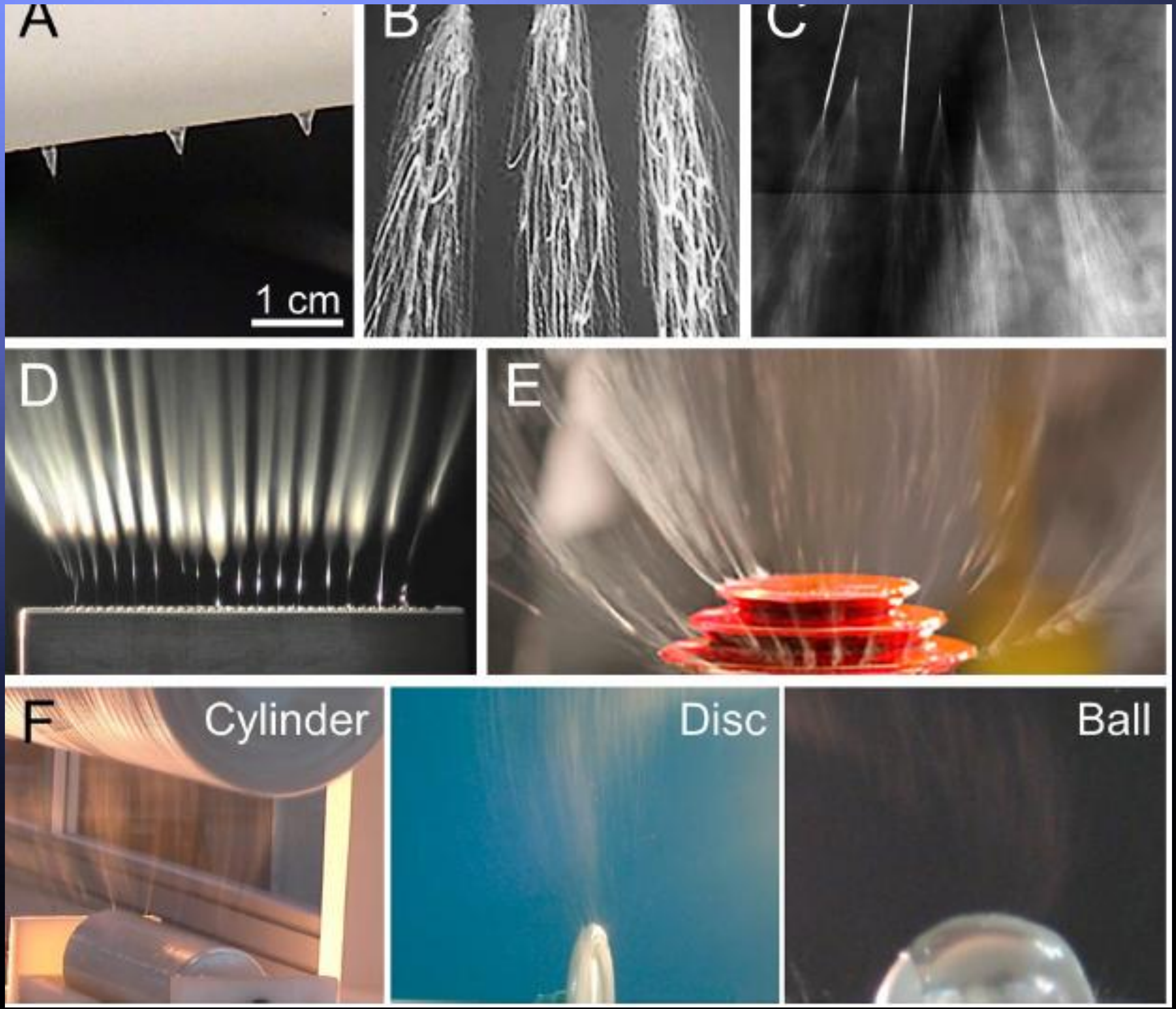


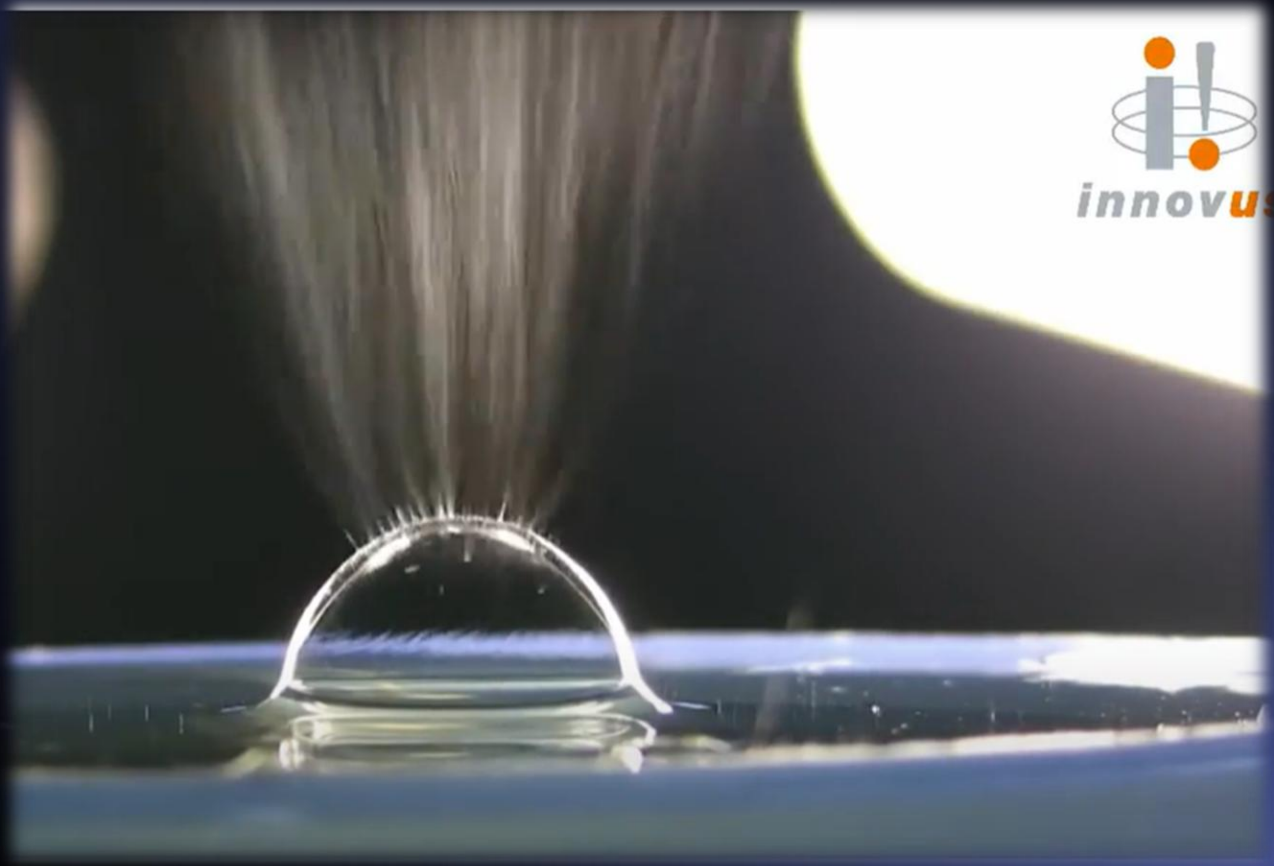


Formals U.S. Patent 1.975.504 in 1934

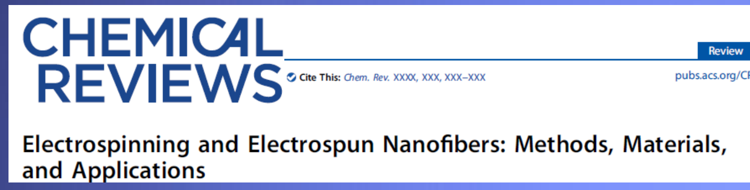


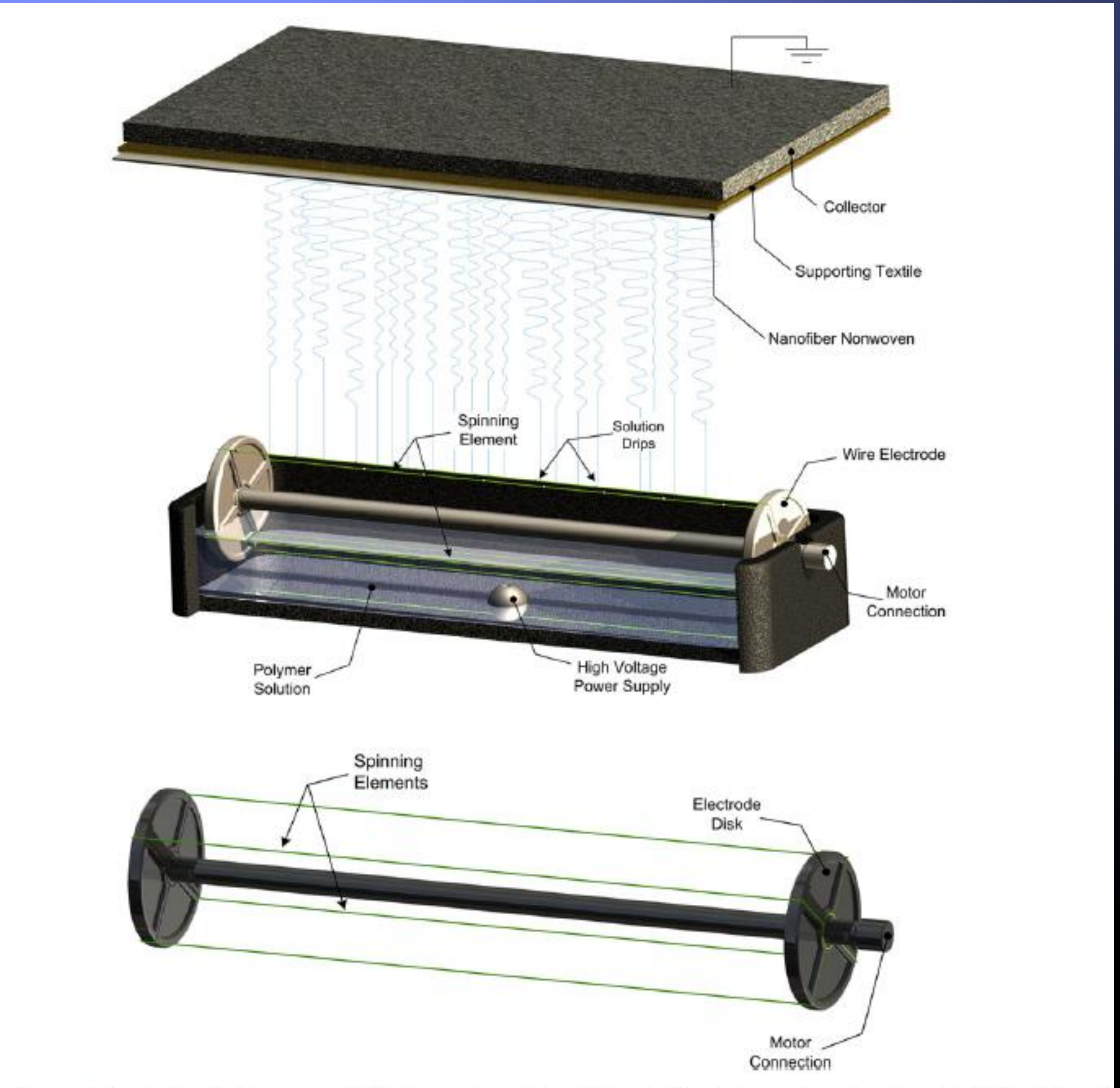
https://doi.org/10.1016/j.desal.2014.09.033
https://doi.org/10.1002/pol.20241010



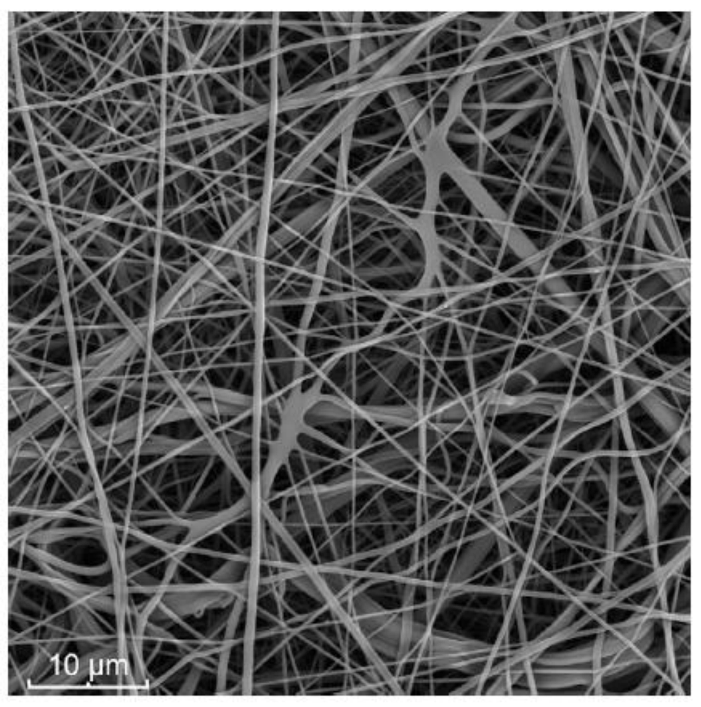


VIDEO


CHEMICAL REVIEWS
Review
Electrospinning and Electrospun Nanofibers: Methods, Materials, and Applications



Scheme of the electrospinning process (at the top) using rotating electrode with cotton cord spinning elements (at the bottom).



SEM image of the PUR nanofiber mat produced by electrospinning process.
W. Sambaer et al. / Chemical Engineering Science 66 (2011) 613–623

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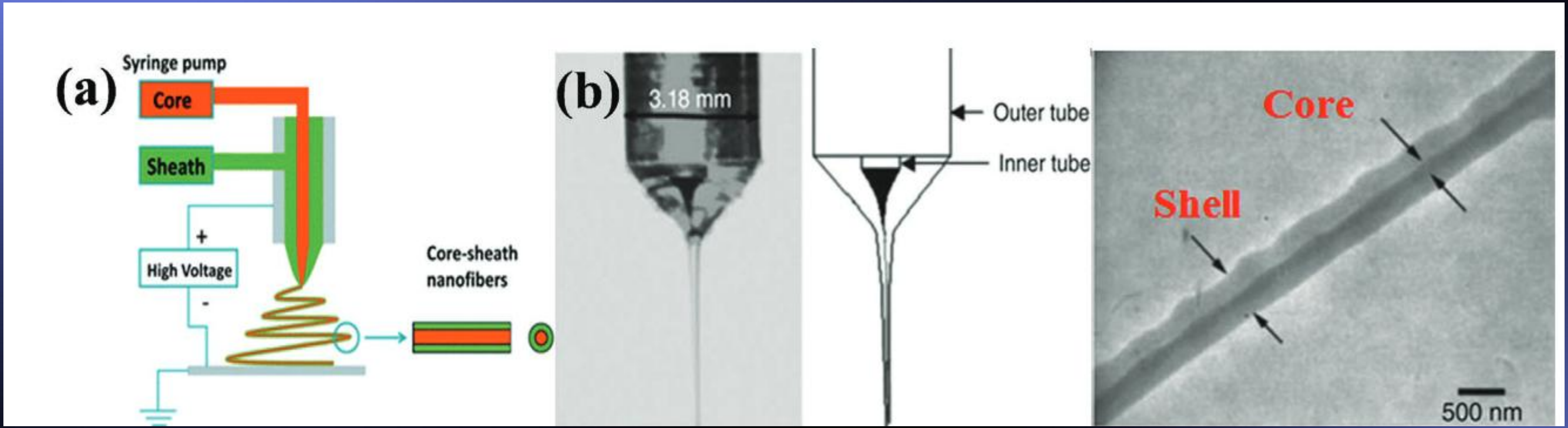
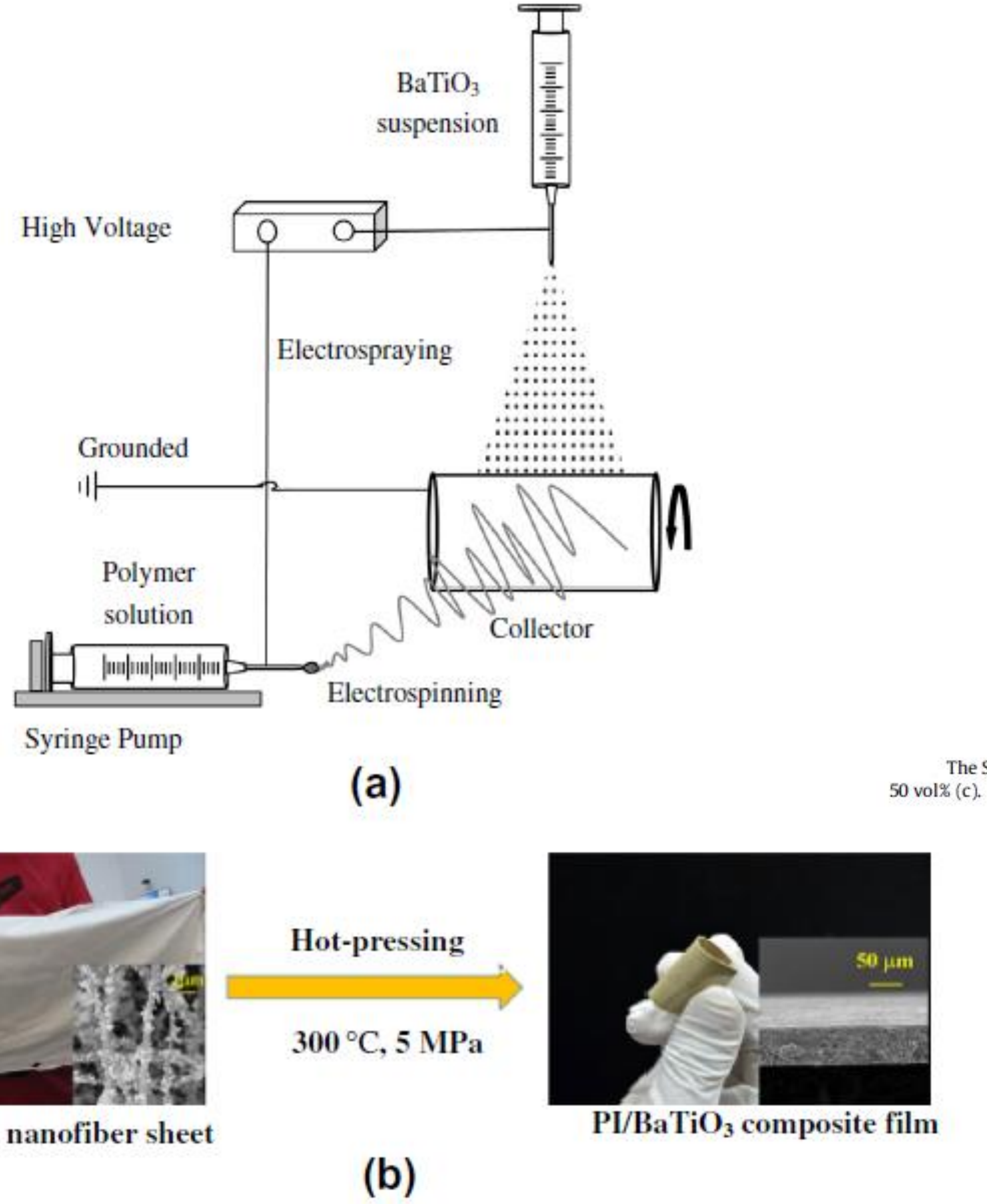
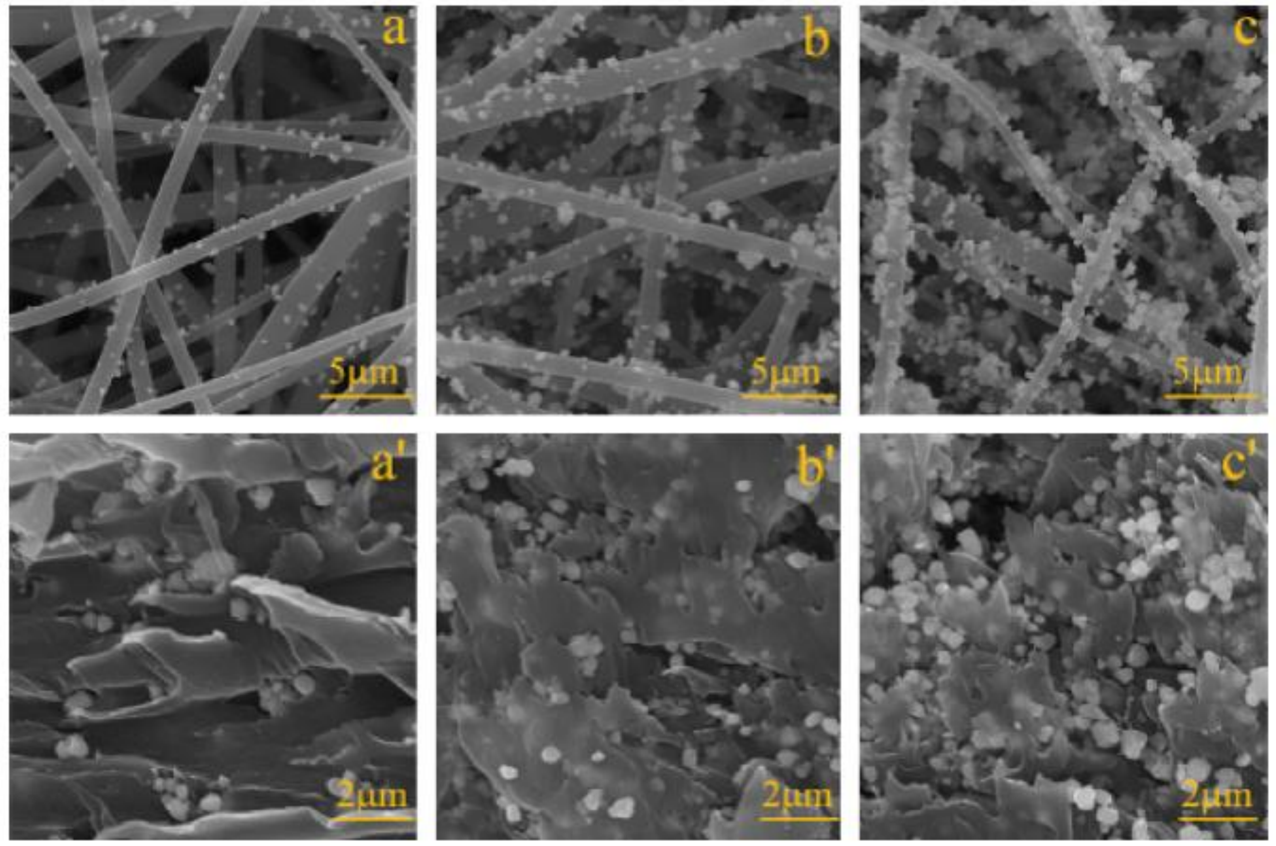
ELECTROSPINNING



https://doi.org/10.1002/admt.202100410



Schematic illustration of the process to fabricate PI/$BaTiO_3$ nanocomposites (a) is the schematic of combined electrospinning and electrospraying; (b) is the photo of real objects containing 40 vol% $BaTiO_3$ before and after the hot-pressing process.



The SEM images of PI/$BaTiO_3$ composite nanofibrous (a–c) and cross-section of the composites (a′–c′) with $BaTiO_3$ content of 10 vol% (a), 30 vol% (b), 50 vol% (c).

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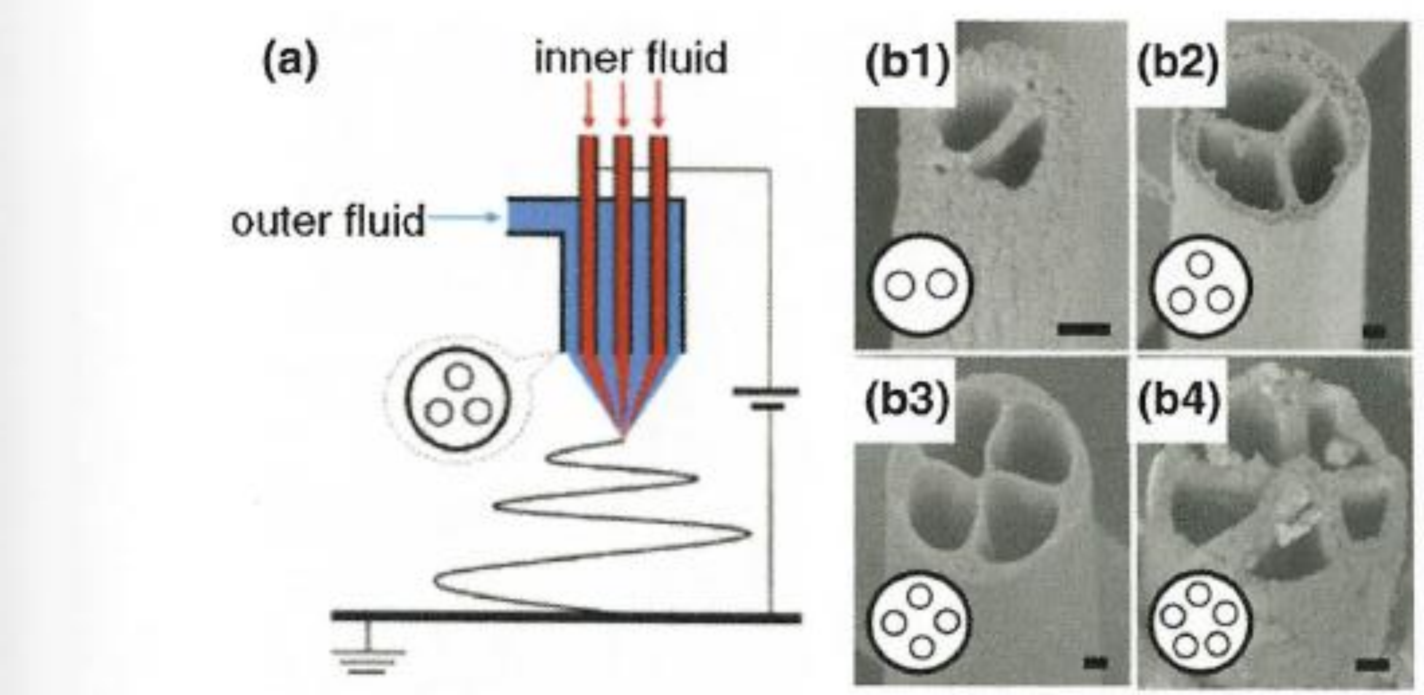
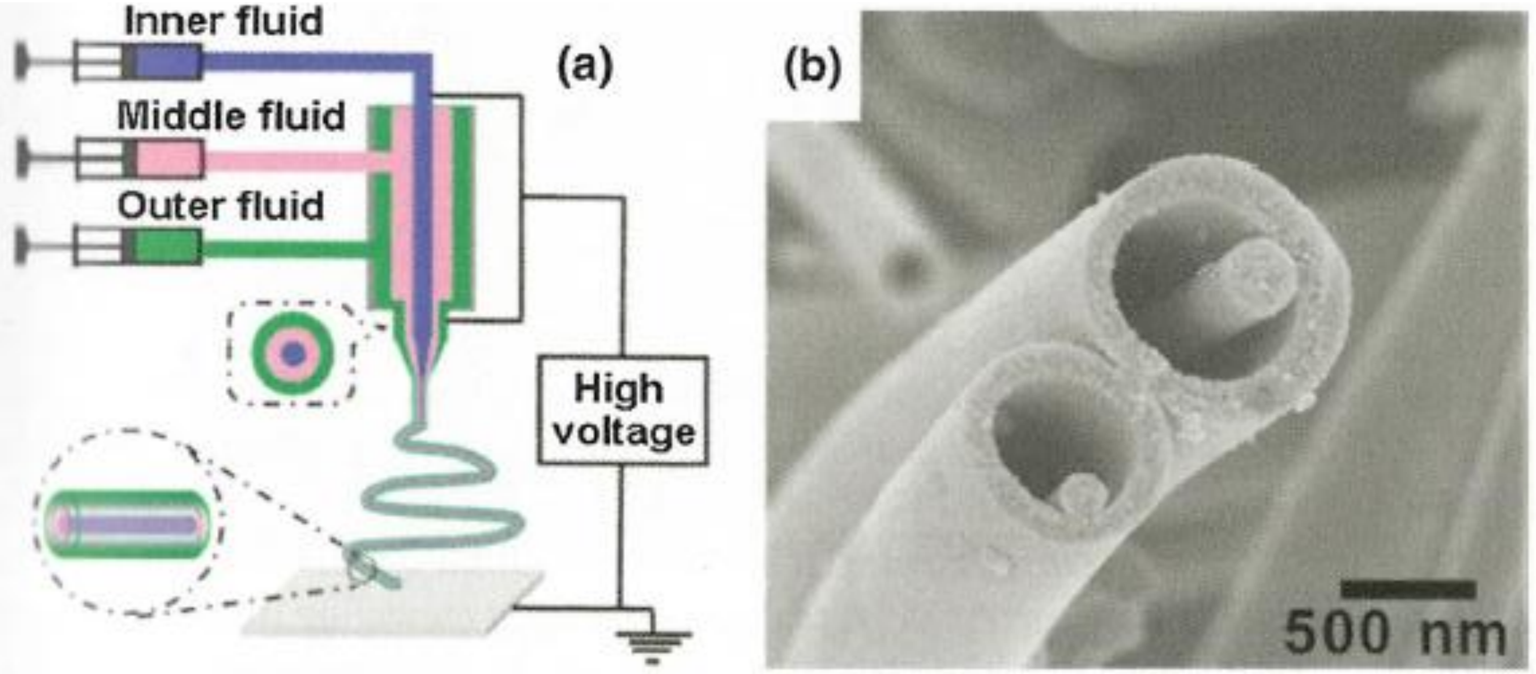
Y.Ding European Polymer Journal 49(2013)2567-2571





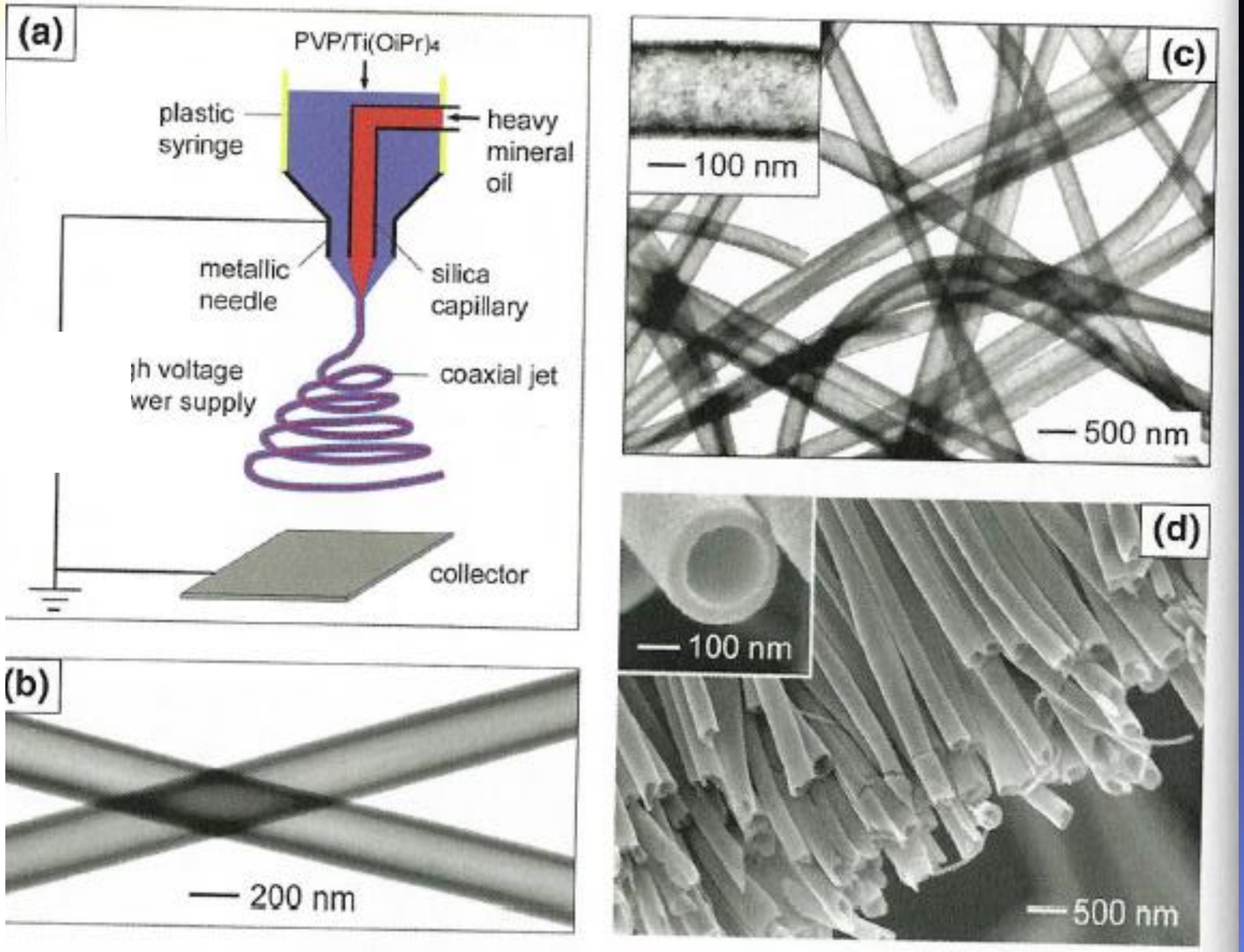


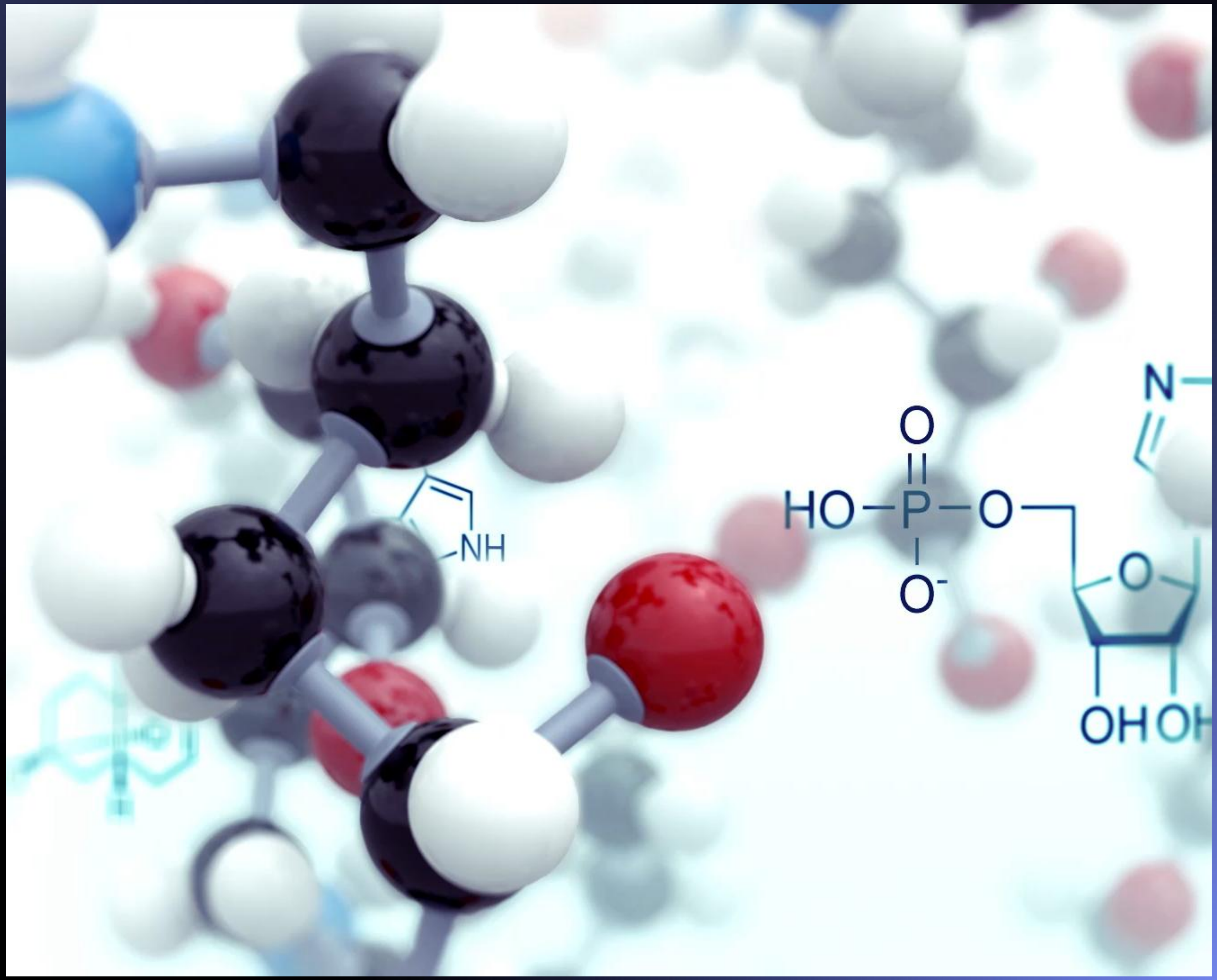
Photo copies from Z. Li, C. Wang, One-Dimensional Nanostructures Electrospinning Technique and Unique Nnanofibers, 2013

The structure, properties of electrospun nanofibers depends from:

1, **Polymer features:**
- type of the polymer;
- molecular weight of polymer;
- solvent type;
- surface tension of polymer solution;
- electric conductivity of polymer solution;
- viscosity of polymer solution;
- solvent evaporation;
- temperature of polymer solution.

2. Technological parameters:

- applied voltage,
- distance between electrodes,
- polymers solution flow rate.



3. Temerature, humidity of environmental.

Examples of polymers which may be used for electrospinning

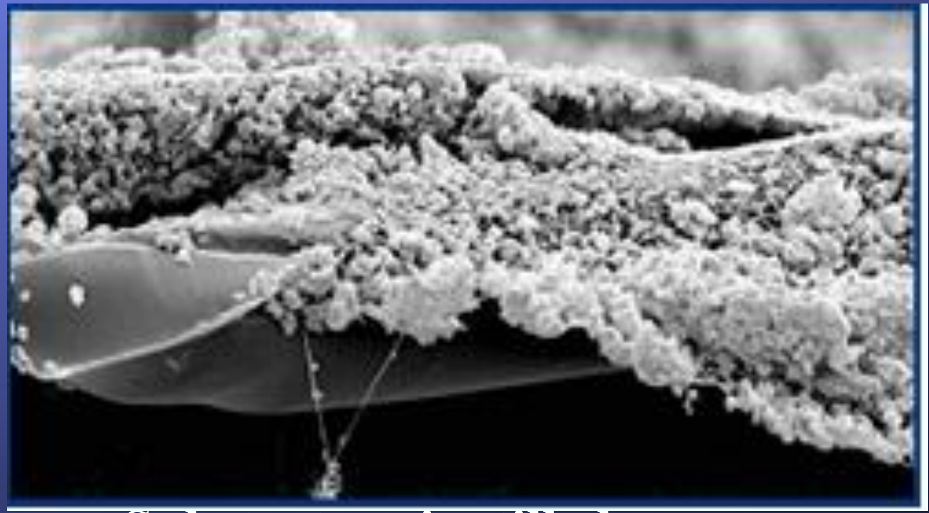
Polymer	Solvent(s)	Applications
Polycaprolactone (PCL)	Chloroform, Dichloromethane, Acetone	Tissue engineering, drug delivery, bone scaffolds
Polylactic acid (PLA)	Dichloromethane, DMF	Biomedical membranes, drug delivery
Polyvinyl alcohol (PVA)	Water	Wound dressings, filtration
Polyacrylonitrile (PAN)	DMF	Carbon nanofibers, filtration
Polystyrene (PS)	THF, DMF	Filtration, catalysis, sensors
PLGA (Poly(lactic-co-glycolic acid))	THF:DMF (1:1)	Tissue engineering, drug delivery
Polyethylene oxide (PEO)	Water, Water:ethanol, Isopropanol:water	Microelectronics, filters
Polyurethane (PU)	DMF	Protective clothing, filters
Polyvinylidene fluoride (PVDF)	DMF:DMAc (1:1)	Sensors, ribbons
Nylon-6,6 / Polyamide 6,6 (PA-6,6)	Formic acid	Smart clothing, filtration
Polybenzimidazole (PBI)	DMAc	Protective clothing

Polymer	Solvent(s)	Applications
Polycarbonate (PC)	DMF:THF, DCM, Chloroform	Sensors, filters, clothing
Polyvinylpyrrolidone (PVP)	Water, Ethanol	Drug delivery, tissue engineering
Chitosan	Acetic acid, Water	Wound dressings, drug delivery
Gelatin	HFIP, TFE	Tissue engineering
Silk fibroin	Water, Formic acid	Wound healing, tissue engineering
Collagen	HFIP	Tissue scaffolds
Cellulose acetate	Acetone, Acetic acid	Filtration, biomedical
Polyethylene-co-vinyl acetate (PEVA)	Not specified	Drug delivery systems
Polyaniline (PANI)	Chloroform, Camphorsulfonic acid	Conductive fibers

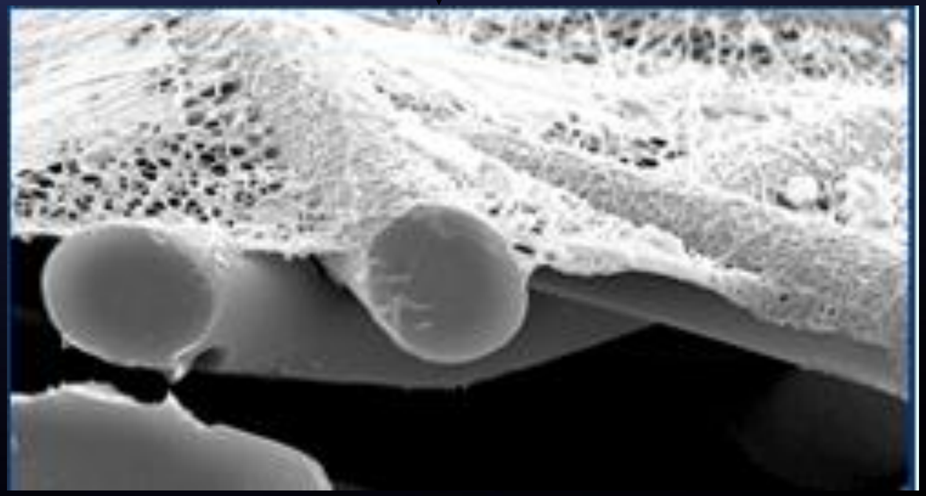
HUMAN SIDE OF TECHNOLOGY

Importance of electrospun mats for nano-microfibers in materials science – application areas

Application of nanofibers
Filters (air, liquid, gas, etc.)



Substratum is still clean



Electrospun nanofibers based filters for industry, household and defense applications have a history of more than 40 years, because electrospun nanofibers mats provides dramatic increase in filtration efficiency at relatively small decrease in permeability.

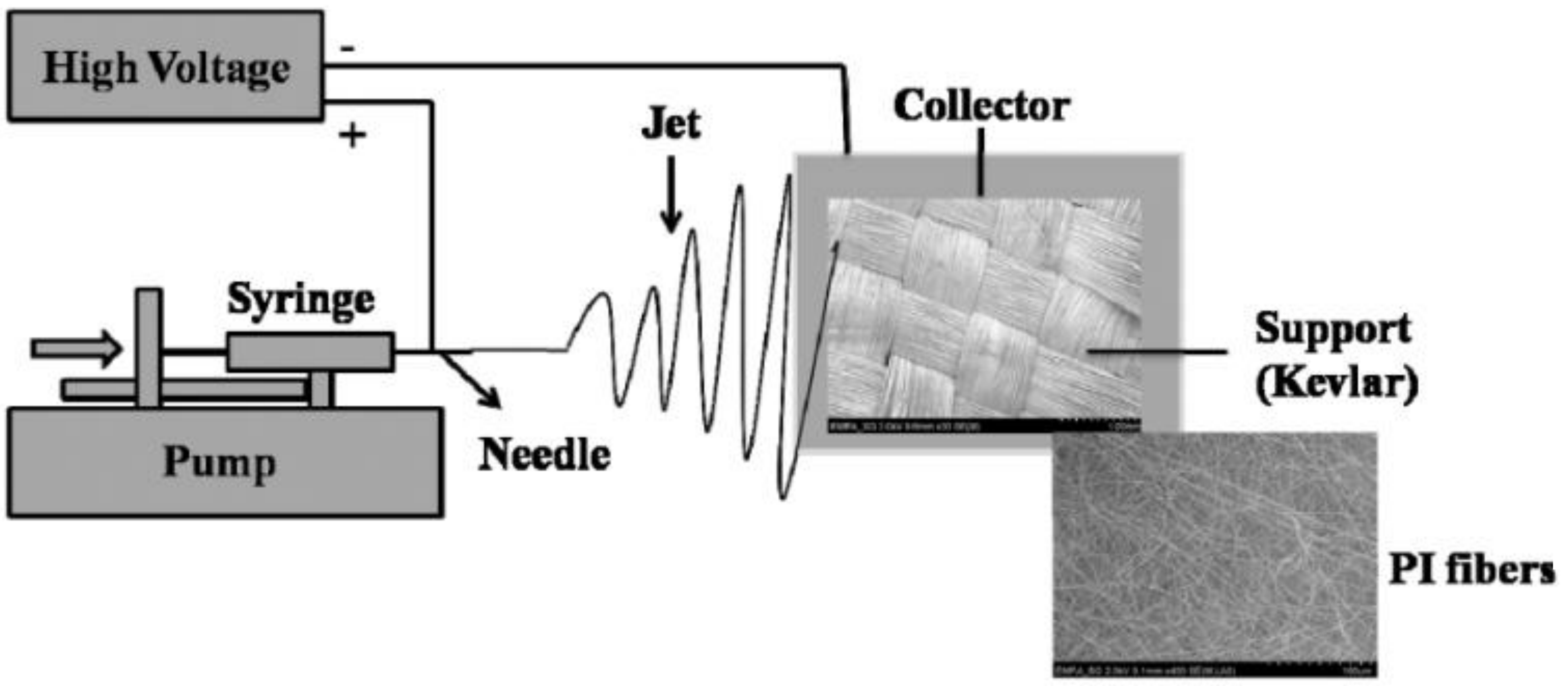
Due to the very high surface area to volume ratio tiny particles of the order of < 0.5 mm can be easily trapped in the electrospun nanofibrous structured filters. Electrospun nonwoven mats have successfully been developed into high-performance air filters. The nanofiber membrane shows an extremely effective removal (100% rejection) of airborne particles with diameters between 1 μm and 5 μm not only by the physical entrapment mechanism but also by the electrokinetic capture in the air filter.

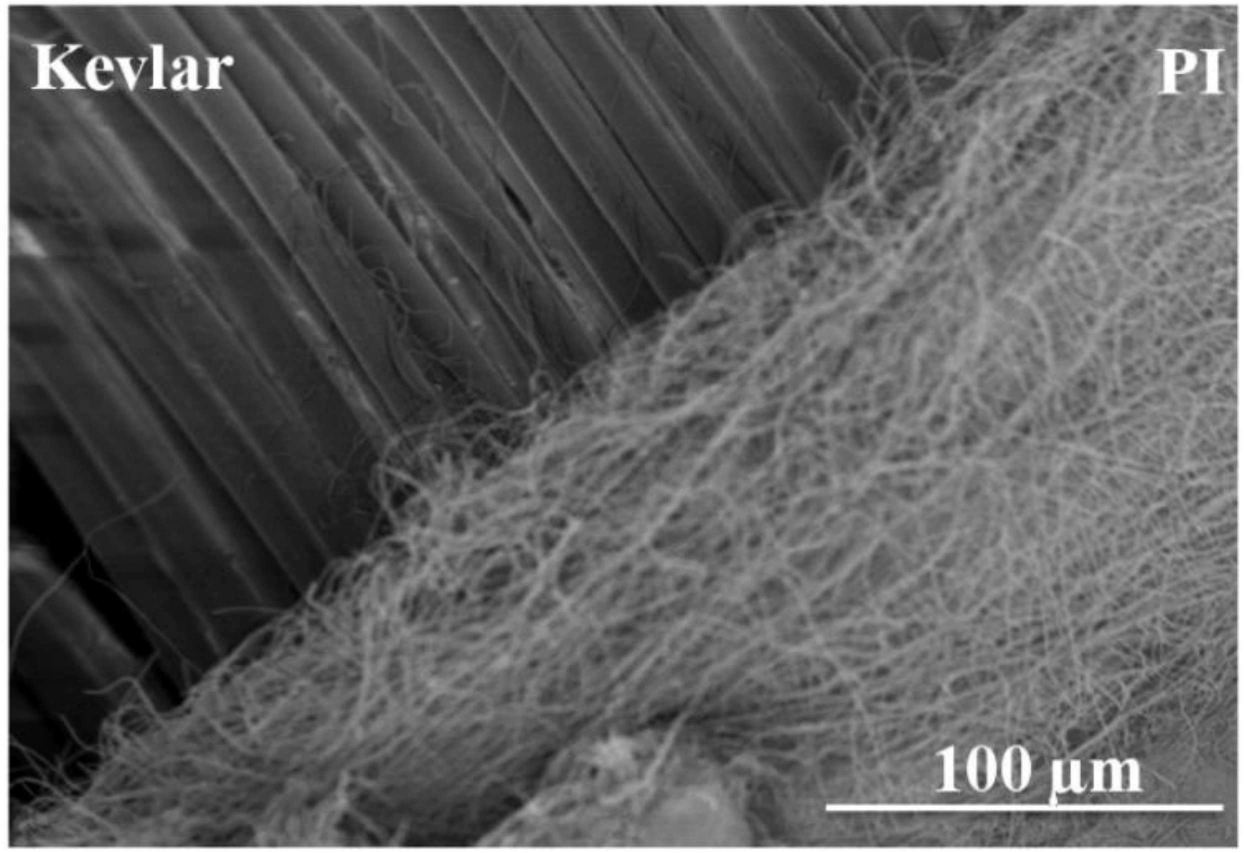
Biotechnology Advances 28 (2010) 325–347

Application of nanofibers
Protective cloths

Protective clothing should have properties such as:
- light weight,
- breathable fabric,
- air and water vapour permeability,
- insolubility in all solvents
- enhanced toxic chemical resistance.

Application of nanofibers
Protective cloths

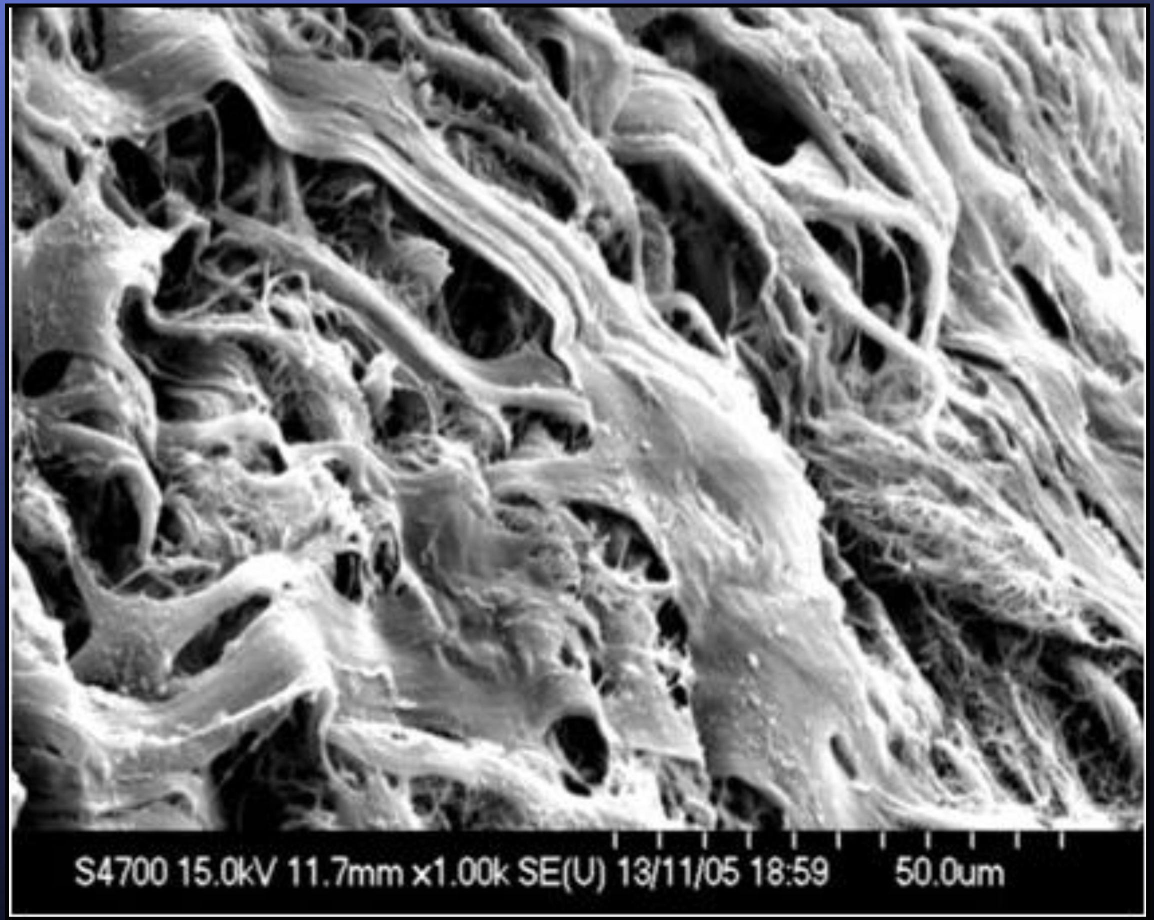


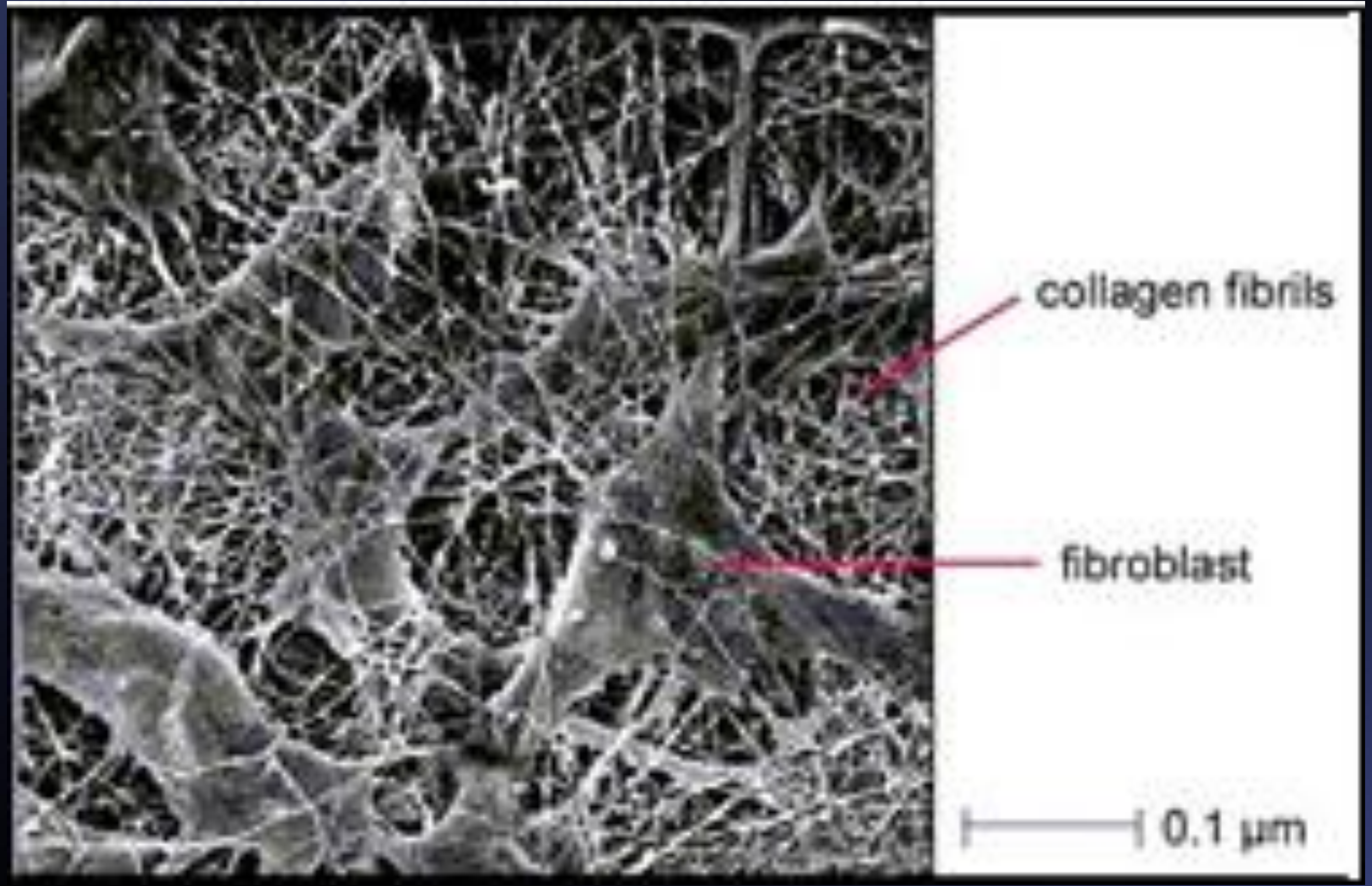


- Electrospinning of polyimides (PI) nanofibers on Kevlar woven fabric. PIs are a class of high-performance polymers that combine high thermal stability with good mechanical properties. PI represents an excellent polymer, due to its remarkable heat resistance, good mechanical strength and chemical resistance to solvents.

Textile Research JournalVolume 85, Issue 17, October 2015, Pages 1763-1775
https://doi.org/10.1177/0040517515576326

Application of nanofibers
Tissue engineering





SEM image of natural ECM (extracellular matrix (ECM) is the extracellular part of tissue that usually provides structural support to the cells in addition to performing various other important functions such as providing support and anchorage for cells, segregating tissues from one another, and regulating intercellular communication).

Biotechnology Advances 28 (2010) 325–347

Application of nanofibers Tissue engineering

Tissue engineering scaffolds should have characteristics:

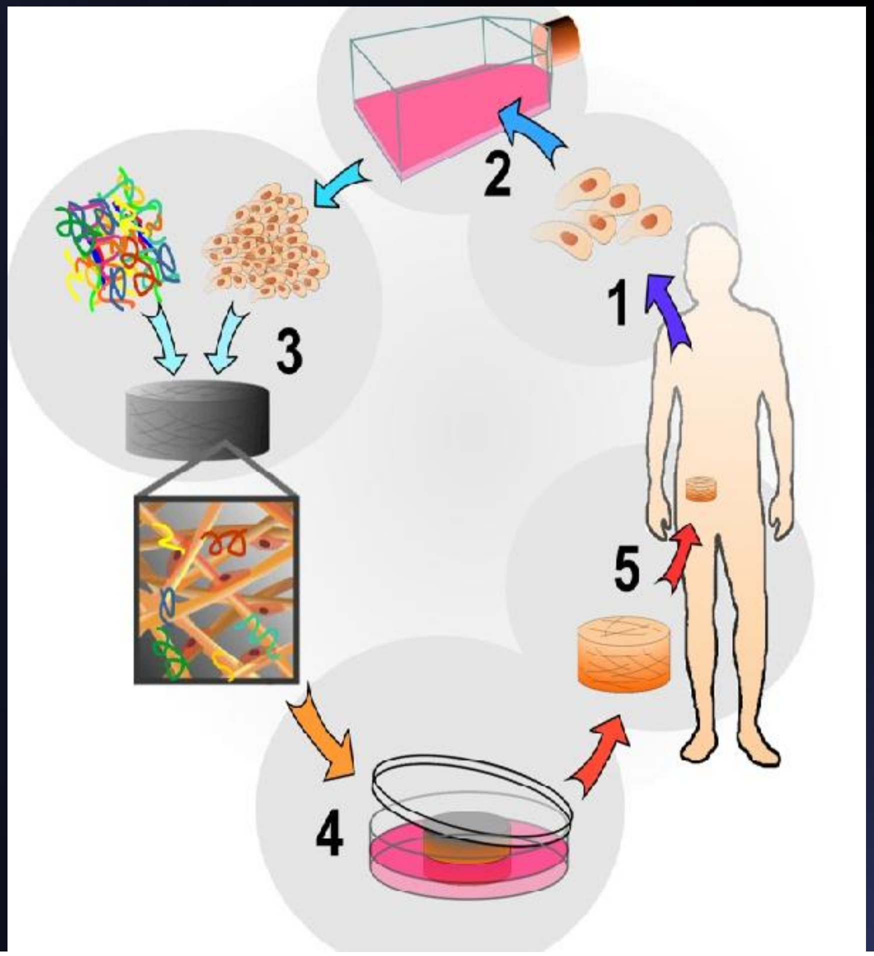
-Porosity of cell migration;

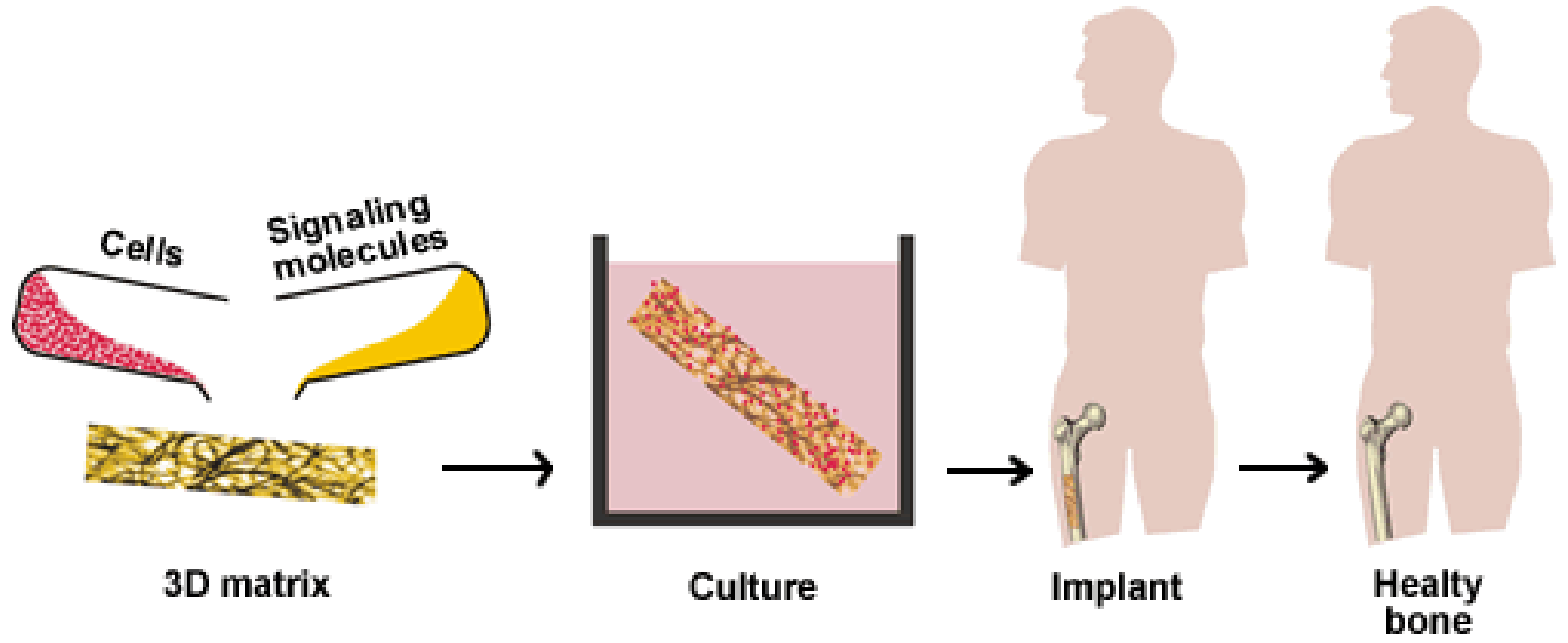
-Mechanical properties comparable to natural tissue to withstand natural loading conditions;

-Degradation capability so that it gets completely reabsorbed after implantation;

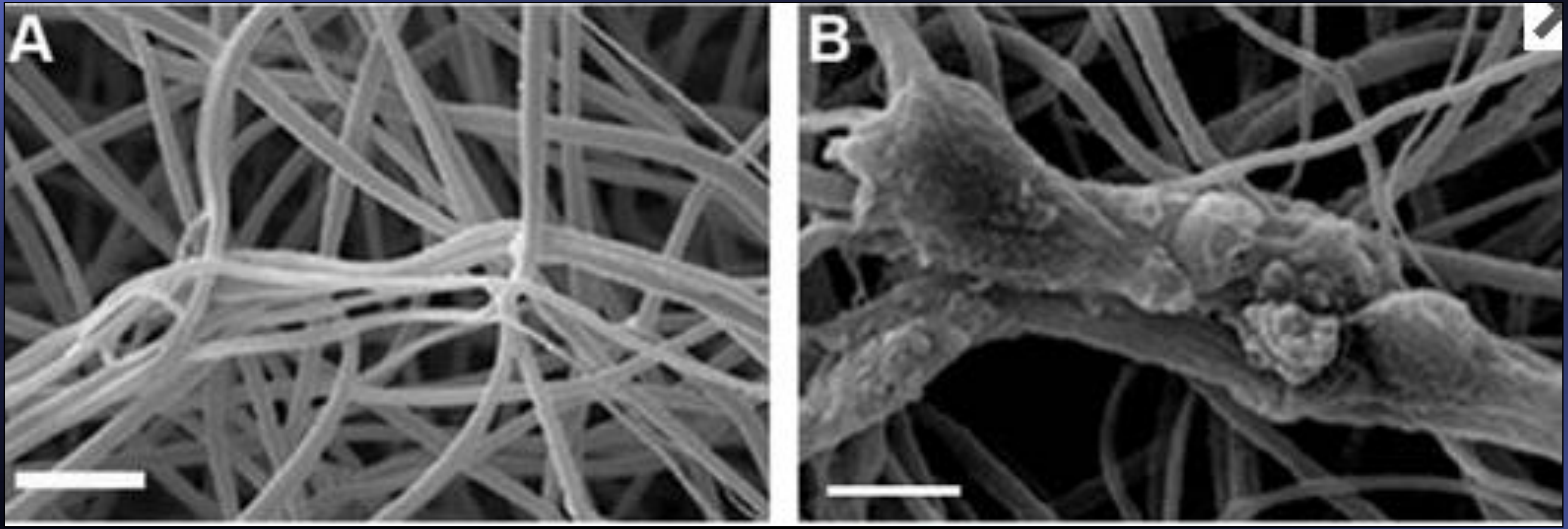
-Nontoxic;

-3D matrix.



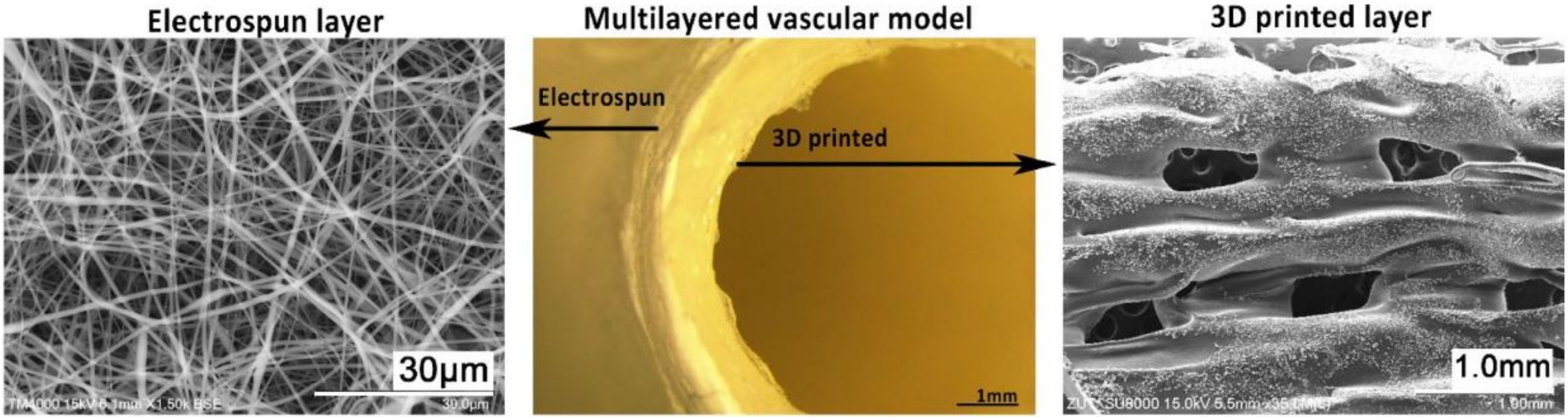


Application of nanofibers Tissue engineering



A) Nonwoven material from PLLA nanofibers B) cell of cartilige after 28 days

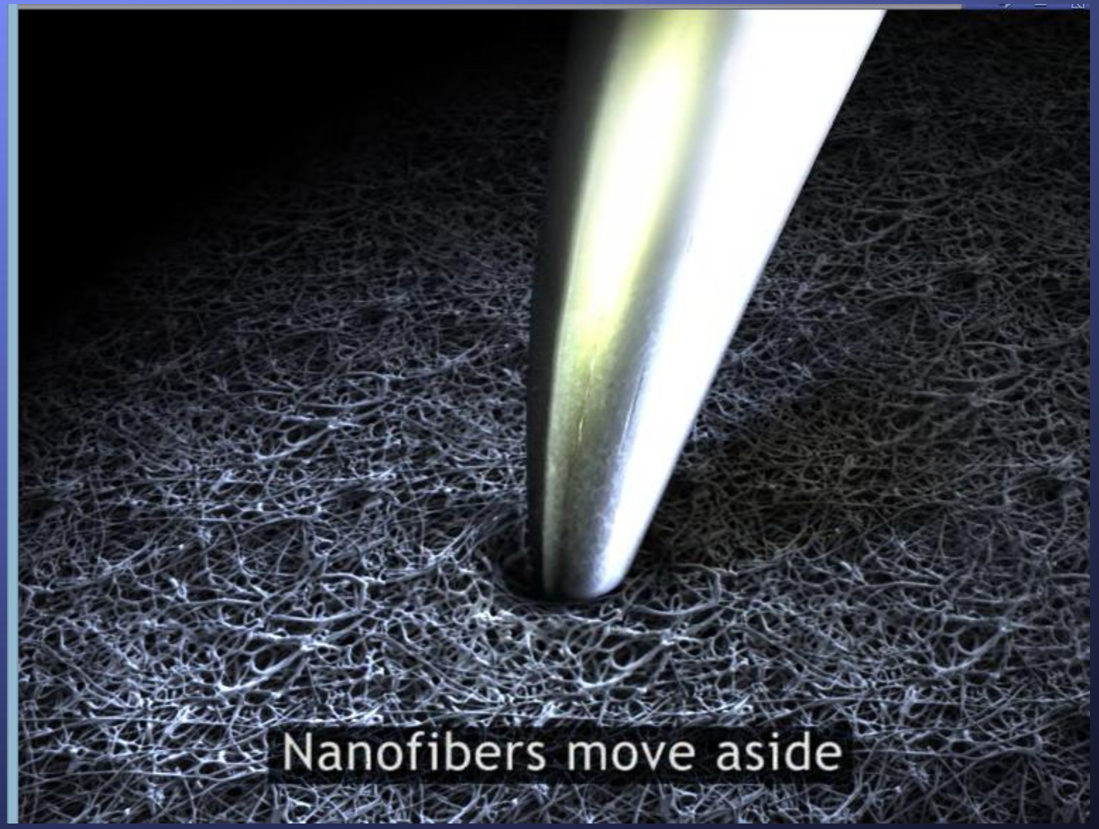
Vascular graft combining 3D printing and electrospinning

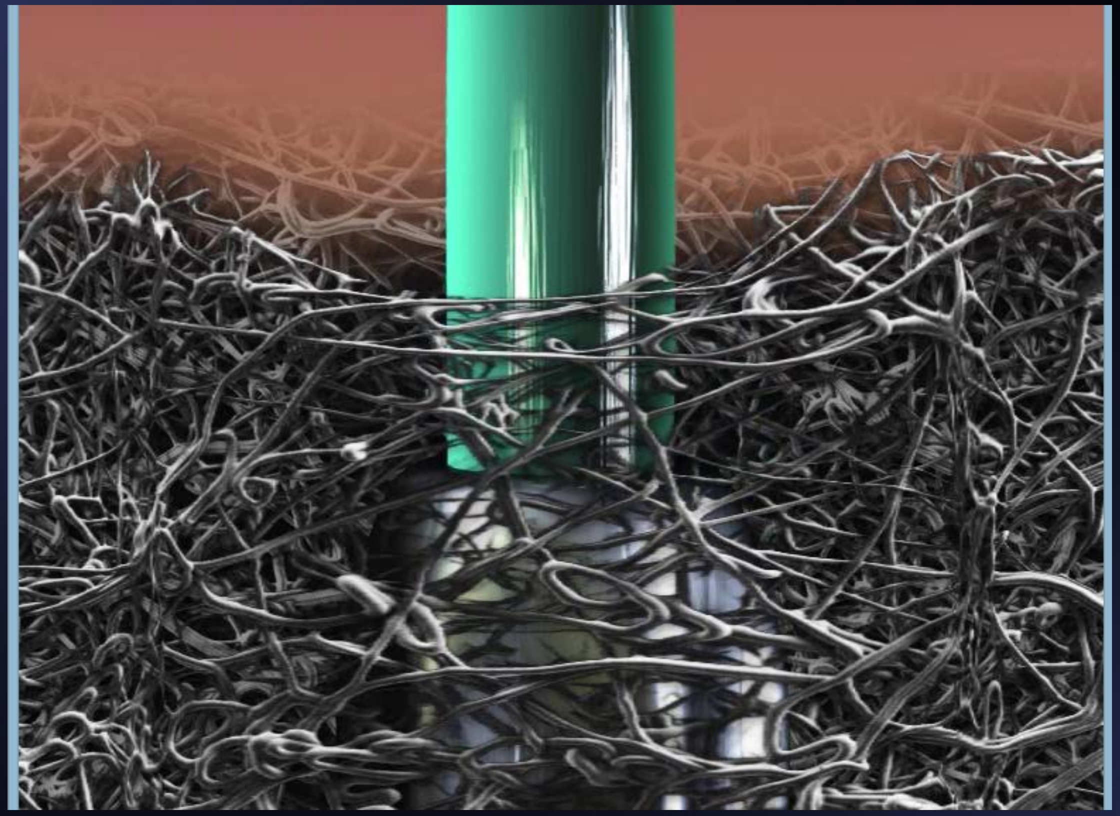


- Multilayered, multiscale tubular graft using the combined 3D-printed and electrospun fibers.

https://doi.org/10.1002/jbm.b.35525

Electrospun vascular graft





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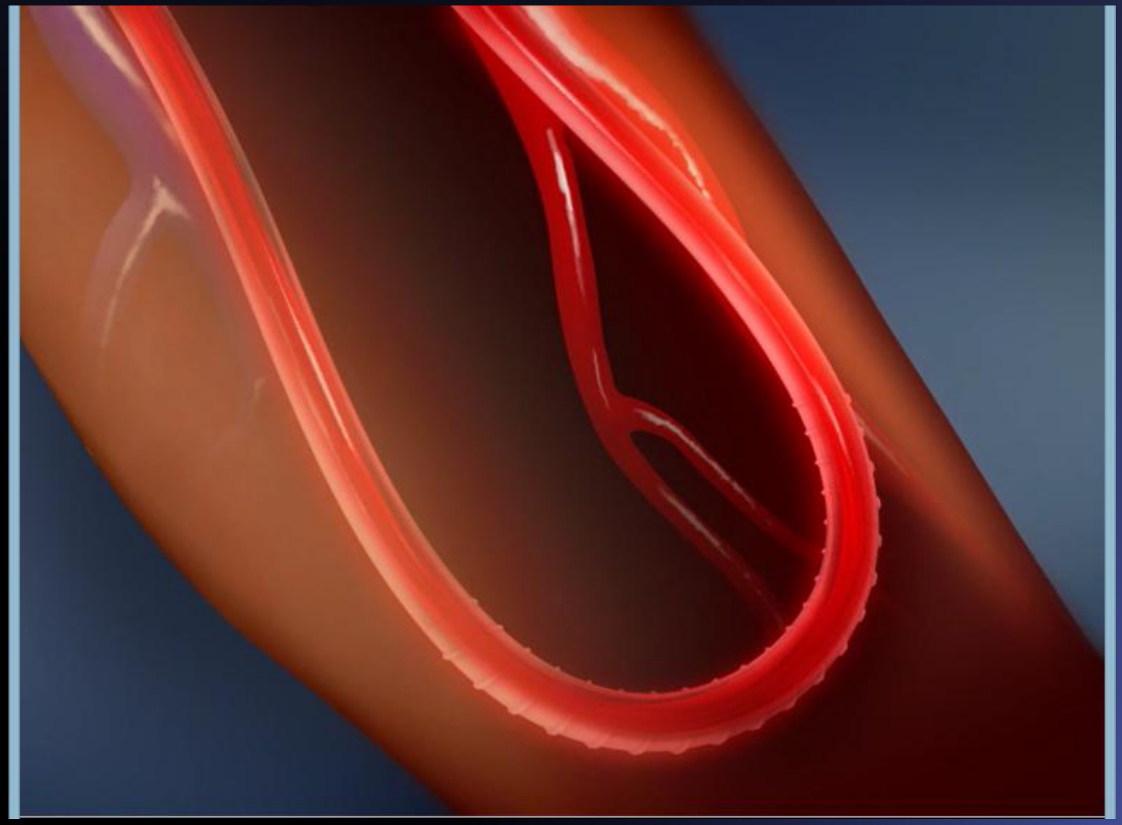
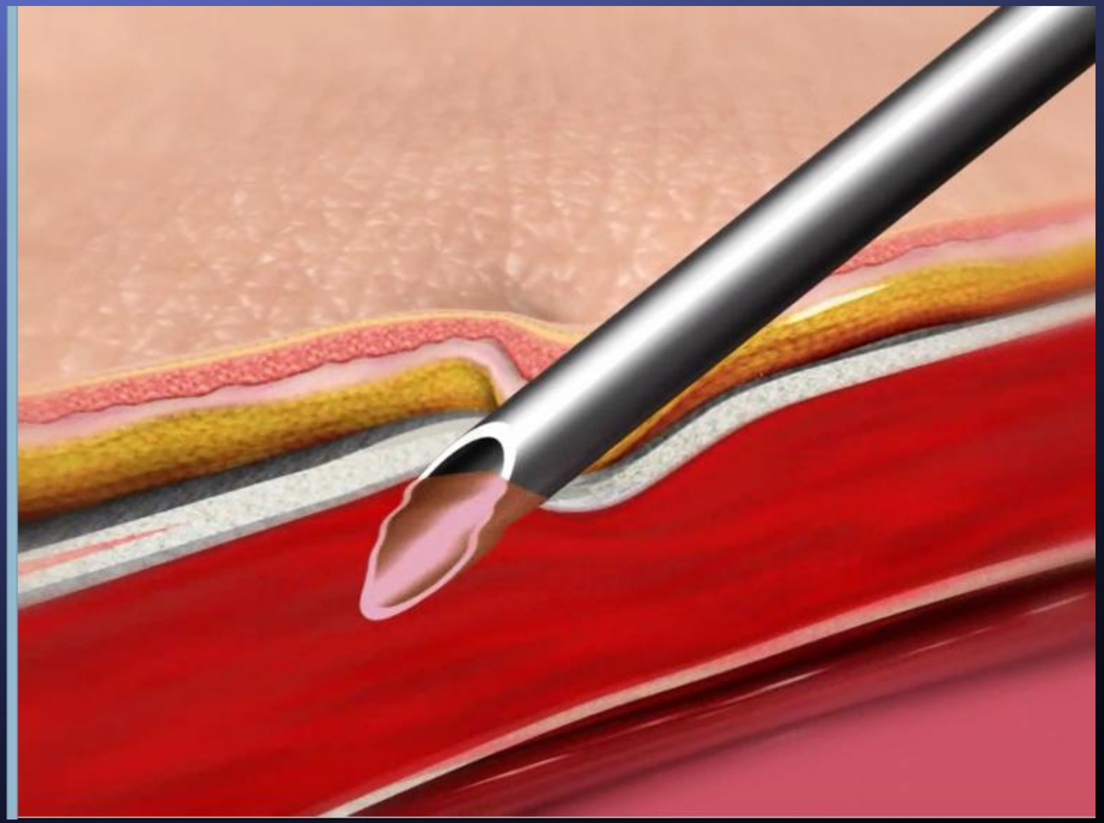
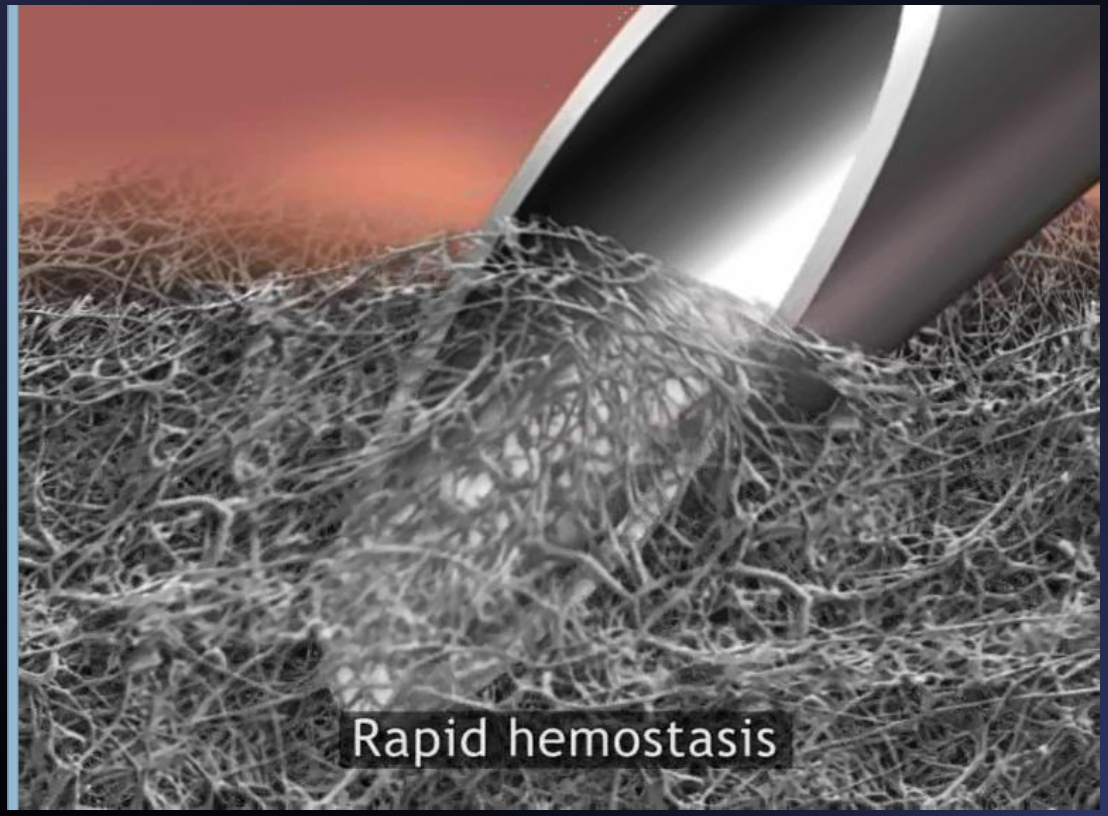
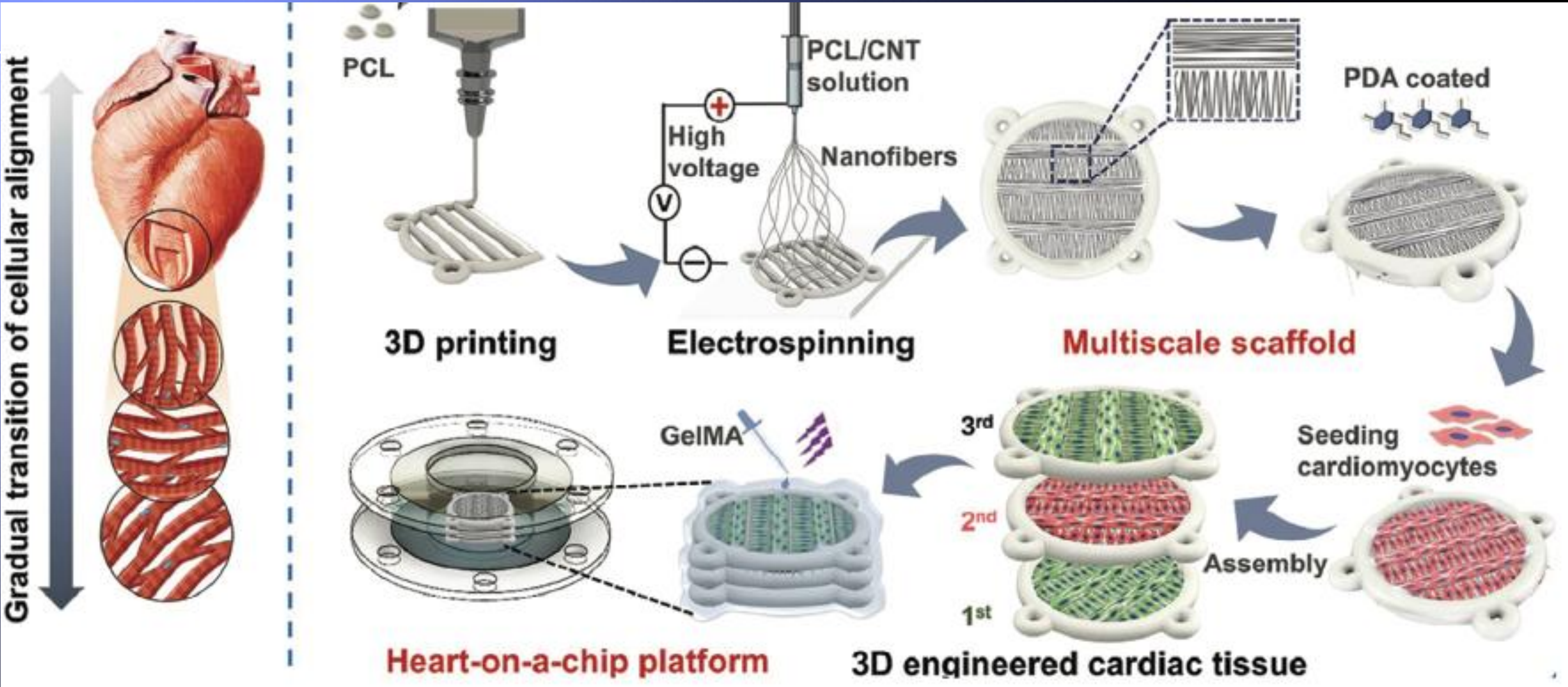


Electrospun vascular graft

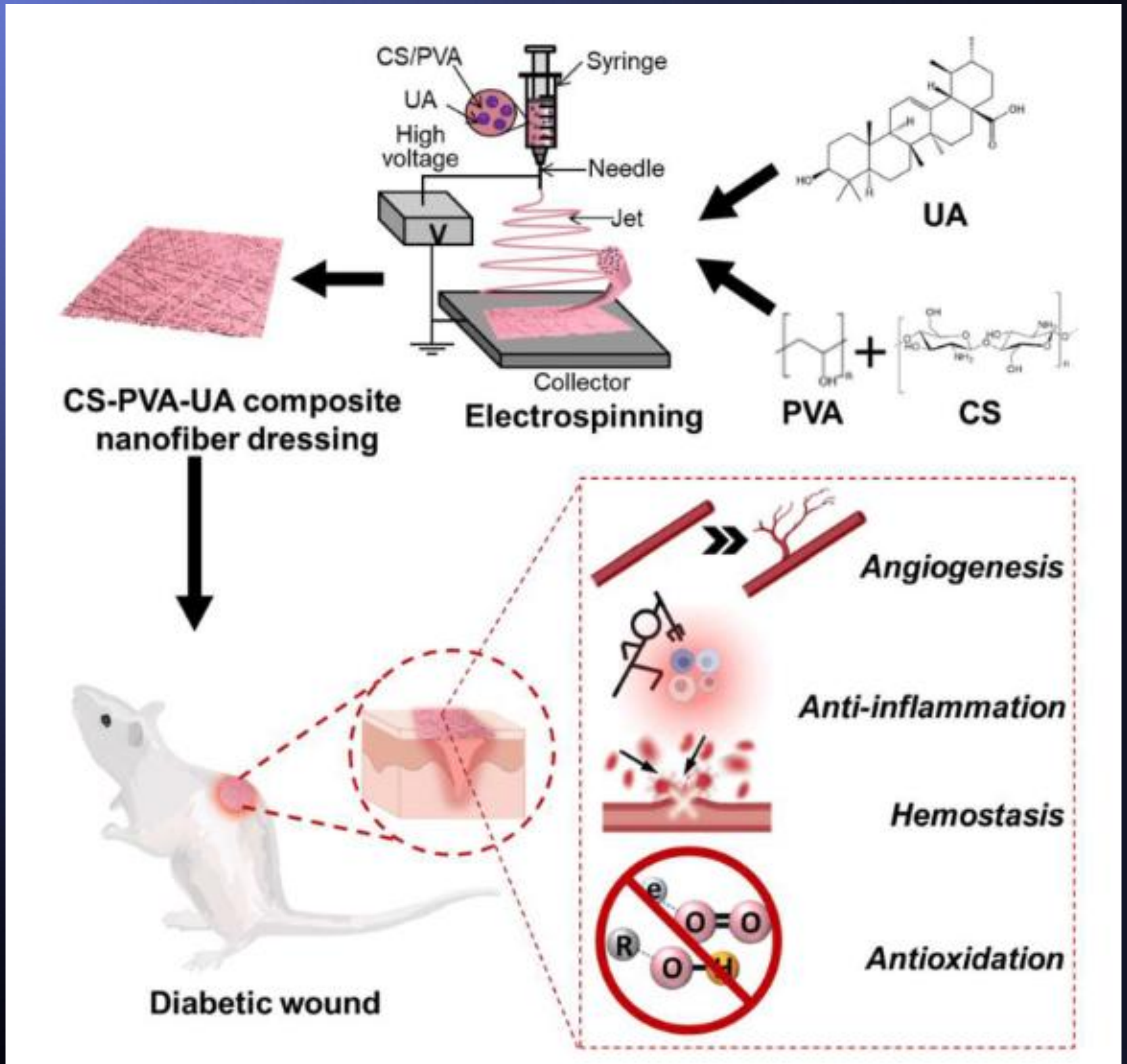






3D printing and electrospinning was used to create an anisotropic multiscale cardiac electrospun mat, which involves fabricating three-layer multiscale EM, and encapsulating them within photocurable GelMA hydrogel shell for evaluating drug-induced cardiotoxicity. The developed multilayer 3D scaffold demonstrates the ability to enhance cardiomyocyte maturation and synchronous beating behavior. Importantly, this scaffold provides individual control over cellular orientation on different layers within a 3D micro-environment. More attractively, the fabricated heart-on-a-chip platform via integrating the 3D bionomic cardiac tissues and a self-designed microfluidic perfusion system has also confirmed its capability for evaluating DIC, which could recapitulate the clinical manifestations of doxorubicin (DOX) and dexrazoxane (DEX) drugs.

https://doi.org/10.1002/adfm.202406950

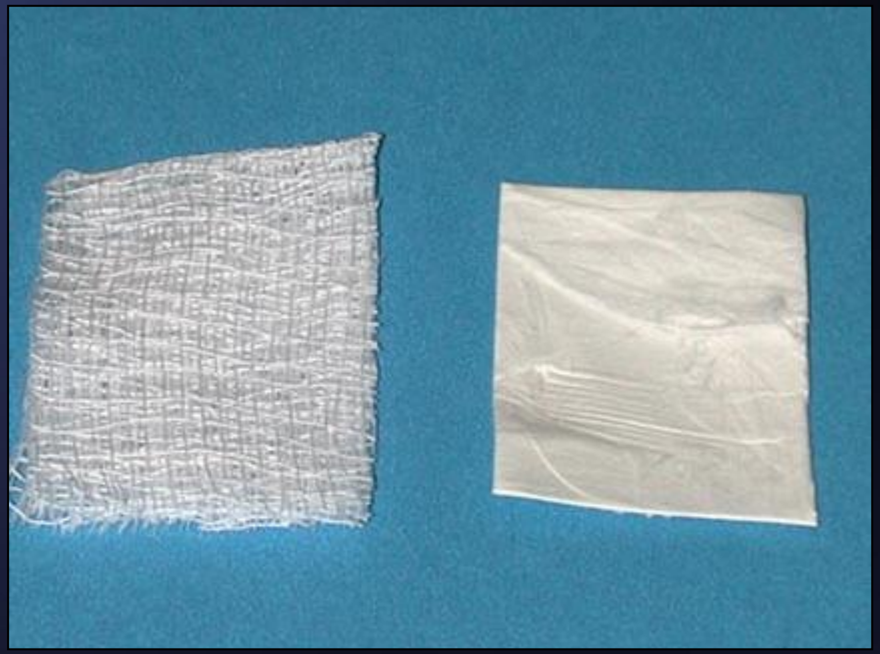


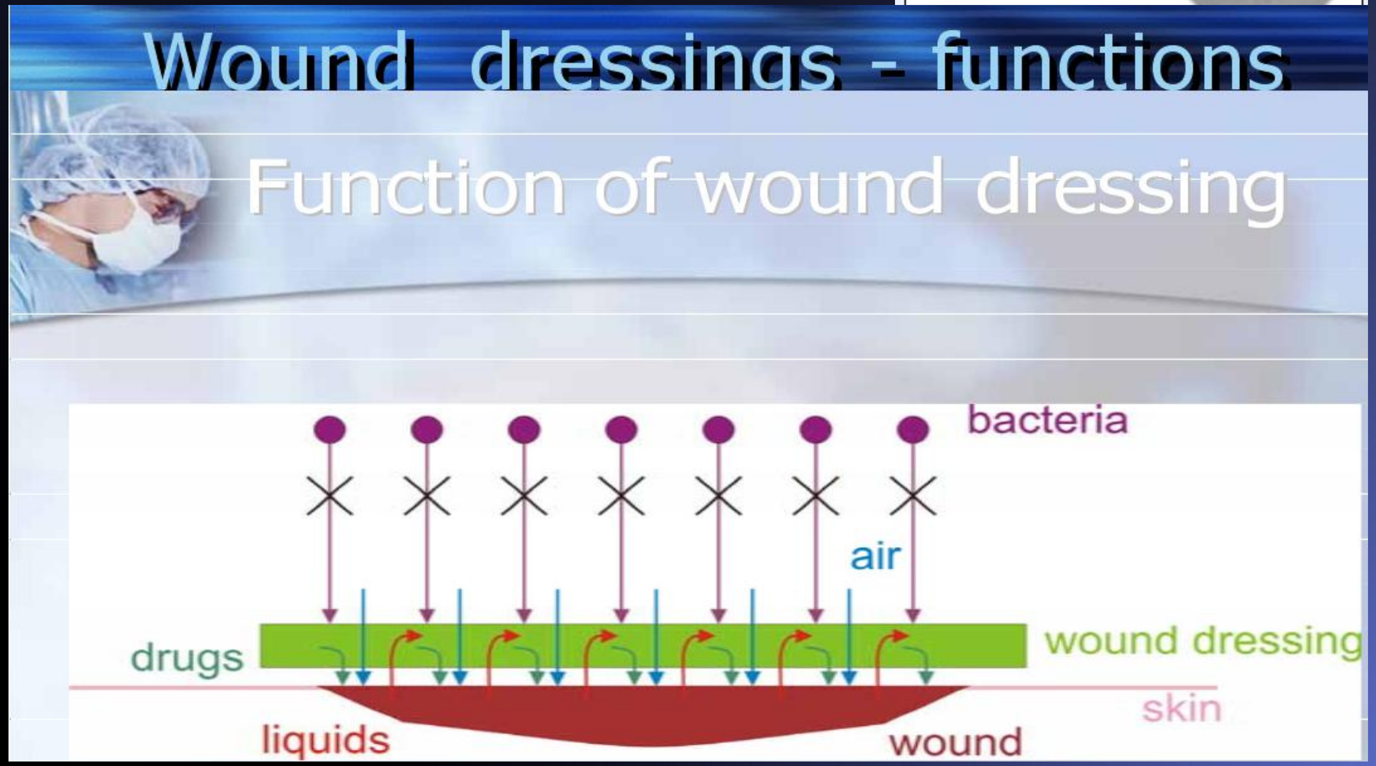
Wound healing is one of the most important applications of nanofibers. Nanofibers surface functionalized with antimicrobial biological macromolecules shows potential wound healing activity.

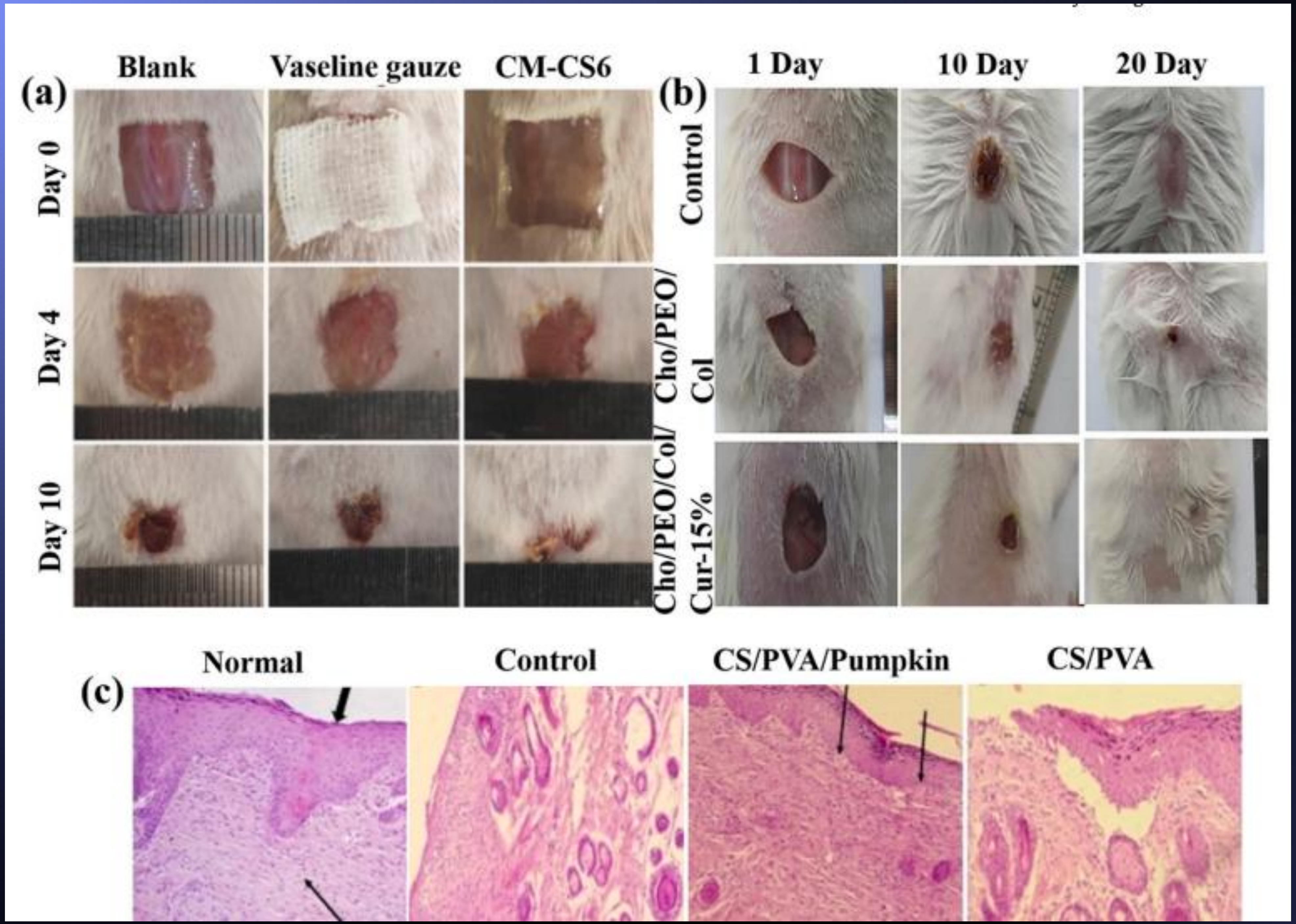
https://doi.org/10.1080/00914037.2024.2335173

Dressing for wound healing

For wound healing, an ideal dressing should has certain characteristics such:
-haemostatic ability,
-efficiency as bacterial barrier,
- absorption ability of excess exudates (wound fluid/pus),
- appropriate water vapour transmission rate,
- adequate gaseous exchange ability,
- ability to conform to the contour of the wound area,
- functional adhesion, i.e., adherent to healthy tissue but non-adherent to wound tissue,
- painless to patient,
- ease of removal.

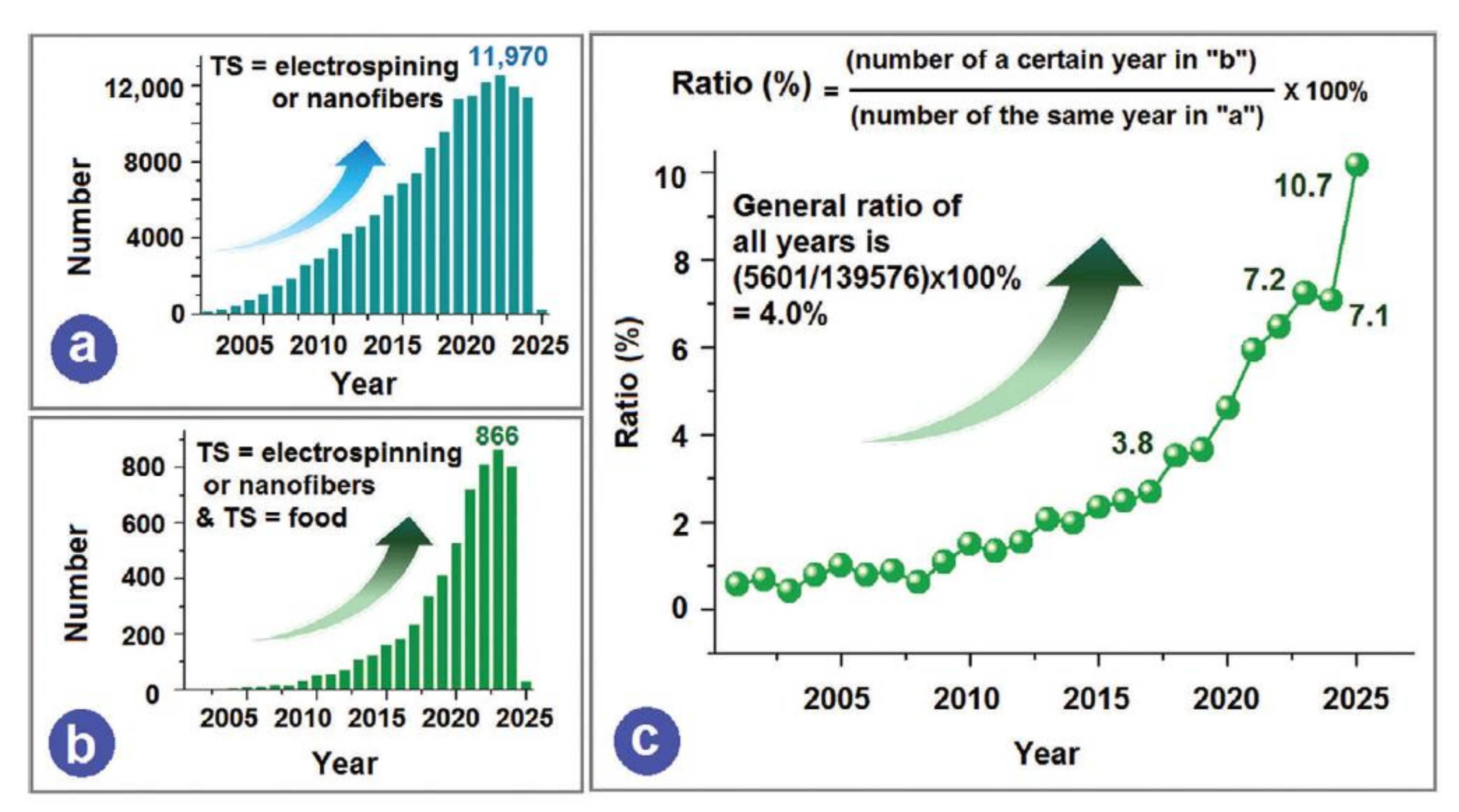






Examination of the wound healing potential of the electrospun nanofibers. (a) Wound healing efficiency of the CS-based nanofibers at indicated periods, (b) Wound healing potential of CS/Col nanofibers at indicated periods, and (c) H&E staining images of skin excisional wound healing of different animal groups after 10 days of implantation. [https://doi.org/10.1016/j.ijbiomac.2024.139426.]

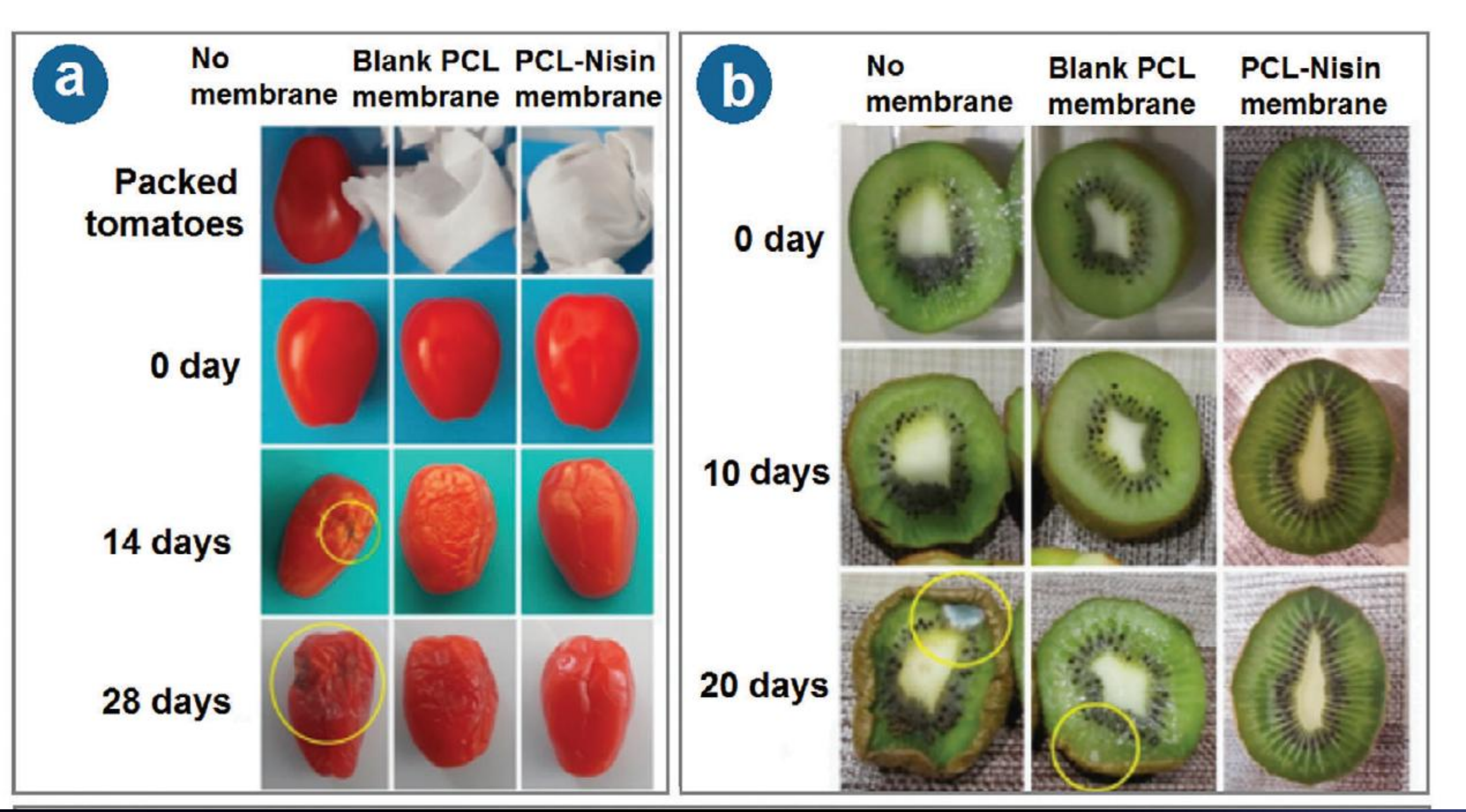
Electrospining for food packaging engineering



The increase trends of a) electrospinning b) electrospinning in food engineering.

https://doi.org/10.1002/marc.202401152

Electrospining for food packaging engineering



Electrospun material for food packing

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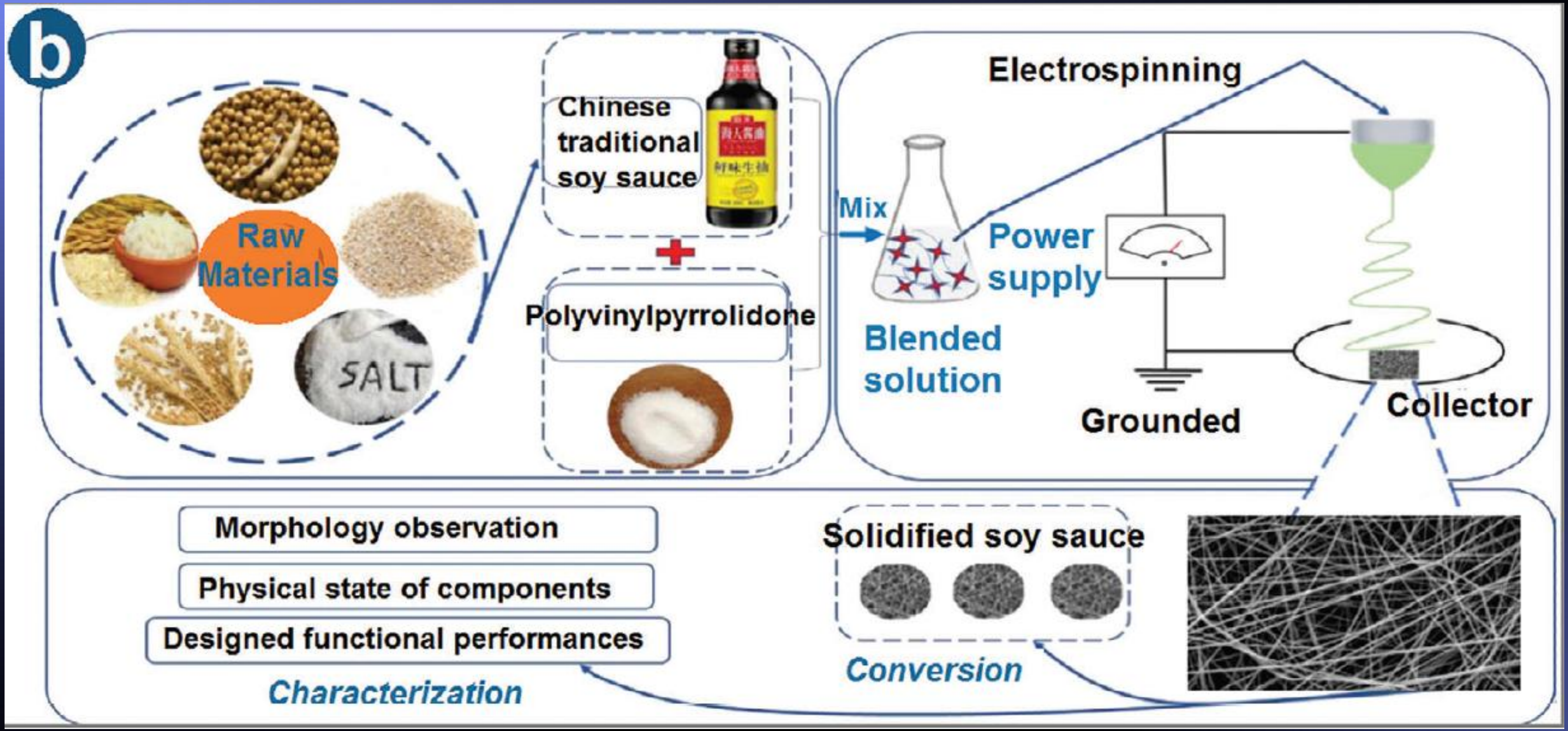
https://doi.org/10.1002/marc.202401152

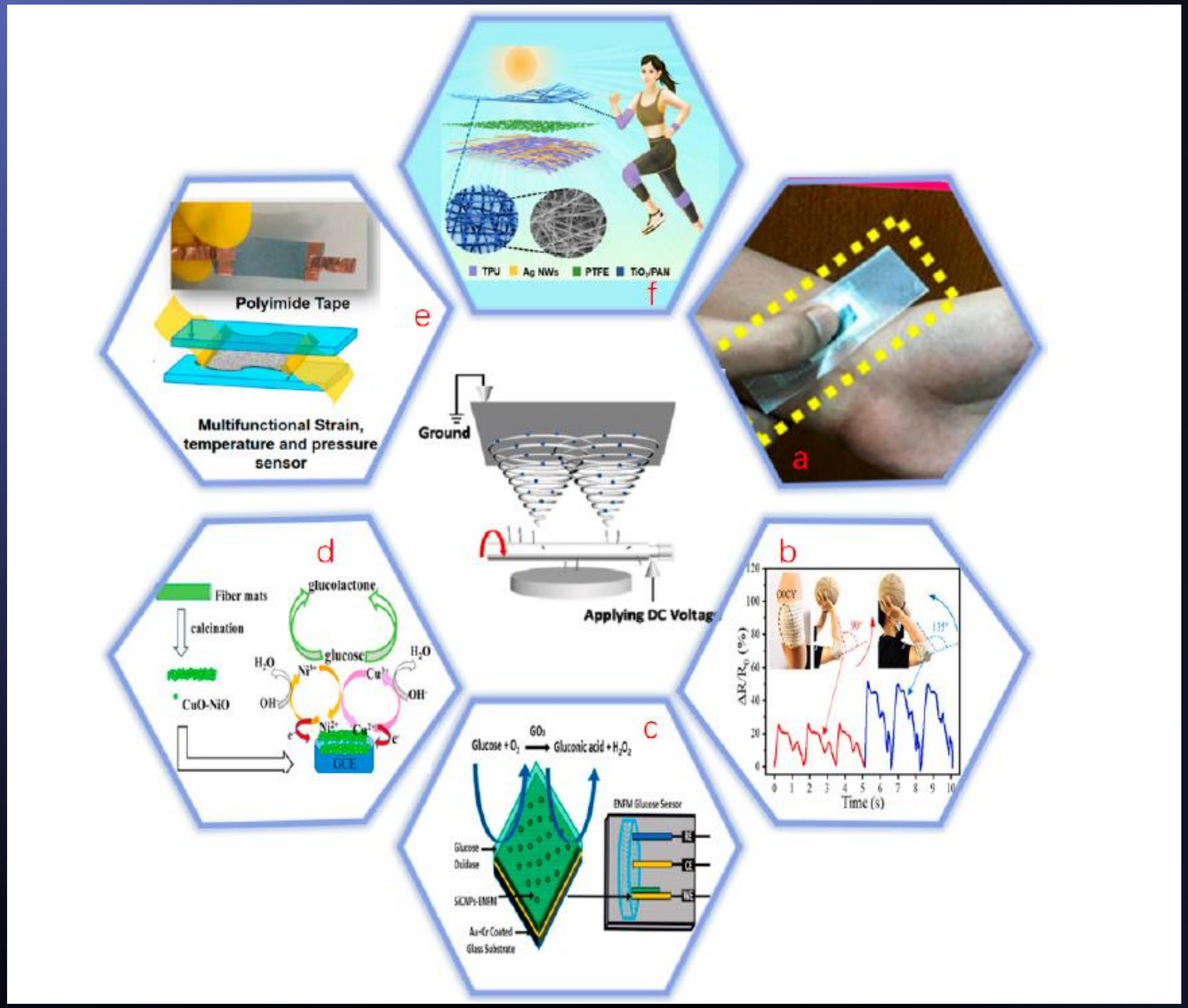
Electrospining for food engineering



Electrospun material for food production:Solid soy sauces produced using electrospinning from the traditional liquid Chinese soy sauces and water-soluble polymer PVP

https://doi.org/10.1002/marc.202401152

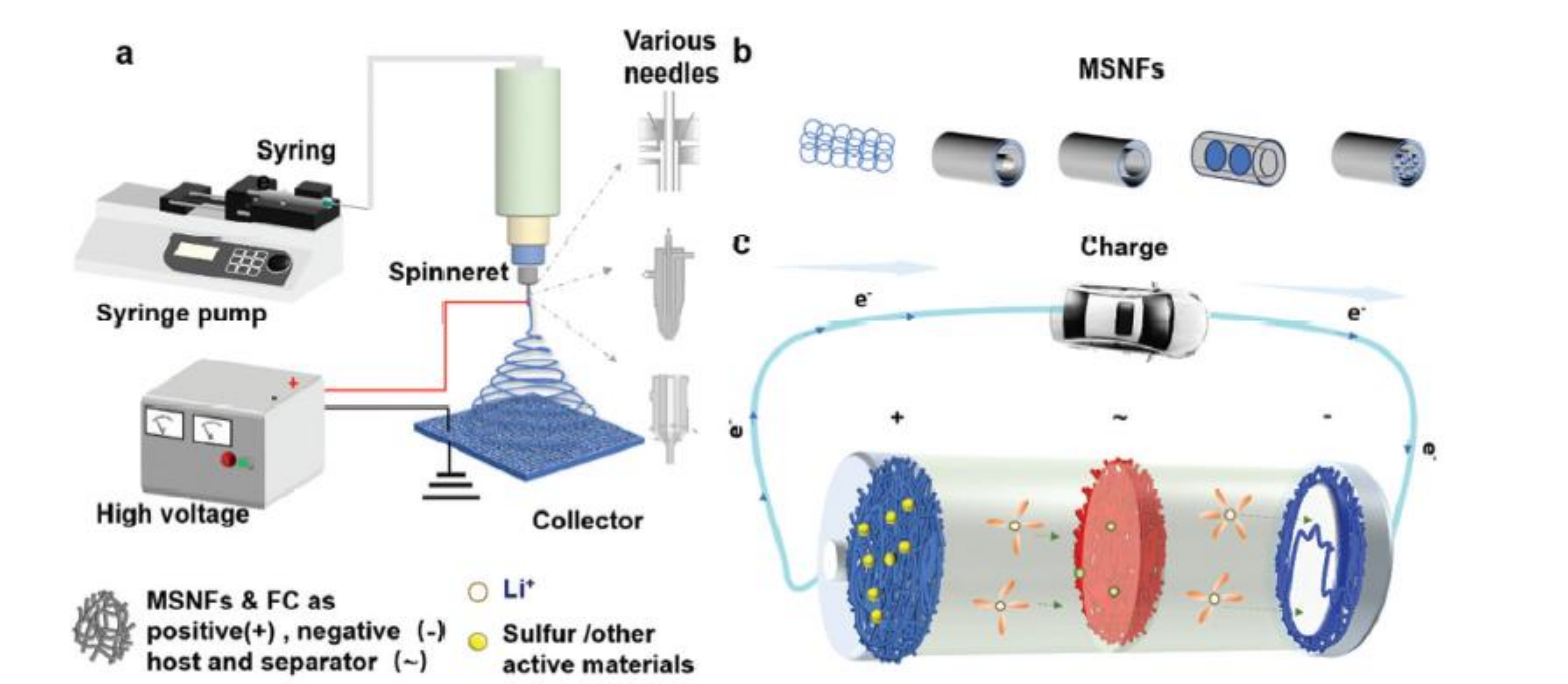
Electrospinning for biosensors



Specific applications of electrospinning-based biosensors: (**a**) monitor heart rate. (**b**) monitor body movement; (**c**) enzymatic biosensor for detecting glucose concentration (**d**) non-enzymatic biosensor to detect glucose concentration; (**e**) detect body temperature. (**f**) detect UV intensity.

https://doi.org/10.3390/bios12100876

Electrospinning for lithium-based batteries



a) Fundamental configuration for electrospinning. b) Multiscale structured nanofibers (MNSF) including hierarchical structure (HR), wire-in-tube (WIT), tube-in-tube (TIT), SMT (segmented tubes) and multichannel (MC) prepared by electrospinning. c) The mechanism of MSNFs to enhance the performance of lithium-based batteries.

https://doi.org/10.1002/aenm.202403983

HUMAN SIDE OF TECHNOLOGY

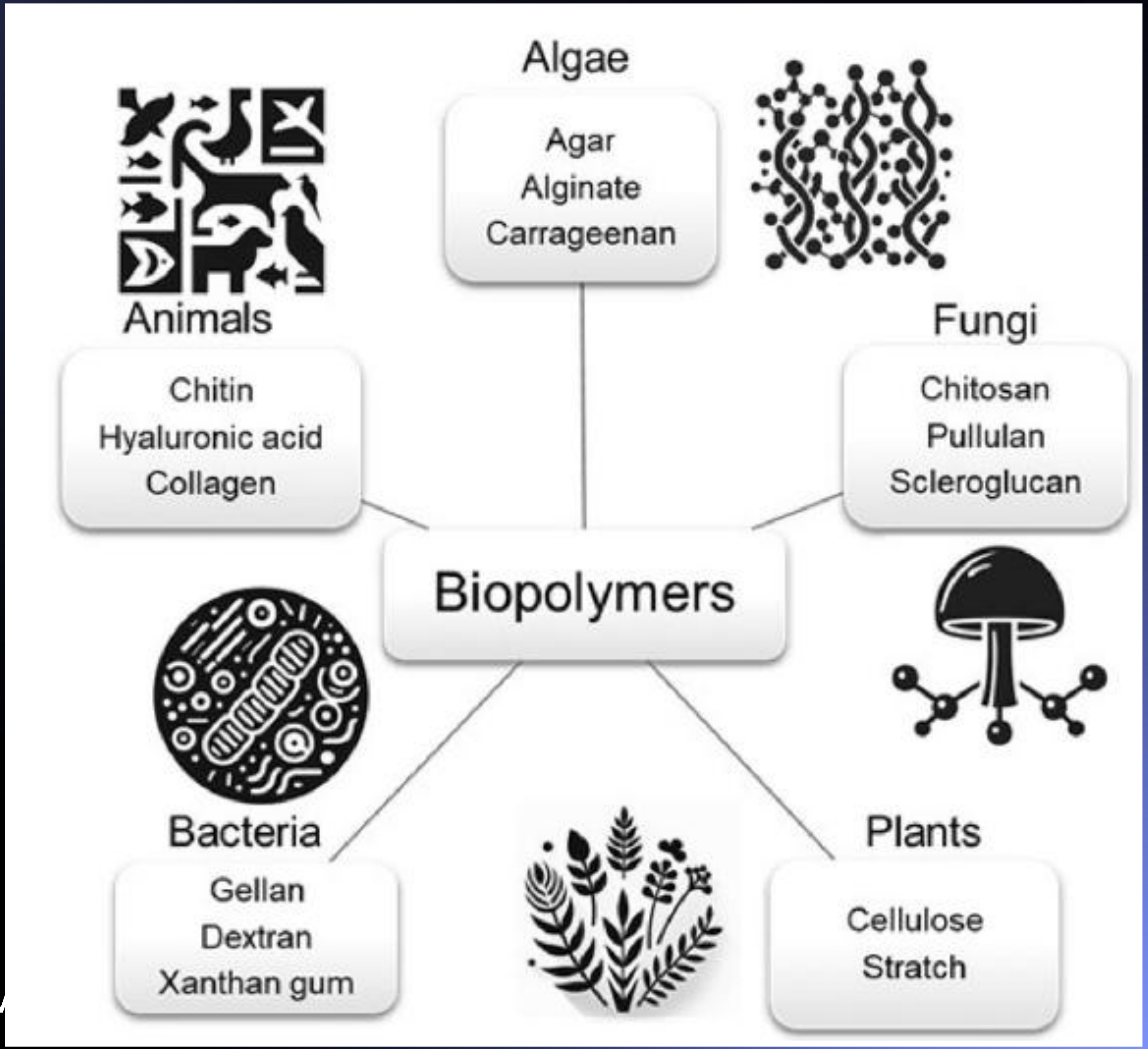
Correlation between growing demand for sustainable materials and electrospinning. Is it possible?

Due to increasing environmental concerns: as climate change, pollution, and depletion of natural resources, pushed societies to seek ***alternatives*** that reduce carbon emissions, waste, and resource use. Also, consumers are becoming more aware and prefer eco-friendly and ethically produced products. Governments also play a key role by introducing stricter regulations, such as limits on plastic use and requirements for recycling and low-carbon production.

One of alternatives to use more biopolymers.

Classification of biopolymers:

Biopolymers			Synthetic biopolymers
Plant - derived biopolymers	**Animal - derived biopolymers**	**Microbes based biopolymers**	
Starch (potato, rice, wheat, corn)	Casein	Polyhydroxy alkanoates	Polylactic acid (PLA)
Cellulose (wood, cotton)	Collagen	Poly-β-hydroxy butyrate (PHA)	Other polyesters (Polyethylene furanoate (PEF), Polybutylene Succinate (PBS))
Soy	Gelatin	Bacterial cellulose	
Lignin	Keratin	Xanthene	
Gums	Elastin	Pullulan	
Alginates	Silk fibroin		
Zein	Chitosan		
Inulin	Hyaluronic acid		
Pectin	Fibrinogen		
Whey protein			



https://doi.org/10.1002/pol.20241010

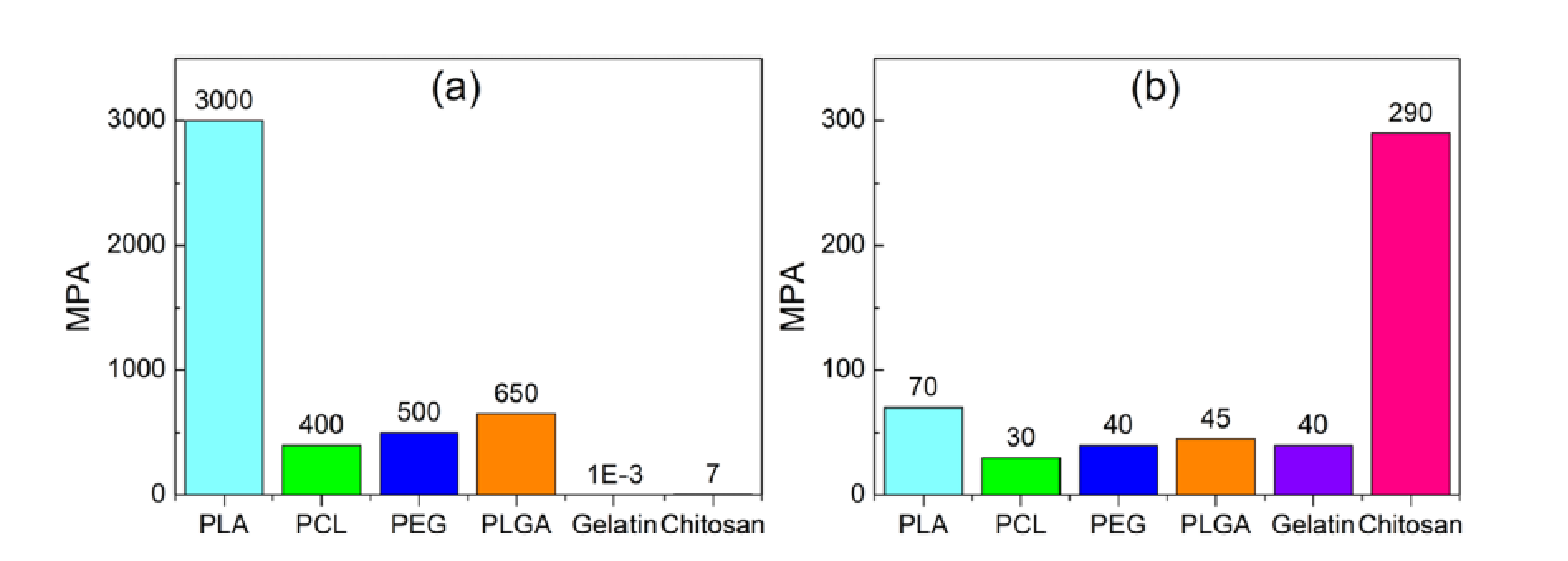
BIOPOLYMER	ADVANTAGE	DISADVANTAGE
Chitosan	Biodegradable, biocompatible, regulate inflammation and promote hemostasis, antibacterial, and adhesive	Weak mechanical strength and poor solubility in water
Colagen	Biocompatible, hydrophilic, ease to functionalize, and promotes tissue regeneration	Limited osteo- inductive potential, and mechanical strength
Silk fibroine	Biocompatible, biodegradable, and promotes tissue regeneration	Limited water solubility and mechanical strength
Alginate	Biocomtatible, biodegradable	Weak mechanical strength
Hialuronic acid	Biocompatible, hydrophilic, and promotes tissue regeneration	Limited mechanical strength and degradation rate
Starch	Biocompatible, biodegradable and good mechanical strength	Limited water retention capacity
Gelatin	Biocompatible, biodegradable, easily available, and low cost	Limited mechanical strength

[https://doi.org/10.1016/j.ijbiomac.2024.139426]

Biopolymers derived from natural resources—such as **Chitosan, Alginate, Colagen, Silf fibroine and starch**—are attractive candidates for electrospun nanofibre fabrication due to their **abundance, low cost, biodegradability, and biocompatibility**.

Thought

Most naturally derived biopolymers lack sufficient **mechanical strength**, limiting their broad applicability.



a) Young modules;
b) Tensile Strength

Biopolymer	Primary degradation mechanism	Degradation rate (in vivo)	Degradation rate (in vitro)	Key factors influencing degradation
PLA	Hydrolysis, enzymatic	Months to years	Months to years	Molecular weight, crystallinity, pH, and temperature
PCL	Hydrolysis	Months to years	Months to years	Molecular weight, crystallinity, and porosity
PEG	Hydrolysis	Days to weeks	Weeks to months	Molecular weight and concentration
PLGA	Hydrolysis	Weeks to months	Weeks to months (faster than in vivo)	Lactic-to-glycolic ratio, pH, and molecular weight
Gelatin	Enzymatic	Days to weeks	Days to weeks	Cross-linking density and enzyme availability
Chitosan	Enzymatic, hydrolysis	Weeks to months	Weeks to months	Degree of deacetylation and molecular weight

This limitation of MECHANICAL PROPERTIES can be addressed through the chemical functionalization of natural polymers or blending with synthetic polymers. Synthetic polymers, such as PVA, PCL and PEO, are commonly employed to fabricate electrospun nanofibers for various applications. Synthetic polymers offer superior mechanical strength compared to natural biopolymers.

https://doi.org/10.1002/pol.20241010

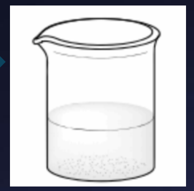
Preparation of natural proteins for electrospinning solution

BY PRODUCT PROTEINS

PROTEIN EXTRACTS WITH HELIX STRUCTURE

MIXURE OF PROTEIN WITH ELECTROSPINAMBLE POLYMER SOLUTION

Bovine Tanned Leather → Concentrate collagen hydrolysate →



Pickled Rabbit Skin → Rabit collagen →

Sheepskin Wool → Keratin hydrolizate →

Sheepskin Wool

Rabbit collagen

Keratin hydrolizate

Keratin, collagen hydrolysate, rabit collagen prepared by projects partners Research and Development National Institute for Textiles and Leather-Division Leather and Footwear Research Institute, Bucharest, Romania

Preparation of extracts from natural biological active materials

Salvia officinalis

Eucalyptus globulus

Matricaria chamomilla

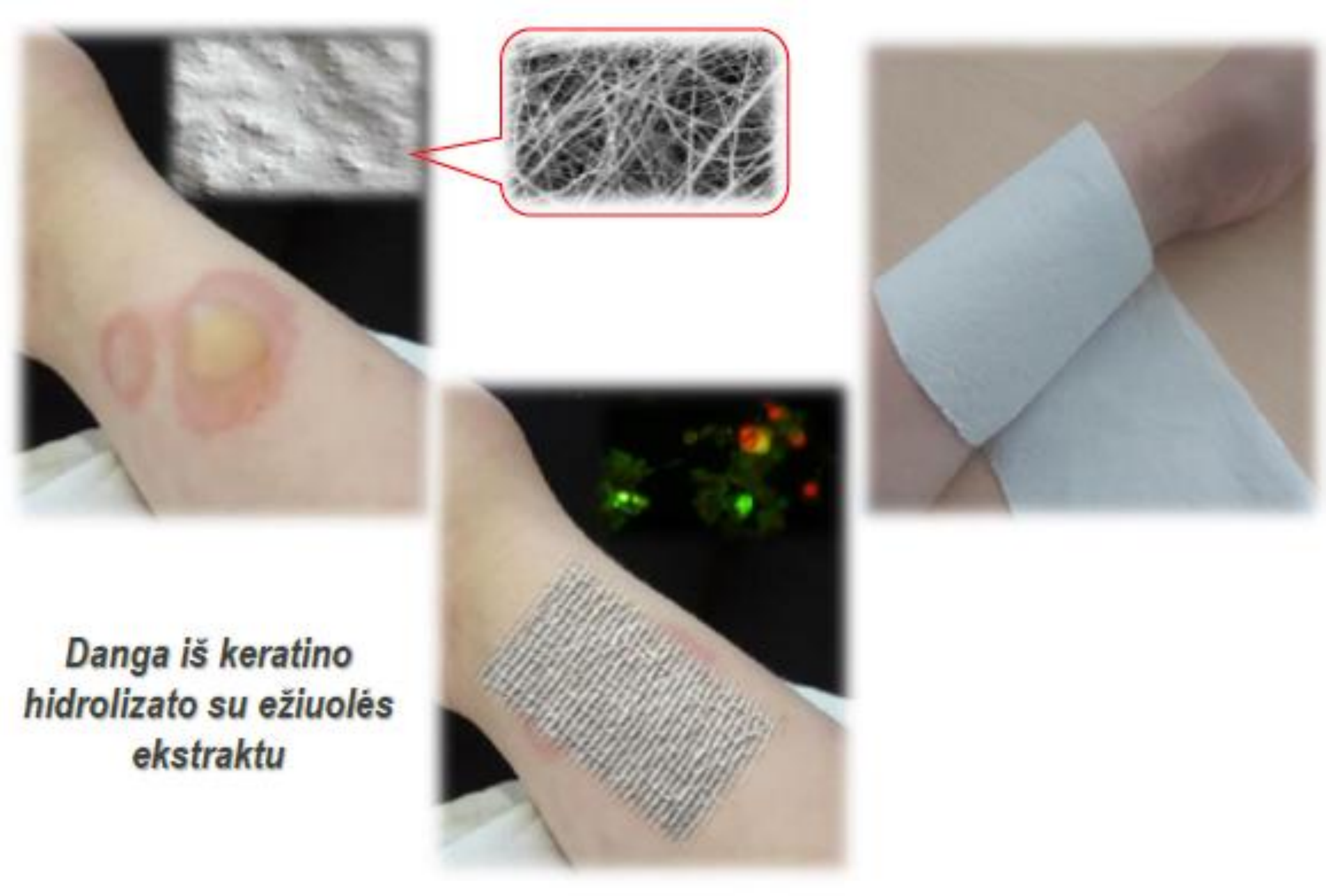
Calendula officinalis

Echinacea purpurea L.

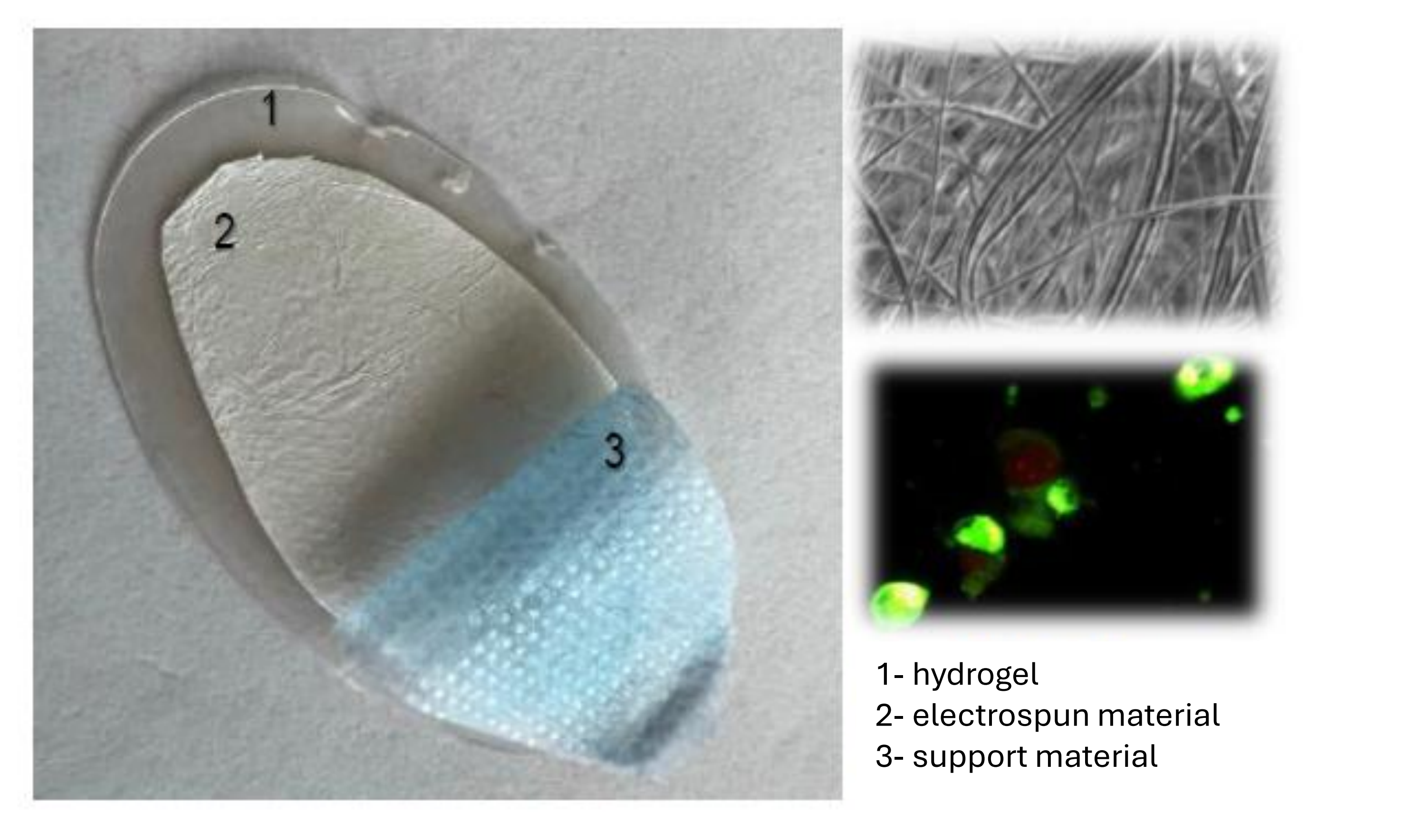
Extraction Filtration Evaporation

Dry biological active materials

Preparation of biological materials solvents

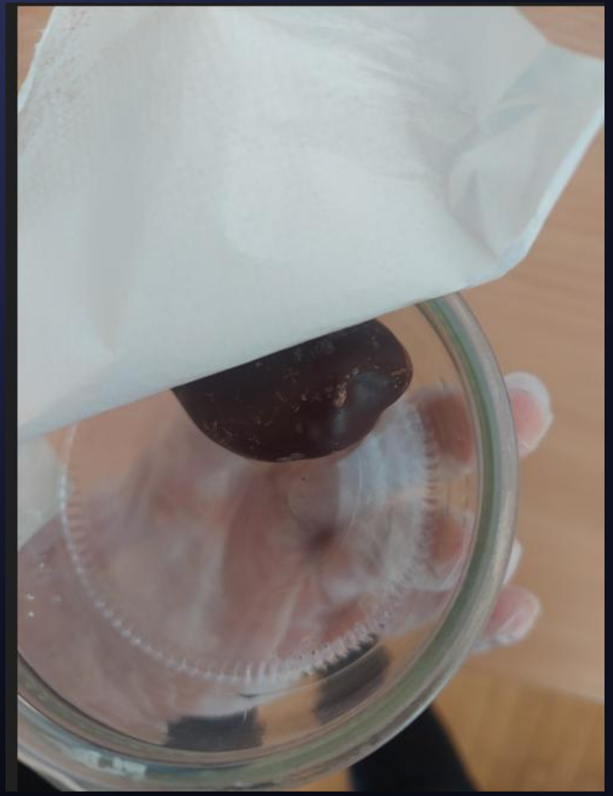


Electrospun keratin hydrolysate with *calendula officialis* on cotton wound dressing



Three-layer patch from collagen hydrolisate with *Matricaria Chamomilla extract and alginate*

Electrospun material as singe use packaking material



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THANK YOU

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This project has been funded with support from European Commission.
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