agronomy

IMPACT FACTOR 3.7

CITESCORE 5.2

Review

Biotechnology of Nanofiber in Water, Energy, and Food Sectors

József Prokisch, Daniella Sári, Arjun Muthu, Antal Nagy, Hassan El-Ramady, Neama Abdalla and Judit Dobránszki

Special Issue
Nano-Farming: Crucial Solutions for the Future

Edited by
Prof. Dr. Hassan El-Ramady, Dr. József Prokisch and Prof. Dr. Eric C. Brevik

MDPI

https://doi.org/10.3390/agronomy13112734 agronomy

Review

Biotechnology of Nanofiber in Water, Energy, and Food Sectors

József Prokisch [1], Daniella Sári [1], Arjun Muthu [1], Antal Nagy [1], Hassan El-Ramady [1,2,*], Neama Abdalla [3,4,*] and Judit Dobránszki [4]

[1] Institute of Animal Science, Biotechnology and Nature Conservation, Faculty of Agricultural and Food Sciences and Environmental Management, University of Debrecen, 138 Böszörményi Street, 4032 Debrecen, Hungary; jprokisch@agr.unideb.hu (J.P.); saridaniella91@gmail.com (D.S.); arjunvmuthu@gmail.com (A.M.); nagy.robert@agr.unideb.hu (A.N.)
[2] Soil and Water Department, Faculty of Agriculture, Kafrelsheikh University, Kafr El-Sheikh 33516, Egypt
[3] Plant Biotechnology Department, Biotechnology Research Institute, National Research Centre, 33 El Buhouth St., Dokki, Giza 12622, Egypt
[4] Centre for Agricultural Genomics and Biotechnology, FAFSEM, University of Debrecen, P.O. Box 12, 4400 Nyíregyháza, Hungary; dobranszki@freemail.hu
* Correspondence: hassan.elramady@agr.kfs.edu.eg (H.E.-R.); neama_ncr@yahoo.com (N.A.)

Abstract: Natural resources including water, energy, and food have an increase in demand due to the global population increases. The sustainable management of these resources is an urgent global issue. These resources combined in a very vital nexus are called the water–energy–food (WEF) nexus. The field of nanotechnology offers promising solutions to overcome several problems in the WEF nexus. This review is the first report that focuses on the suggested applications of nanofibers in the WEF sectors. An economic value of nanofibers in WEF sectors was confirmed, which was mainly successfully applied for producing clean water, sustainable energy, and safe food. Biotechnological solutions of nanofibers include various activities in water, energy, and food industries. These activities may include the production of fresh water and wastewater treatment, producing, converting, and storing energy, and different activities in the food sector. Furthermore, microbial applications of nanofibers in the biomedicine sector, and the most important biotechnological approaches, mainly plant tissue culture, are the specific focus of the current study. Applying nanofibers in the field of plant tissue culture is a promising approach because these nanofibers can prevent any microbial contamination under in vitro conditions, but the loss of media by evaporation is the main challenge in this application. The main challenges of nanofiber production and application depend on the type of nanofibers and their application. Different sectors are related to almost all activities in our life; however, enormous open questions still need to be answered, especially the green approach that can be used to solve the accumulative problems in those sectors. The need for research on integrated systems is also urgent in the nexus of WEF under the umbrella of environmental sustainability, global climate change, and the concept of one's health.

Keywords: WEF nexus; wastewater treatment; food packaging; energy harvesting; medicinal; pharmaceutical; biomedicine; nanoparticles

Citation: Prokisch, J.; Sári, D.; Muthu, A.; Nagy, A.; El-Ramady, H.; Abdalla, N.; Dobránszki, J. Biotechnology of Nanofiber in Water, Energy, and Food Sectors. *Agronomy* **2023**, *13*, 2734. https://doi.org/10.3390/agronomy13112734

Academic Editor: Baskaran Stephen Inbaraj

Received: 6 October 2023
Revised: 25 October 2023
Accepted: 26 October 2023
Published: 30 October 2023

1. Introduction

Agriculture is the main source of our food, feed, fiber, and fuel. Fibers are one of the important agro-productivity sources. Fibers can originate from two main sources, natural and synthetic fibers. Natural fibers refer to the fibers obtained from plants, animals, and minerals. Concerning plants, natural fibers may originate from leaves, seeds, bark, fruit, and stalks as sources of fiber, whereas animal ones are derived from silk, wool, and hair as well as mineral fibers like asbestos [1]. The main properties of natural fibers may include renewable, safe, non-polluting, and legitimate sources of fiber, which could be employed for the manufacturing of several composites in the future [1]. Several recent publications issued on different applications of natural fibers, such as important sources for producing polymers (e.g., [1–3]). These applications may include the following fields, such as biomedicine [2], 4D printing technology [4], aerospace [5], filtration of water/wastewater [6], textiles [7], additive manufacturing applications [8], the automotive industry [9,10], the construction industry [11], thermal structure engineering [12], food packaging [13], harvesting and the storage of energy [14]. The water–energy–food (WEF) nexus has a strong relationship with nanofibers, which can support their components through mainly the following activities: food packaging [15], energy processing [16], and water handling [17].

Nanofibers are a kind of fiber that can be in natural and synthetic nanoforms (less than 100 nm). These fibers have several distinctive properties compared with natural fibers such as high porosity, large specific surface area, and high size uniformity [6]. Apart from natural fibers, nanofibers have been applied in many major sectors of our life, including agricultural [18], pharmaceutical [19], biomedical [20], and industrial fields [21] of the global water [22,23], energy [24], and food sectors [25]. Biotechnological applications of nanofibers have gained sound interest from scientists and industrial workers due to their promising roles in many fields such as delivering bioactive compounds [26], and the biomedical field [27]. The suggested roles of nanofibers in the main sectors of water, energy, and food are linked to the security of these sectors, and their nexus. Nanofibers in the water sector were discussed in many publications focusing on water treatment [6], water purification [28], and wastewater treatment [23]. Additional studies on energy and food industry applications of nanofibers could be noticed, which mainly focused on harvesting/storage of energy [24] or food packaging [25].

This study, as far as we know, is the first report discussing the relationship between nanofibers and the WEF nexus. The biotechnological applications of nanofibers in WEF and biomedical sectors also were included. This work was also designated to highlight the promising applications of nanofibers in the field of plant tissue culture and other further applications (e.g., mainly on a large scale in the industrial fields).

2. Nanofibers in Water, Energy and Food

What are the main properties of nanofibers? Nanofibers are polymeric fibers on a nano-scale, which have certain properties and can be produced using both natural and synthetic polymers. Plant natural fibers are the main sources for producing such fibers along with animal and mineral sources, which depend on the used plant fraction such as leaves, stems, stalks, and seeds (Figure 1). The most common plant fiber sources may include seed fibers from cotton (*Gossypium arboretum* L.), fruit fibers from coconut (*Cocos nucifera* L.), bark fibers from jute (*Corchorus olitorius* L.), leaf fibers from sisal (*Agave sisalana* L.), and banana (*Musa* sp.). Synthetic or artificial polymers of nanofibers are widely used due to their easy production, low cost, and higher mechanical properties, but they can cause long-term environmental and human health problems due to their nonbiodegradable disposal, toxic nature, and their persistence in the ecosystem for a long time [29]. Nanofibers possess several desired properties such as extremely high porosity, low density, high specific surface area, and a highly porous matrix. Nanofibers also have specific functionalities due to their large specific area, which allow immobilizing nanoparticles (NPs), metal–organic frameworks, and zeolites [29].

Due to the previous advantages, nanofibers have many applications such as drug delivery systems [30], industrial building design [31], biomedicine [32,33], 4D printing industry [34], textile industry [35,36], and wastewater remediation [37]. Nanofibers could be produced by electrospinning and non-electrospinning techniques (Figure 2). Several unique properties of electrospun nanofibers are well-known compared with other bulk materials such as adjustability of pore sizes, large surface area, and porosity, as well as the extracellular matrix [26]. These production methods with advantages and disadvantages can be presented in Figure 3. Microbial sources for producing nanofibers are considered an important approach, which is applied to many fields such as bacterial cellulose nanofiber [38], microbial fuel cells [39], microbial polysaccharides for controlled drug release [40], and monitoring of food packaging [41]. These fields will be discussed in the following sections.

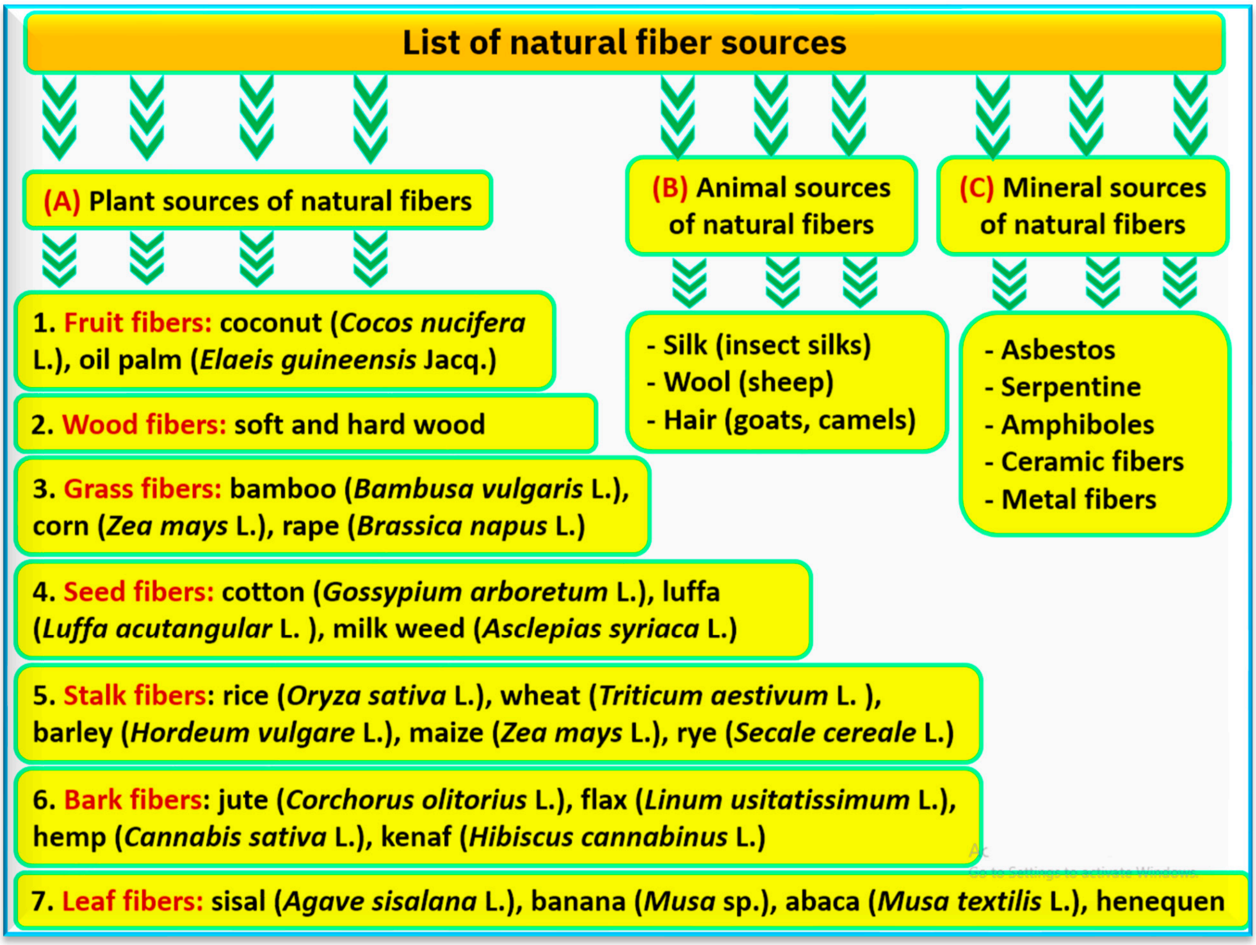


Figure 1. The main sources of natural fiber resources that can be used in the agro-productivity, whereas (**A**) refers to the plant sources of natural fibers, (**B**) animal sources, and (**C**) is mineral sources.

The electrospinning method is the most widely used compared with other techniques for producing electrospun fibers due to its efficiency, operational simplicity, practicality, cost-effectiveness, and versatility [26]. The production of nanofibers is not only the main limiting factor but also the properties of these fibers, which should be evaluated by scanning electron microscopy (SEM) and other methods. Certain properties of nanofibers, which are important for their functions, will be discussed in the next section including physico-chemical, mechanical, and biological characteristics. On the microscopic level of nanofibers, SEM images of the fabrics revealed that the enhancement in fiber strength can be attributed to the formation of structures resembling bamboo nodes or wheat stem nodes within the fibers (Figure 4). The production of nano-sized fibers and the use of these fibers to create non-woven fabric was achieved by our lab (Nano Food Lab, Debrecen University, Debrecen, Hungary). These nanofibers were applied as specialized filtering materials for gases (air) and liquids, as well as for manufacturing functional filters. Several scientific attempts for producing nanofibers in our lab were developed on different levels including a laboratory scale, a pilot-scale device, and a full-scale manufacturing facility. Design, development, and optimization of nanofiber formation using different parameters (e.g., flow rate, voltage, electrode distance, surface, time, and solution concentration) were evaluated. Construction of a full-scale manufacturing facility included design, implementation, test production, and machine adjustment, as well as mass production of products, quality control, and implementation of a quality assurance system.

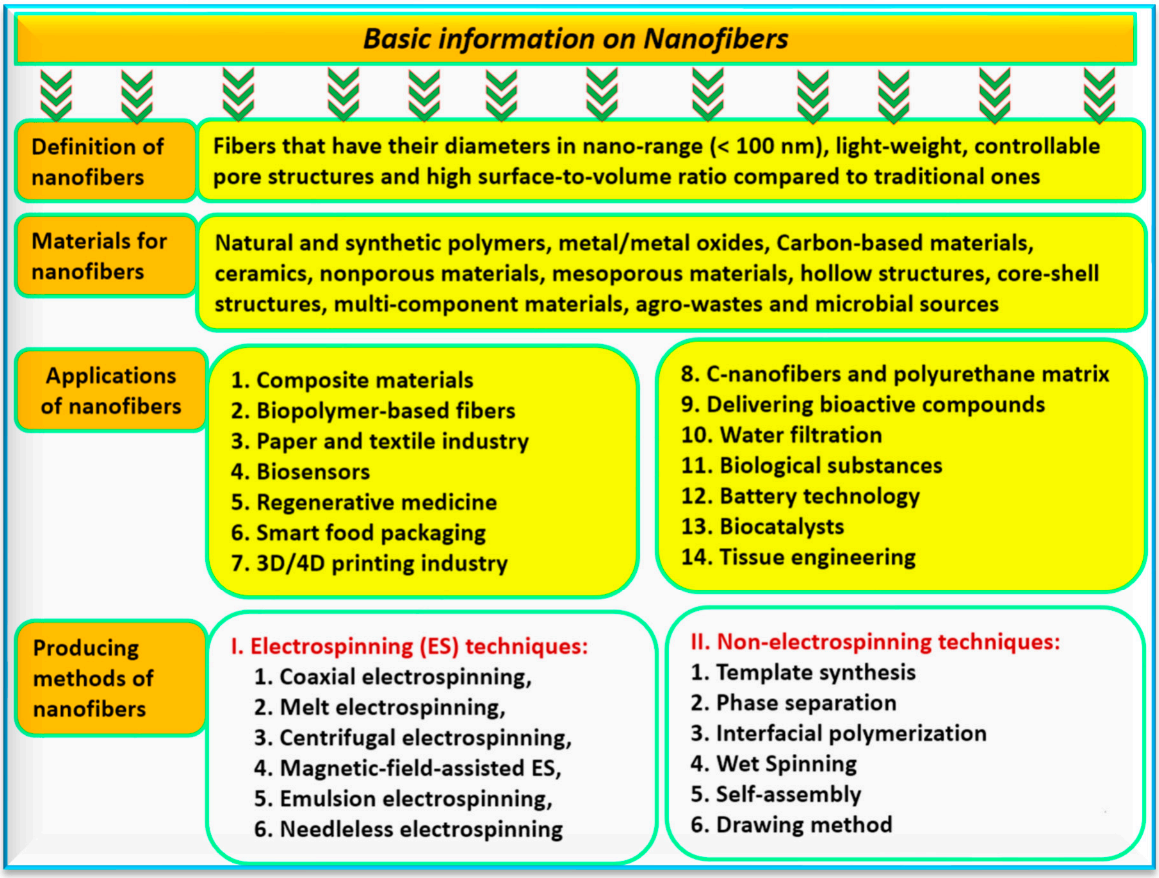


Figure 2. The main basic information on nanofibers, their definition, classification, and applications.

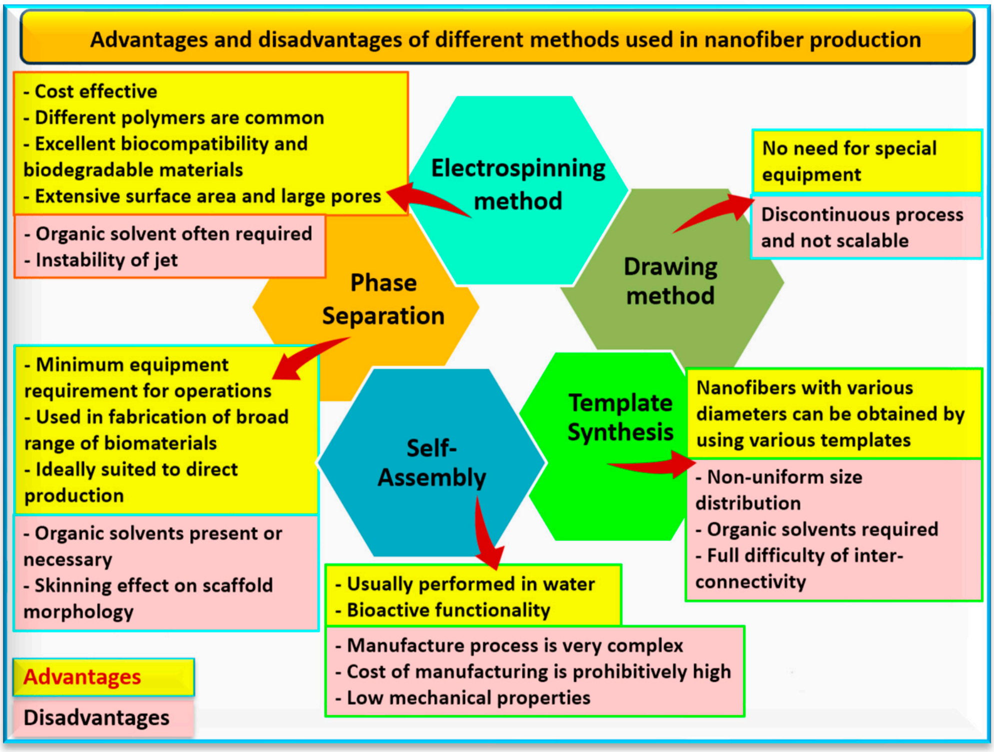


Figure 3. Suggested advantages (in the yellow boxes) and disadvantages (in the pink boxes) of producing methods of nanofibers.

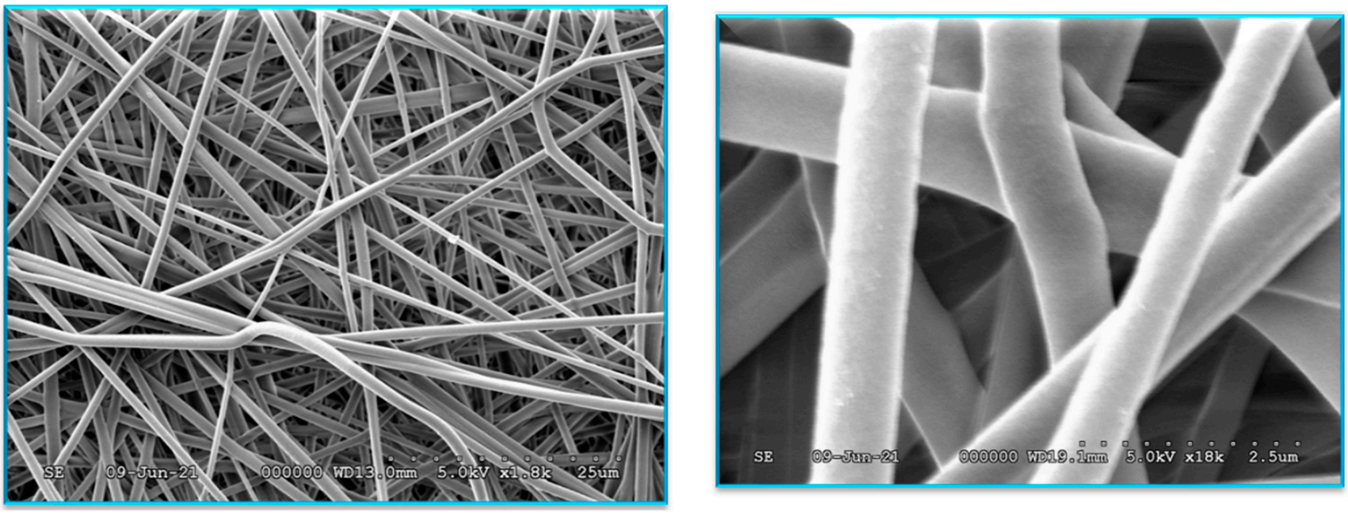


Figure 4. The electronic microscopic images using SEM of the fibers also demonstrate the production of nanofibers with homogeneous diameters. The source of SEM photos is Nano Food Lab, Debrecen University, Hungary.

2.1. Nanofibers in the Water Sector

Nanofibers have certain properties that support their function including physico-chemical, mechanical, and biological characteristics (Figure 5). These properties have a great role during water filtration and wastewater treatment. They allow nanofibers to be preferable for many water processes such as wastewater treatment [37], desalination [42,43], removal of heavy metals [23], and eco-remediation of highly concentrated wastewater streams [44]. Water-based nanofibers are considered attractive alternatives to organic solvents, which are used during the electrospinning methods [45]. This kind of fiber can be applied to nanofibers such as water-resistant polyvinyl alcohol nanofibers [46], modified cellulose nanofibers [47], and cellulose succinate nanofiber [16]. Such hydrophilic cellulose nanofiber as a separator has a high porosity (60%), and a hydrophilic surface, which can enhance a strong electrostatic repulsion between facilitating ion transportation and fibrils and increase negative surface charges [16]. Microbial nanofibers are considered a favorable alternative to petrochemical-based membranes due to their higher flux rate, higher tensile strength, flux recovery, and favorable stability ratios, as well as sustainable and eco-friendly membranes [48].

For a long time, nanofibers synthesized using polymers synthetized from petroleum caused several environmental problems because they are non-degradable and persistent in the environment. So, green nanofibers are considered a promising approach on the industrial and academic levels to produce plant-derived nanofiber polymers instead of synthetic polymers derived from petroleum due to their sustainable, renewable, completely biodegradable, and eco-friendly nature [29,49,50]. More published studies on green nanofibers are presented in Table 1. Along with green nanofibers, animal sources of nanofibers were reported such as chitin from crab shells for coloring dyes [51], and wool keratin nanofibers for the biomedical field [52]. It has also recently reported on developing green tires using chitin nanofibers (from prawn shells), natural rubber, and carbon black as a sustainable and circular economy approach [53]. Interestingly, a new green approach for the wearable biosensors that can be used in monitoring the physiological metabolism in biofluids (e.g., sweat, blood, saliva, urine, and tears) was reported by detecting glucose and uric acid [54] or a non-green approach [55].

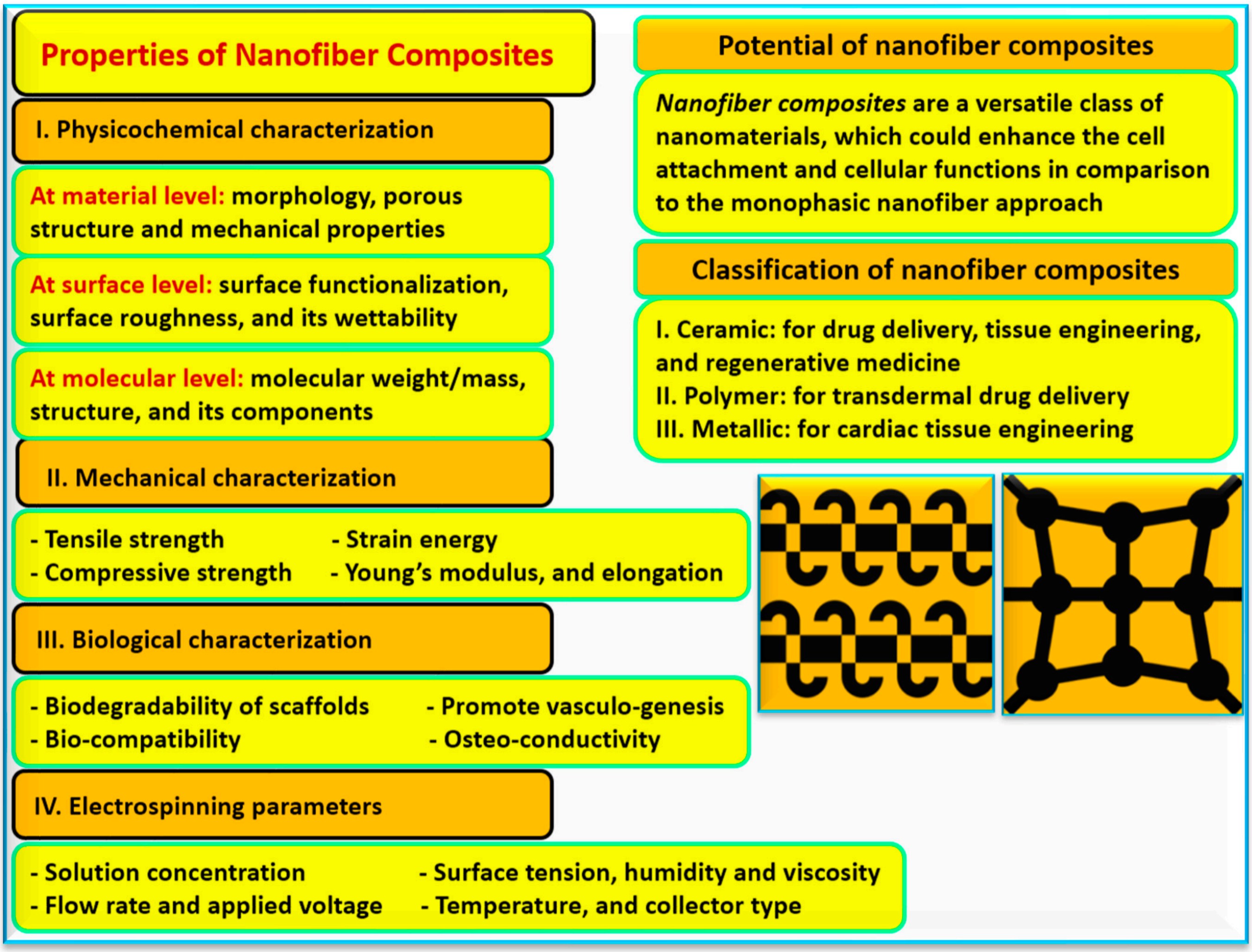


Figure 5. The main characterization of nanofiber composites.

Table 1. Studies on green nanofibers and their applications.

Nanofiber Type	Plant Source	The Main Findings	Refs.
Cellulose nanofiber	Cassava pulp	Nanofibers improved the mechanical properties of injectable hydrogels for meniscus tissue engineering by promoting cell viability, and physico-chemical properties	[56]
Green flexible nanofibers (GNF)	Rice straw	Isolated GNF was used in combination with ZnO-NPs to prepare flexible nano-paper films for electronic components	[57]
Lignin-containing cellulose nanofibers (LCNFs)	Sugar cane bagasse	Sustainable and eco-friendly nanofibers for producing LCNFs using microwave-assisted natural deep eutectic solvent with high-performance	[58]
Lignin-based electrospun nanofiber	Bamboo pulp	This nanofiber membrane decorated with photo-Fenton Ag@MIF-100(Fe) was with good wettability and high porosity as a green, sustainable, and efficient membrane for methylene blue dye removal and degradation (99%)	[37]
Starch-based green electrospun nanofiber	Natural polymer of pullulan	Green nanofibers as fast-dissolving nanofibers for delivery bioactives (cumin) in food and pharmaceutical fields	[59]
MXene–cellulose nanofiber (CNF) composites	Cellulose from biomass (wood, cotton, hemp, etc.)	Green nanofibers are low cost and have biodegradability, process-ability, and a hydrophilic behavior, which leads to acceptable dispersion in water treatment by using the vacuum-assisted filtration	[60]

Table 1. *Cont.*

Nanofiber Type	Plant Source	The Main Findings	Refs.
Cellulose nanofibers	Bamboo chips	Cellulose nanofiber-blended polylactic acid composite can be produced from bamboo under high-pressure steam and high-temperature for low-strength biodegradable polymer	[61]
Lignin-containing cellulose nanofiber/glycerol composite	Poplar pulp	This nanofiber composite can be applied for engineering light management, solar cells, food packaging, anti-glare film, and flexible optoelectronic devices	[62]
Nano complexes-based nanofibers	Cellulose extracted from rice straw	Polyvinyl alcohol/NC/cellulose nanocrystals could be applied for multi-functional water treatment and removing pathogenic microorganisms and other pollutants	[63]
Nanofiber-hydrogel composite	Dried chamomile flower	A polyamide/*Pistacia atlantica* (P.a) gum nanofiber and PEBAX/Polyvinyl alcohol/Ag hydrogel showed a high anti-microbial activity towards the *E. coli*	[64]
Cellulose nanofibers (CNFs)	Sugar beet pulp	CNFs had higher hydrophilicity, and tensile strength properties, whereas a decrease in air porosity when coated paper sheets after hydrothermal-depectinated pulp coating	[65]
Cellulose nanofibers (CNFs)	*Salicornia ramosissima* waste	Produced nanofibers can be used as reinforcing agents of polymeric composites, food packaging, pharmaceutical medical, and cosmetic industries	[66]
Cellulose nanofiber-polyvinyl alcohol	Oil palm bunches	A good nanocomposite film has water vapor transmission rate and transparent film layer (1294.82 and 1395.91 g/(m^2 0.24 h), resp. for gas barrier application on paper packaging	[67]
Cellulose nanofiber	Artificial produced by a company	Using basil essential oil and corn starch coated nanofiber to prolong the shelf life of the mandarin orange by maintaining the fruit quality, and reducing weight loss of the coated fruits	[68]
Stabilized cellulose nanofibers	From wood fiber	Coating nanofibers with chitosan NPs as edible coating for maintaining fruit quality against antifungal activities (*Rhizopus stolonifera* and *Penicillium digitatum*)	[69]

The 2D layered materials are called "MXenes".

The microbial role in water treatment is noteworthy during water/wastewater processing. Many studies indicated this potential approach of applying microbes as immobilized carriers during wastewater treatment (e.g., [46,70,71]). Apart from microbial nanofibers, the microbial immobilization of wastewater treatment has proved its efficiency in removing and biodegradation of many types of wastewater pollutants for a low cost, highly efficient, high surface area, chemically and physically stable carriers, and excellent biological compatibility [72]. More concerns were focused on the microbial removal of emerging pollutants, and the green catalysts using enzymes such as laccase during wastewater treatment [73]. Concerning the suggested mechanism of nanofibers during the water treatment, this is presented in Figure 6, as well as the list of some suggested kinds of nanofibers as well.

Nanofibers have been used in the sector of water treatment as adsorbents, electrochemical electrodes, photocatalytic materials, and membranes for removing specific pollutants such as persistent organic pollutants, heavy metals, emerging pollutants, and oily molecules. Electrospun nanofiber membranes have many advantages during water treatment, such as a homogeneous pore distribution, high surface area to volume ratio, a wide variety of polymers, ease of fabrication, high porosity, and high hydrophobicity [29]. Whereas, the disadvantages may include high voltage, differential pore size and fiber thickness, and toxic solvents. The mechanisms of removing pollutants (e.g., heavy metals and others) from wastewater using nanofibers involve the photocatalytic process, adsorption, ion exchange, diffusion dialysis, electrostatic processes, and metal–organic framework crystal or polymers [73]. The application of nanofibers as adsorbents mainly depends on their functional groups in the polymeric matrix, which have high selectivity for removing the target pollutants [29].

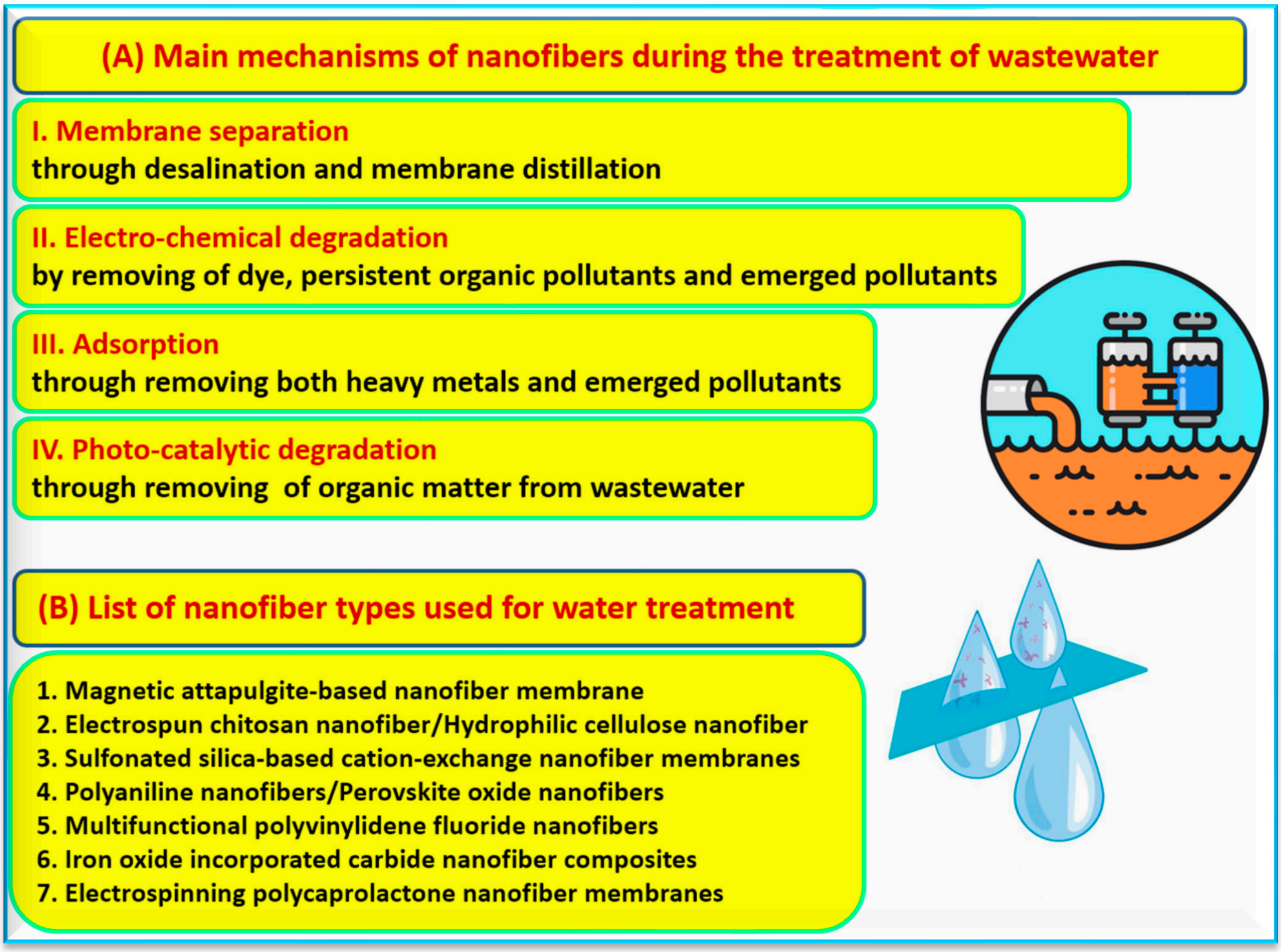


Figure 6. Main mechanisms of nanofibers during the water treatment (**A**), and list of the common types of nanofibers used in water treatment (**B**).

2.2. Nanofibers in Energy Sector

The energy sector represents a crucial resource for our life. At all times, a global urgent concern is needed for searching for new untraditional sources for producing and maximizing energy production. This approach could be achieved by applying different reliable agro-wastes as renewable, excellent, and affordable resources [74]. At the same time, the accumulation of agro- and industrial waste causes harmful environmental issues, which should be valorized into energy. The most important suggested approaches for the energy crisis may involve microbial and green energy, as sustainable strategies for producing energy apart from fossil sources. Microbial energy conversion or microbial energy technologies are sources where microbes can make fuels out of raw organic materials and convert the chemical energy in the agro-biomass into chemical energy in the form of hydrogen or ethanol through the bioenergy process (Figure 7) [75]. The main applications of nanofibers in the energy sector are lithium-ion batteries, solar cells of crystalline silicon using nanofiber, dye-sensitized solar cells, supercapacitors for electrospun carbon nanofibers, hydrogen storage using nanofiber membranes, and pressure-retarded osmosis (Figure 8). Using biomass-based nanofibers in energy storage has many advantages such as high specific surface area, unique porous structure, low cost, and easy availability [76].

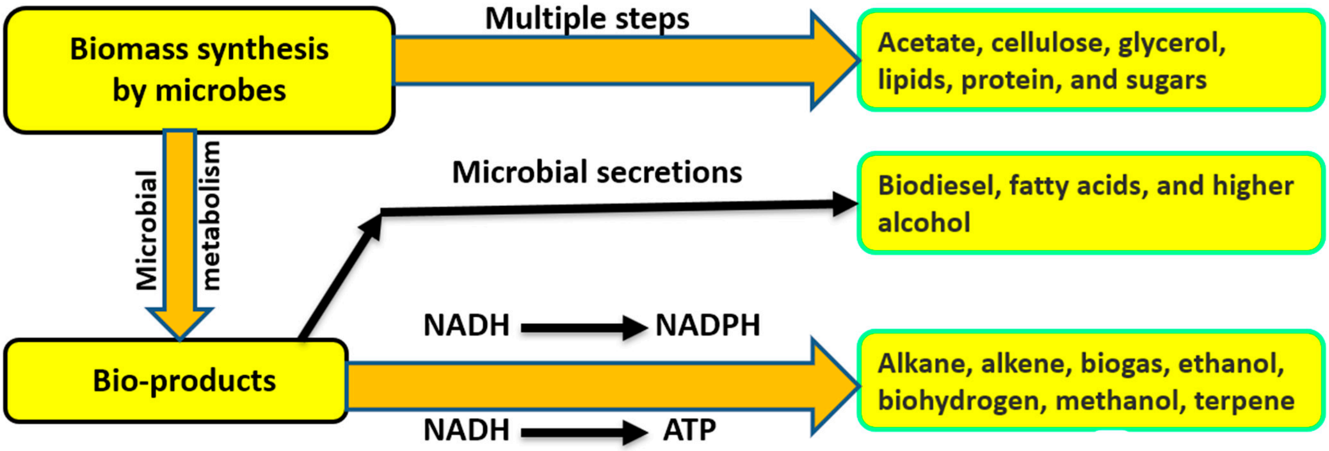


Figure 7. Main microbes converting the renewable feedback through bioprocessing to produce energy.

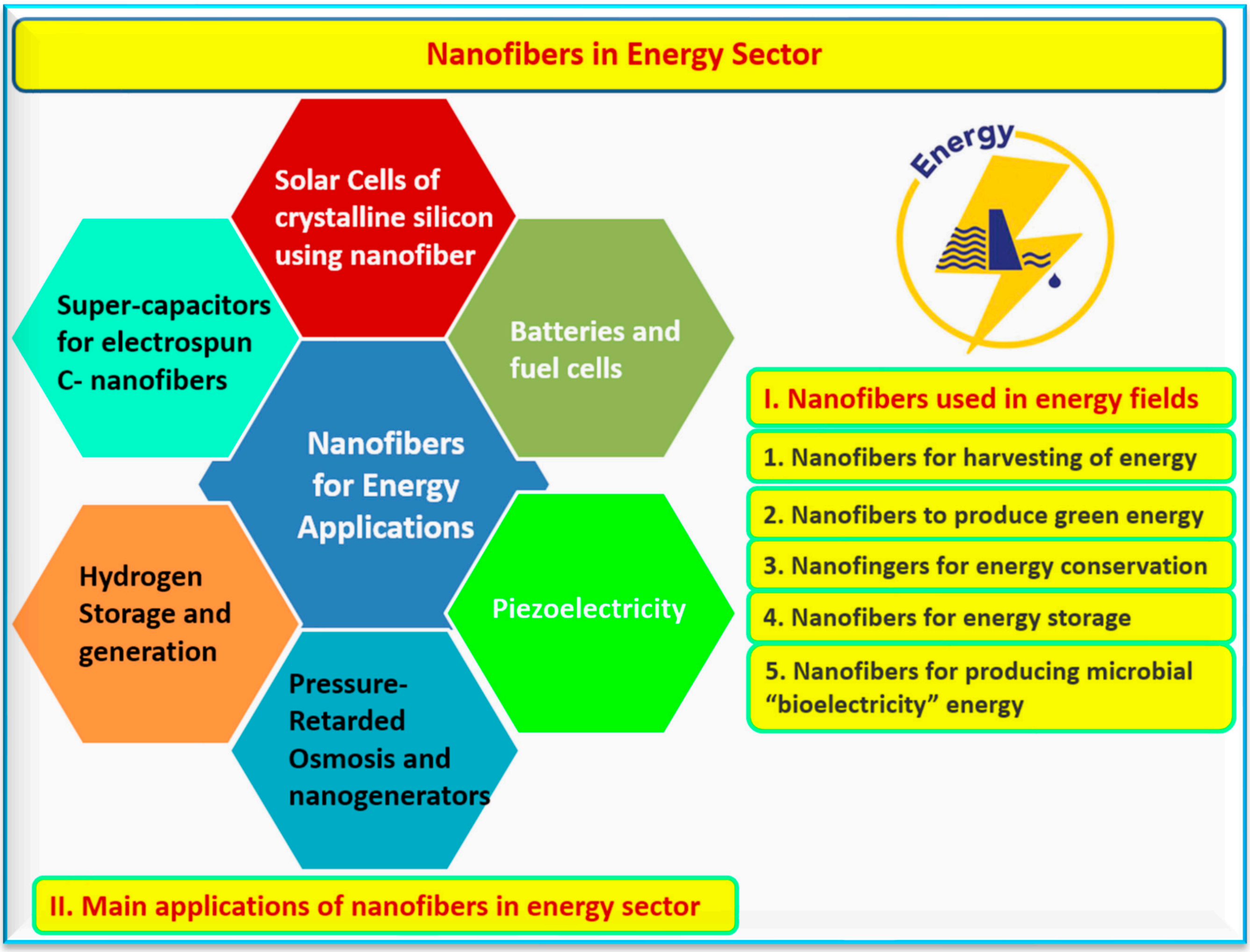


Figure 8. Main use of nanofibers in different fields of energy (part I) and suggested applications of nanofibers in the field of energy (part II).

Concerning green energy, cellulose nanofibers (CNFs) in addition to wood and other lignocellulose materials (e.g., agro-residues) are the most common renewable materials that can be used for producing this kind of energy [77]. Green nanofibers have a specific surface area, and high strength, and are lightweight, stiff, renewable, and biodegradable [59].

CNFs can be applied in different fields such as membranes and polymer films [47,48], reinforcing agents in plastic composites [56], wastewater treatment [21], food additives [15], paper coatings [65], energy storage [16], medicines [78] and cosmetic products [66]. It is worth mentioning that carbon nanofibers derived from nanocarbon materials have several integrated advantages, such as reducing chemical functionalization [62], chemical and structural flexibility [79], bulk production potential [80], better electrical conductivity [81], and use during different electrochemical processes [74]. Furthermore, generated carbonaceous NPs from biomass have shown a significant potential for use in bioimaging, fuel cells, medicinal delivery, catalysis, carbon fixation, and gas sensors [74]. Many kinds of nanofibers could be listed and their application for energy harvesting is as follows:

1. Carbon nanofiber network-based Zn-ion capacitor delivers [82];
2. Three-dimensional electrospun porous nanofiber materials for energy storage [83];
3. SiO_2 nanofiber-reinforced P-based microporous polymer electrolytes [84];
4. Electrospinning polyvinylidene fluoride nanofibers [85];
5. Carbon nanofibers decorated with copper–metal–organic frameworks [86];
6. Nanofiber-reinforced clay (montmorillonite)-based 2D nanofluidic for osmotic harvesting energy [87];
7. Electrospun nanofiber for electrochemical energy storage/conversion [88];
8. Electrospun metal–organic framework-derived nanofibers, as a next-generation technology for electrochemical energy storage [89];
9. $BaTiO_3$:La embedded nanofiber membrane for wireless power transmission and harvesting energy [90];
10. Electrospun organic piezoelectric nanofibers due to their biocompatibility, eco-friendliness, flexibility, and biodegradability for energy harvesting and other bioapplications [91].

On the other hand, the biotechnological approach to energy can be found in microbial fuel cells (MFCs), which are considered sustainable bioelectrochemical systems. In an MFC system, electroactive microbes (e.g., bacteria or yeast) can be utilized in the biological treatment of wastewater via biochemical reactions to convert directly chemical energy into electrical energy [92]. The electricity can be generated in MFC systems through biodegrading organic pollutants in water bodies to obtain a new eco-friendly energy technology that has no biofouling, low operating cost, and a wide range of substrate sewage treatments [93,94]. Several recent studies focused on microbial energy under different conditions as presented in Table 2. These MFC systems used nanofibers, as mentioned in many studies, with a focus on converting and storing energy [92,95–97].

Table 2. Studies on the role of nanofibers in improving microbial fuel under certain cases.

Nanofiber Type	Method of Producing	The Adapted and Used Nanofibers	Refs.
Polyacrylonitrile nanofibers	Electrospun nanofibers	Enhanced oxygen reduction upon Ag-Fe-doped polyacrylonitrile@UiO-66-NH_2 nanofibers	[92]
Nitrogen-doped carbon nanofiber	Electrospinning	N-doped carbon nanofiber (Co/CoP/Co_2P@N-CNF, Co/CoS_2@N-CNF)	[98]
Polyvinylidene fluoride nanofibers	Electrospinning	Free molding polyvinylidene fluoride @Ag nanofiber	[99]
Carbon nanofiber-decorated graphite rods	Electrospinning	An effective and low-cost anode using a polyvinylidene fluoride electrospun nanofiber for industrial wastewater-driven microbial fuel cells	[100]
Aligned C-nanofiber-bacteria hybrid	Electrospinning and co-filtration method	This nanofiber has high-power output, low cost, facial fabrication, high-performance, and cost-effective microbial fuel cells in a large-scale	[101]
Carbon nanofiber on (CoCu@N-CNFs)	Metal–organic frameworks and electrospinning	Bimetal Cu/Co-N-doped porous C-nanofibers have high anti-bacterial capacity, inhibited the biofouling on the cathode surface, and best electrochemical activities were exhibited when Co to Cu was 1:1	[97]

Table 2. *Cont.*

Nanofiber Type	Method of Producing	The Adapted and Used Nanofibers	Refs.
Fe-Co bimetallic with carbon nanofibers	Electrospinning and metal–organic framework	Enhances the bioelectrocatalysis activity and promotes the direct electron transfer process of electroactive bacteria to improve the sluggish extracellular electron transport process of microbial fuel cell anode	[96]
Carbon nanofibers	Electrospinning	Decorated electrospinning C-nanofibers can save more exoelectrogens colonization, higher electrocatalytic activity, and more efficient interspecies interactions in the microbial fuel cell	[92]
N-doped carbon nanofibers	Electrospinning	N-doped C-nanofibers embedded in vertical-grown nanosheets improved the surface area of the material, preventing the agglomeration of Co and Co-Fe alloy NPs as a new approach for regenerating and conversion of the clean energy	[94]
Bacteria/electrospun oriented C-nanofibers	Electrospinning	These nanofibers have a self-supporting anode using filtration strategy; electrospinning technology for bacteria colonization and fully utilized interior surface area	[102]
Polymerized nanofiber polyaniline	In situ oxidative chemical polymerization	*Cystobasidium slooffiae* JSUX1 yeast enhancing both hydrogen production and bioelectricity from xylose in microbial fuel cells by polymerized nanofiber polyaniline	[95]

2.3. Nanofibers in the Food Sector

The production, handling, preservation, and storage of global food are essential items for the optimum management of food security. They need a suitable fiber or polymer for improving and controlling the properties of food. Maintaining freshness and food quality via food packaging has gained a great concern. As a multidisciplinary area, food packaging involves several sciences in addition to food science, which includes mainly food chemistry, food engineering, and food microbiology [103]. Recently, food packaging has had great progress thanks to the use of nanofibers (Table 3). Several applications of nanofibers in the food industry include three sectors: food analysis (antibiotics, food compositions, pathogens, and pesticide residues), food production (beverage filtration and delivery system for functional food), and food packaging (Figure 9). Using nanofibers in food packaging is a major contributor in the food sector, which may include the following applications, such as active packaging, edible packaging, gas sensors, food freshness sensors, intelligent packaging, time–temperature indicators, moisture removal packaging, and ethylene removal packaging [104]. In addition, pH indicators, functional bioactive packaging, antibacterial (thymol, gallic acid, curcumin), antifungal (curcumin, essential oils, etc.), and antioxidants (ascorbate, tocopherol, phenols) are common applications [105].

Table 3. Use of nanofibers in food packaging and multifunctional food packaging.

Nanofiber Type	Functional Item	The Outcome from Used Nanofibers	Refs.
Gelatin/chitosan nanofibers	Curcumin	Electrospun nanofibers have the potential as multifunctional packaging in protecting and monitoring the freshness of protein-rich animal foods (e.g., seafood and meat)	[106]
Gelatin-based nanofibers	Xanthan gum and propolis	Nanofibers containing propolis showed a homogenous morphology with high antibacterial and antioxidant activities	[107]
Gelatin/zein-based nanofibers	Cinnamaldehyde/thymol	Used nanofiber films showed blocking for UV light, excellent antioxidant, antibacterial, and reduced water vapor permeability	[108]
Gelatin/pullulan nanofibers	Carvacrol/cyclodextrin	Studied nanofibers recorded the potential of carvacrol as a promising antioxidant and antibacterial that accelerated shelf-life test at 40 °C during active food packaging and as a bioactive compound	[109]

Table 3. *Cont.*

Nanofiber Type	Functional Item	The Outcome from Used Nanofibers	Refs.
Carboxymethyl chitosan/polyethylene oxide nanofibers	Nisin from *Lactococcus lactis*	Nanofiber had mechanical strength and good antibacterial activity that extended the shelf life of packed bass fish from 9 days to 15 days as preserved aquatic product	[110]
Polyurethane nanofiber	Polyurethane-enrolled Fe_3O_4-NPs	Green synthesis of Fe_3O_4-NPs using food waste (molasses) promoted packaging cheese as an antimicrobial and maintained quality, freshness, and extended its shelf-life to 40 days	[111]
Ag-coated nanofiber	Nitrite detection	Gluten/zein film-based Ag-coated nanofiber was effective for rapid nitrite detection in food and the nitrite content ranged from 10^{-1} to 10^{-4} mol L^{-1}	[112]
Gluten/zein nanofibers	Anise essential oil/β-cyclodextrin	Suggested sustainable, antioxidant, antimicrobial-loaded nanofibers against *Staphylococcus aureus* and *Escherichia coli* as a promising tool for active food packaging	[113]
Sulfonated cobalt phthalocyanine–titanium dioxide NPs	Ethylene scavenging capability	Studied nanofiber inhibited antibacterial activity of both *Escherichia coli* and *Staphylococcus aureus* (over 90%) and ethylene removal during vegetable and fruit preservation	[114]
Lycium barbarum polysaccharide nanofibers	Eugenol–silk fibroin NPs	Studied nanofibers were antibacterial, thermal stable, and encapsulated eugenol into silk fibroin NPs suppressed its volatility and extended the needed time against bacteria activity	[115]
La_2NiO_4 functionalized carbon nanofiber	Vanillin	Studied nanofiber was applied for detecting the vanillin in studied food samples (i.e., ice cream and chocolate), through a promising electrochemical sensing strategy	[116]
Composite films of cellulose nanofibers	Packaging film of halochromic C-dots; anthocyanin	The film had antimicrobial, antioxidant, and UV barrier properties, as an intelligent and active food packaging by changing color from red to colorless yellow during storage at 25 °C for 48 h during storage of fish, pork, and shrimp	[117]
Poly (lactic acid)/polyethylene glycol nanofibers	Peppermint essential oil	This hydrophobic nanofiber enhanced strawberries' shelf-life by decreasing water vapor permeability, reducing weight loss after 5 days, and increasing firmness of fruits	[118]
Chitosan/cellulose nanofiber	γ-Cyclodextrin/curcumin	Coating film is used to extend the shelf-life of tomato, banana, and cut apple slices by reducing water loss, and microbial attack due to its excellent antimicrobial/antioxidative properties	[119]
Polycaprolactone/chito-oligosaccharide nanofiber-films	(EGCG)/2-(HP-β-CD)	This film had thermal stability as a good antibacterial agent for post-harvest fruit packaging due to its antifungal nanofiber membrane activities	[120]

Abbreviation: Epigallocatechin gallate (EGCG)/2-hydroxypropyl-β-cyclodextrin (HP-β-CD).

It is well-documented that the common methods for preparing nanofibers may include centrifugal spinning, electrospinning, and solution blow spinning toward active food packaging [121]. This active packaging of food is a crucial strategy for food maintenance, extension of their shelf life, and ensuring integrity, freshness, and safety, to meet the consumer demand for higher quality, healthier, and safer food [121]. What are the main advantages of nanofibers for packaging food? Nanofibers have been applied in food packaging because of their high porosity, specific surface area, and loading capacity of active compounds. There are several kinds of nanofibers that can be applied in the food industry, in general, and for food packaging, in particular, depending on the purpose, and which bioactives are needed (Table 3). For intelligent food packaging, electrospun nanofibers are considered to be promising tools due to their higher sensitivity and accurate pH labels [122]. In seeking sustainable and green approaches in the food sector, great progress in plant-based natural fibers has been achieved in the sector of food packaging [13]. These natural green fibers have several benefits compared with synthetic fiber, which includes lighter weight, low density and cost, superior life cycle, biodegradability, and good mechanical properties [123]. The main sources of natural nanofibers for food packaging involve cellulose [15], chitosan from chitin [124], gelatin from collagen [107], and silk fibroin from silkworms [125], and starch-based polymers can also be used to produce biodegradable food packaging [126].

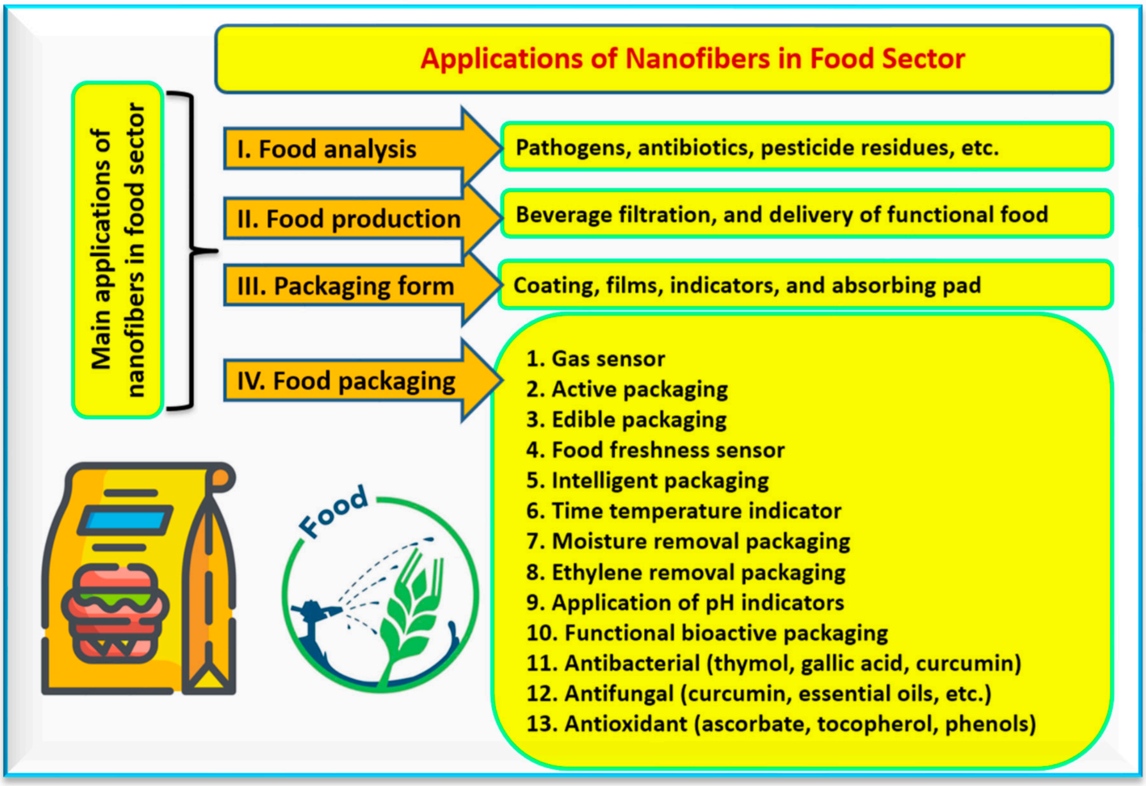


Figure 9. Main applications of nanofibers in food industry, food analyses, food production, and food packaging.

2.4. *Nanofibers in Water–Energy–Food Nexus*

It is well-documented that by 2050, the global population will be around 9.7 billion, which means greater demand for all the major resources of our lives. This demand rate differs from sector to sector, for example, it increased by 70, 50, and 20–55% in the food, energy, and water sectors, respectively [127]. Therefore, these main sectors of water, energy, and food combine a crucial nexus (WEF) that requires urgent global management, as confirmed by several studies discussing this nexus from different points of view (e.g., [128–130]). This nexus has a very close relation to global climate change [131], the sustainable use of these resources [132], the sustainability of desalination [133], the ecosystem [134], and rainwater harvesting in arid zones [135]. This WEF nexus has a very closed relationship among all its components (water, energy, and food), which the factors of each component depend on each other, as well as it is impossible to secure any resource (e.g., food) without securing the others (i.e., water and energy) and vice versa [129,136].

Several applications of nanotechnology have been globally added to new strategies for improving and sustaining the components of this nexus, but still, environmental risks associated with this science need to be fully understood [128,137]. In the current study, nanofibers are the nano-form that can be applied to the components of this WEF nexus (Figure 10). Several research areas can be identified under the WEF nexus and apply nanofibers, such as using nanofiber-based biosorbents for ecological remediation [22,37], applying the microbial nanofibers for wastes and organic pollutants for remediation [138,139], the approach of producing nanofibers from food waste by converting energy using microbial fuel cells [101], and the general approach of how to use nanofibers in producing products of water–energy–food in integrated system research. The microbial role in this nexus and its components are very clear and involve several fields in all components such as biotechnological applications in agriculture, healthcare, and energy [140]. Under the WEF nexus and toward integrated system research, many investigations are needed including different relationships among these resources, in addition to integrated nexus management for enhancing the resilience and sustainability of the whole nexus system [129]. More suggested research areas and gaps are shown in Figure 11 in the entire nexus as well as in each one.

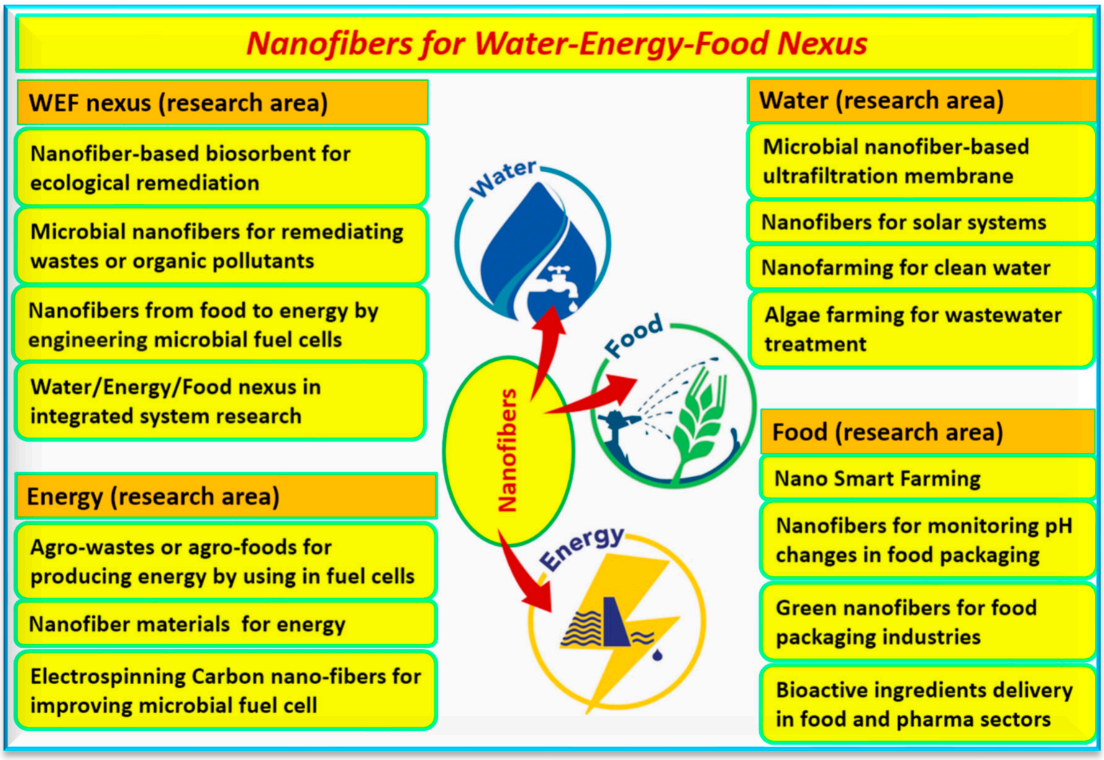


Figure 10. Different suggested research areas in WEF nexus and in each component as well.

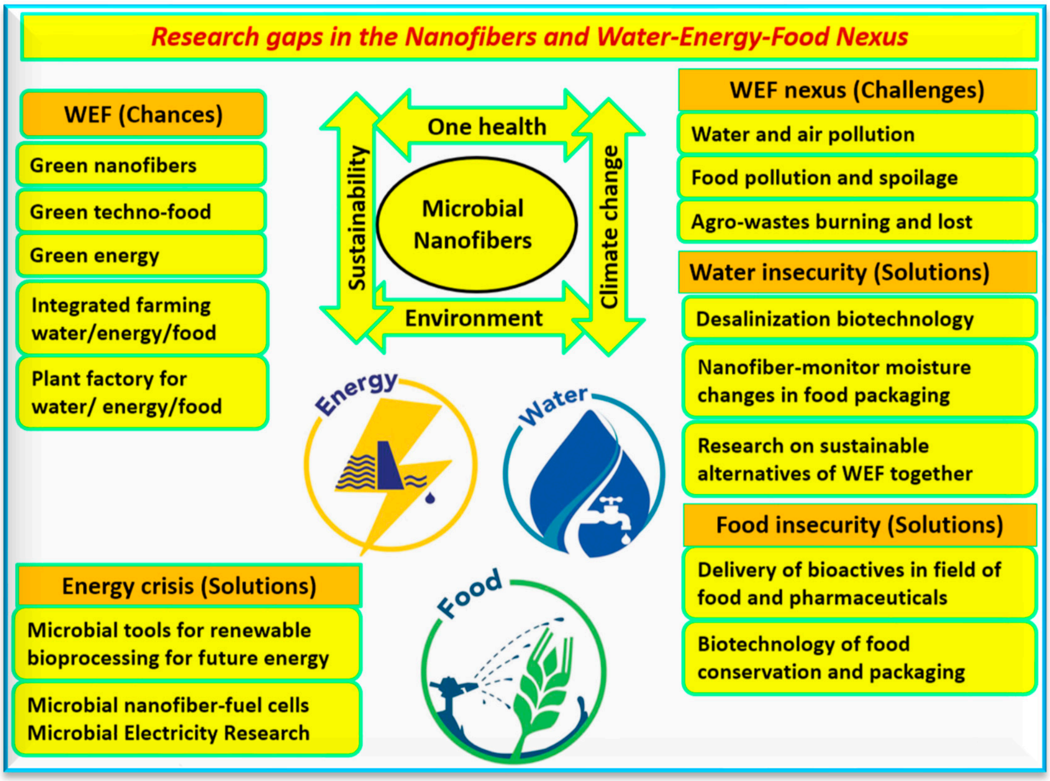


Figure 11. Different suggested research gaps in the WEF nexus and some solutions for each component in this nexus.

Green technologies under this nexus (WEF) have great outputs, which can achieve many goals of global sustainable development [141]. These green technologies are a hot topic, which has spread in the water, energy, and food sectors. These technologies mainly depend on plant species and their used part and/or microbe species (bacteria, fungi, or yeast). This technology produced different kinds of nanofibers (green and microbial), which have several excellent properties such as degradability, green, and biocompatibility, in addition to their high porosity, and high specific surface area [142]. Under the WEF nexus, green research is expected to include the following issues: green nanofibers for water activities, green techno-food for all food industries, and green energy production and handling. The main global issues including one health concept, sustainability, climate change, and the environment can be managed by using microbial nanofibers. These former questions are closely related to nanotechnology, whose nano-applications are a key approach to solving many environmental problems [143]. This approach was confirmed in many published studies such as the importance of environmental sustainability and health systems/healthcare as one concept [144], nano-based smart farming [145], eco-sustainability under nano additives for diesel engines [146], and waste management for sustainable future [147].

3. Most Common Applications of Nanofibers

It is well known that natural fibers derived from plants have gained great concern as a sustainable alternative to synthetic materials depending on plant species and the part used. Several cultivated plants have been used in fiber production such as the stem of the following plants *Himalayacalamus falconeri* [148], *Lankaran acacia* L. [149], *Ficus benjamina* L. [150], *Waltheria indica* L. [151], *Myriostachya wightiana* [152], and *Cyperus platystylis* R. Br. [153]. Chemical treatment is the main process for producing natural fibers, which may involve alkaline, acetylation, benzoylation, peroxide, potassium permanganate, silane, and stearic acid in addition to the surface treatments [6]. The biomedical sector has major applications of nanofibers among other different sectors including water, energy, and food. Enormous applications of nanofibers in biomedicine and therapy sectors are well-known and shown in Figure 12. Nanofiber composites can be used to deliver drugs, genes, or other biomolecules. Furthermore, they can be applied for engineering different tissues, from the skin through the blood to neural tissues as summarized in Figure 12. The therapeutic application of nanofiber composites is extensive, they can be used orally, transdermally, or intravenously in different types of therapies (Figure 12).

These applications may involve the delivery of drugs [30], bionanocomposites [154], and genes [155], as well as different applications in the field of tissue engineering for many human organs including bone [156], tendon [157], skin [158], cartilage [159], skeletal muscle [78], cardiac [160], vascular [161], and neural tissues [162]. Nanofibers exist in every branch of the medical sector, which contributes to several fields such as tissue engineering [163,164], regenerative medicine [165], and sensing and biomedical approaches [166]. These applications may involve drug delivery carriers [30], wound dressing [167], and facemasks [168]. These nanofibers are useful for tissue regeneration by mimicking a porous topography, enhancing the adhesion cells, and improving physiological acceptability and mechanical strength [169].

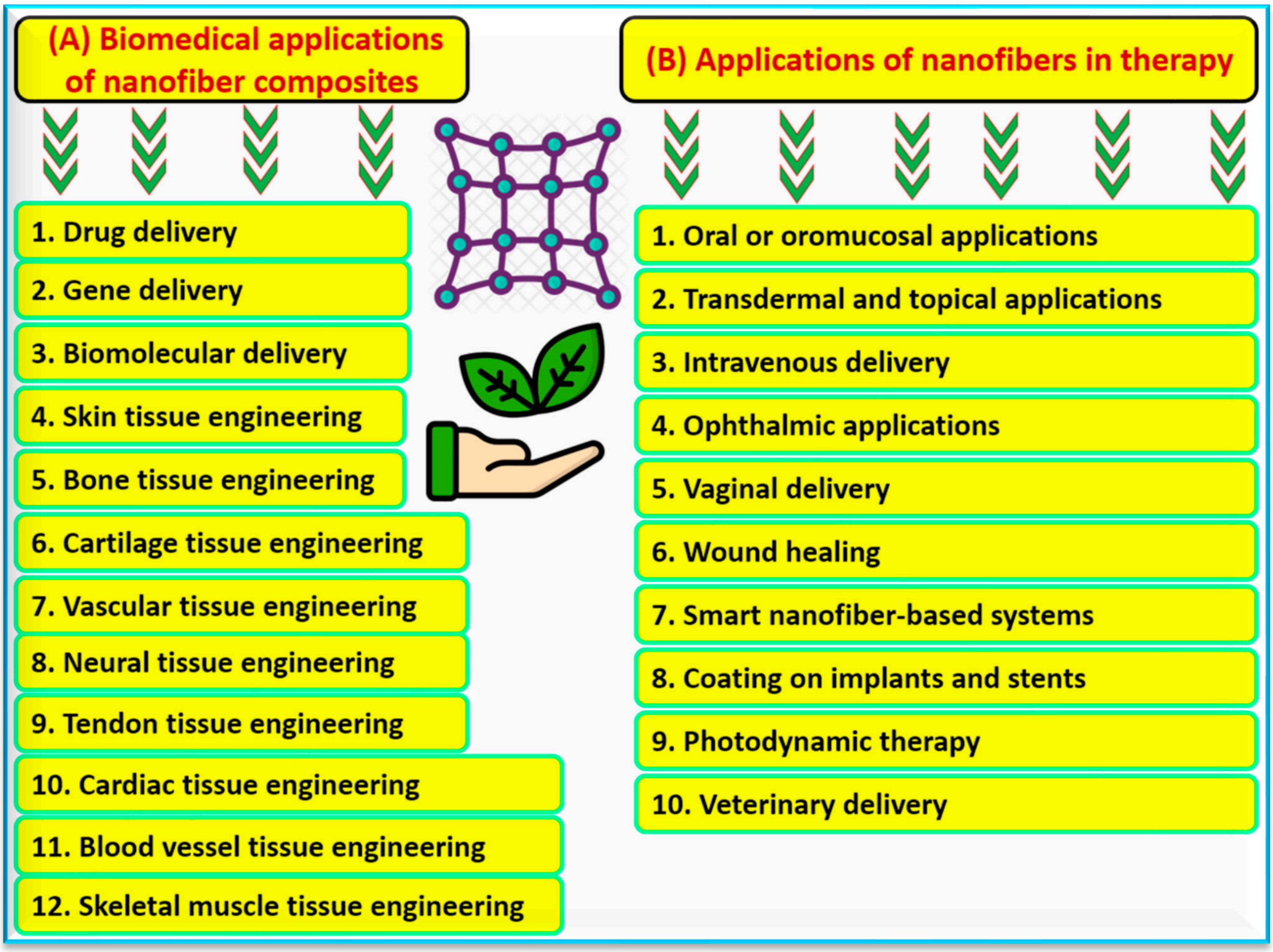


Figure 12. List of suggested biomedical applications of nanofiber composites (**A**), and list of applications of nanofibers in the therapy sector (**B**).

4. Further Applications of Nanofibers

Nanotechnology is one of the fastest growing fields of advanced technology and has been proven to have an essential role in achieving significant development in agricultural systems and many different scopes of science and technology [170]. It has an extremely wide range of applications that could be employed for modern industry, agriculture as nanofertilizers [171], nanopesticides, the food sector, electronics, bioengineering, renewable energy, medicine, pharmacy, cosmetics, and sensor technology [172,173]. Nanotechnology has changed the delivery properties of metal elements into plant cells and has affected the biological systems including plant survival, biosynthesis, antioxidant status, enzyme activity, growth, and development processes, and it has an active interference with the environment [174]. Nanoparticles (NPs) have proven to exhibit catalytic, optical, antibacterial, and antifungal properties [175,176]. With the advancement of nanotechnology, numerous potential applications of nanoparticles have attracted considerable attention due to their unequaled physiochemical, non-toxic properties, and practical effects of their very tiny molecules as well as the low cost and stability at high temperatures [170].

Plant tissue cultures are the center of plant biology and play a significant role in the conservation of plant resources, mass propagation, genetic manipulation, bioactive metabolites production, and plant improvement [177]. In recent years, plant tissue culture applications using nanotechnology, called plant nanobiotechnology, have become feasible and more popular [173]. The promising applications in plant tissue culture field include callus induction and proliferation [170,173–175], biodiversity preservation of plants by cryopreservation [178], embryogenic callus formation and plant development via somatic embryogenesis [172,179,180], and in vitro shoot multiplication and plant regeneration or organogenesis [170,177,181–184].

Moreover, NPs have been used in plant tissue cultures to improve in vitro seed germination for commercial production of seedlings by nano-priming [185], antifungal nanocomposite [186], copper oxide nanoparticles [187], and iron nanoparticles [188]. NPs also have been applied for enhancing root induction [170,182,186] and stimulating the production of bioactive compounds as they can be used as elicitors in plant tissue cultures [177,180,189–194]. On the other hand, NPs may induce or reduce the somaclonal variation of in vitro cultured plants [177]. Genetic and phenotype variations that could be stimulated in vitro by Ag-NPs are very desirable in breeding programs and plant improvement [195]. Furthermore, nanoparticles could be utilized for the genetic transformation of plants via gene delivery "Nanoparticles-based delivery technique" into the plant genome, with the purpose of improving the quality and quantity of agricultural crops [196].

In addition to the direct actions of NPs on in vitro cultures, silver and cobalt nanoparticles (Ag-NPs, Co-NPs) have been used to overcome leaf abscission and enhance the growth, development, and survival rate of the in vitro propagated plantlets. They act as ethylene inhibitors [197]. Ethylene could accumulate in culture vessels and negatively affect the growth of the tissues by increasing the activity of hydrolytic enzymes leading to abnormal phenomena of leaf abscission, yellowing, and hyperhydricity of some species accordingly, which decreases the shoot quality [182]. Ag-NPs were successfully applied to reverse hyperhydricity and regain the normal growth of in vitro shoots [198]. NPs were proven to have the ability to enhance the tolerance of in vitro plants to abiotic stress. The application of iron nanoparticles could significantly mitigate the harmful effects of salinity or drought on the plant tissues cultured in vitro. This is an efficient method to produce plant materials that are tolerant to various abiotic stresses [188,199,200].

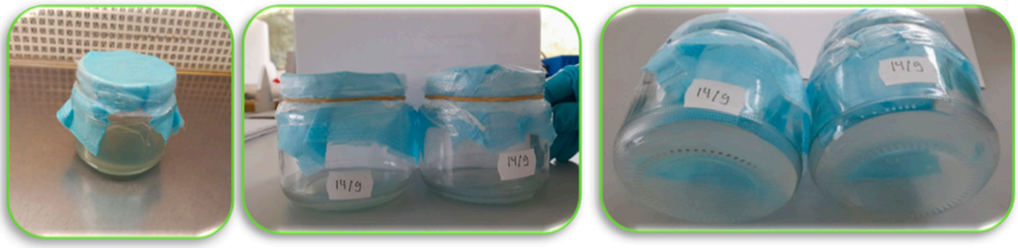
Several in vitro studies reported the antimicrobial behavior of NPs. They have the potential use to reduce the fungal and bacterial contamination of tissue-cultured plants [176,186], consequently ensuring aseptic environmental culture conditions. However, they should be used at optimal concentrations, to avoid possible toxicity to plant tissues, due to the cytotoxic behavior of the element itself (i.e., copper). CuO-NPs and Ag-NPs are considered the most effective antimicrobials commonly used in plant tissue cultures mainly for in vitro propagation of plants. They are applied by supplementing the culture media or as an explant disinfectant by surface sterilization [186,197,201–203]. Titanium dioxide nanoparticles (TiO_2-NPs) showed potential for inhibition of bacterial growth in plant tissue culture media [204].

Preliminary trials on the possible use of the nanofiber as an antimicrobial in plant tissue cultures were carried out as reported in both Table 4 and Figure 13. These experiments were performed in order to answer the following questions: what kind of nanofibers did we apply? What is the main source of these nanofibers? What is the main target of this application? What are the main results of these experiments? To what extent can we use nanofibers in the plant tissue culture field? What are the main limitations and future perspectives of this application? More justifications and validations can be extracted from these experiments by answering the previous questions.

This study was carried out using the electrospinning method for preparing the nanofibers produced by Dispomedicor Ltd. (Hajdúböszörmény, Hungary). The nanofiber was between two melt-blown nonwoven PE layers. The nanofiber was used as a closure of culture vessels. We aimed to determine whether nanofiber could be used to eliminate microbial contamination in plant tissue culture media or not, and to what extent these nanofibers allow good ventilation for enhancing the growth and quality of tissue-cultured plants as well. The recorded observations for these initial experiments indicated that nanofibers are promising tools and could be used efficiently to eliminate microbial contamination in the culture medium but they need some more modifications in further studies to control the high rate of evaporation from the medium, which may cause stress to the cultured tissues, and to keep the explants alive so they can grow and develop. Accordingly, obtain clean and high-quality tissue-cultured plants. Therefore, future investigations are needed on these kinds of nanofibers for more applicability. The future aim is to use these nanofibers for closing the culture vessels, not only at a small scale in the scientific labs, but also in the tissue culture companies that use big bioreactors, and/or in the nurseries of plant propagation for commercial production in a large scale.

Table 4. Some trials on the possible application of nanofibers in the plant tissue technique.

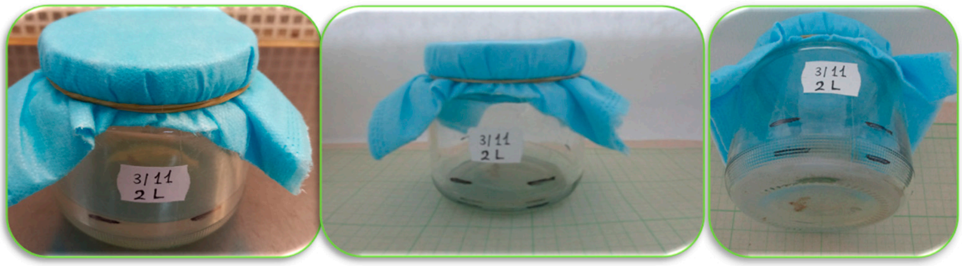
The Trials and Their Details	Observations
Trial 1: The plastic cover of the jar, which contained a sterilized medium without plants, was replaced by nanofiber in one layer and wrapped with plastic stretch and rubber.	After 10 days, the medium was very clean, where there was no contamination noticed but the problem was that a part of the medium was evaporated. (Figure 13a)After five weeks, the medium was nearly evaporated but still clean, and the fiber started to decompose due to its exposure to the dry air (Figure 13b).
Trial 2: To overcome the evaporation of the medium, the nanofiber is used in two or double layers to cover the jar which contains sterilized medium.	After 10 days, the medium evaporated but less than one layer, however still without contamination (Figure 13c).
Trial 3: To decrease the evaporation of the medium, we reduced the surface area of the nanofiber exposure to the dry air (we try to modify the nanofiber to decrease the evaporation to a minimum, after that we can try using plants. We made a double-face nanofiber and made a hole in the plastic cover of the jar.	After 10 days, the medium evaporated but still clean (Figure 13d).
Trial 4: Double-layer nanofiber without modified plastic cover.	The medium became dry after 10 days and the explants (Royal Gala apple shoots) died (Figure 13e).
Trial 5: Double-layer nanofiber with modified plastic cover.	The medium evaporated partially after 10 days, and the explants started to grow but the medium dried after a while and the plants died (Figure 13f).



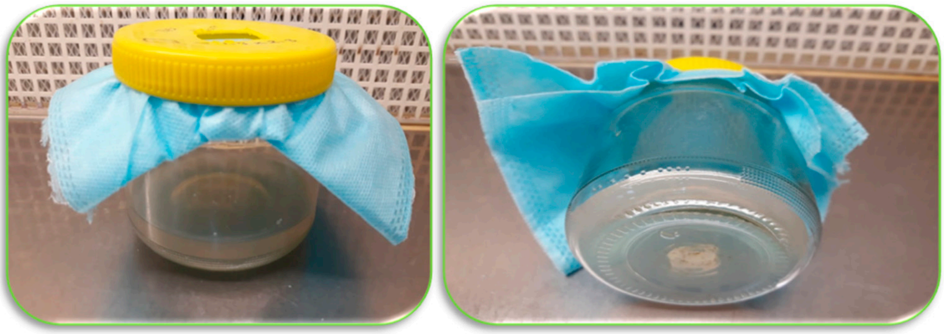
(**a**)

(**b**)

Figure 13. *Cont.*



(**c**)



(**d**)

(**e**)

(**f**)

Figure 13. (**a**) One layer of nanofiber as a closure of the jar containing sterilized medium. (**b**) Evaporation of the medium and decomposition of the nanofiber after five weeks. (**c**) Double layers of

nanofiber with less evaporation and without contamination. (**d**) Modified nanofiber (double face with a hole in the plastic cover of the jar of sterilized medium). (**e**) Double layers nanofiber (drying up the medium and death of the explants (RG apple shoots). (**f**) Modified nanofiber: the explants started to grow then died due to drying of the medium Photos were taken by Neama Abdalla.

We successfully developed a laboratory-scale electrospinning device capable of producing nanofibers from different composition solutions. By combining atomization and electrospinning, we managed to develop and apply nanofiber-producing heads suitable for industrial-scale production. Various nano-powder additives for the fibers were tested and developed using a 3% graphite, 3% nano-selenium, and 10–12% PVB alcohol solution for nanofiber production (unpublished data). Further remaining tasks may include controlling and depositing the fibers produced by the atomization-based electrospinning technology onto a carrier, further investigation of the filtration efficiency of nano-fabrics, and exploring the potential applications of nanofibers with nanoparticle additives. Industrial optimization of these nanofibers may significantly contribute to the advancement and potential commercial applications of the developed technology.

5. General Discussion

In this section, some questions will present more justifications to highlight the potential of applied nanofibers in different sectors. What are the economic benefits of nanofibers in WEF sectors? To what extent can nanofibers be applied in the plant tissue culture sector? Are nanofibers promising tools for producing sustainable, clean, and safe water/energy/food? What are the main challenges of nanofiber production and application? What are the open questions that still need to be answered? It is well documented that nanofibers were produced using the electrospinning method several years ago. The electrospinning nanofibers are preferred over other methods due to their high quality.

Based on green and sustainable photocatalysis technology, photocatalytic fibers are considered innovative strategies for the remediation of water and air environments in addition to energy conversion [205,206]. They are promising for the degradation of volatile and gaseous pollutants in the air because of their high light utilization efficiency, high specific surface area, easy regeneration, and sustainability [207]. Many recent studies reported on the effective photocatalytic degradation using nanofibers in oilfield-produced water treatment [208], degradation of organic dyes [209], and for degradation of antibiotics using heterojunction photocatalytic nanomaterials [210] or ceramic nanofibers [211].

What is the scientific research progress concerning nanofibers in the energy sector? Many recently published articles answered this question by presenting different published materials. These publications focused mainly on sectors of energy production and the harvesting of energy, tools of green energy, energy conservation and storage, as well as nanofibers for producing microbial "bioelectricity" energy. Nanofibers are considered promising tools in both energy and water sectors when both can be applied for producing energy and water remediation at the same time [212]. Using nanofibers for the separation of oil spills from water is an emerging technology for treating oil/water emulsions [213]. More improvement in nanofibers and their functional structures or physicochemical characteristics are needed to increase their efficiency for energy generation and storage [214]. Applying piezoelectric catalysis is an engineering strategy for water treatment (sterilization, degradation of organic pollutants) and energy regeneration (CO_2 reduction, H_2 production). Water and energy are rich sectors, and scientific research every day can find innovative [215] solutions like applying polymeric polyvinylidene fluoride nanofibers in such fields [216].

Concerning the economic value of nanofibers in WEF sectors, these benefits are common in the applications of these sectors, which were mainly successfully applied for producing clean water, sustainable energy, and safe food. Applying nanofibers in the field of plant tissue culture is a promising approach because these nanofibers can prevent any microbial contamination under in vitro conditions, but the loss of media by evaporation is the main challenge in this application. The main challenges of nanofiber production and application depend on the type of nanofibers and their application. In the case of biomedical applications, the major sector for applying nanofibers, there have been many recent advancements in the fabrication of nano-fibers and their technology [217,218]. For WEF sectors, each one has many challenges such as water and air pollution, food pollution and spoilage, agro-waste burning and loss, whereas the possible solutions using nanofibers may involve green nanofibers, green techno-food, green energy production, integrated farming water/energy/food, and plant factory for water/energy/food production. Regarding the open questions that still need to be answered, there are many questions for each sector such as to what extent can nanofiber monitor moisture changes in food packaging? Which nanofiber criteria can save the sustainable alternatives of WEF? Which microbial biotechnological approaches are needed using renewable bioprocessing for future energy systems? To what extent can nanofibers deliver different bioactives in the field of food and pharmaceuticals?

6. Conclusions and Future Perspectives

During our life, there is a need for water, energy, and food, as essentialities for livelihood. There is an increased global demand for these issues, which may pose an increased decline in their abundance in the future. The WEF nexus has a very strong link with these resources, which should be investigated on all levels including local, national, and global ones. WEF nexus has sustainable and green approaches when we can use many applications of nanotechnology (mainly in this study, nanofibers). After the amazing progress in nanotechnology, nanofibers have penetrated several fields, nearly all aspects of human life, due to their distinguished characteristics. The main fabrication methods of nanofibers may include drawing, self-assembly, template assist, interfacial polymerization, phase separation, and electrospinning. The electrospinning technique is a sophisticated method enabling both researchers and companies to fabricate nanofibers with a variety of arrangements, architecture from different sources of materials, and morphology.

Therefore, the production and storage of energy, obtaining fresh and clear water, and maintaining the food and packaging are the main suggested benefits of nanofibers in this review. More biotechnological applications were discussed in the three previous sectors, primarily microbial applications in such areas. A novel application of nanofibers in the plant tissue culture field was presented in this review. Due to the very wide biotechnological applications of nanofibers, more highlights were shed on the biomedical sector as well. Furthermore, enormous questions still need to be answered, which mainly focus on integrated research in such areas.

In general, there is no doubt that water, energy, and food are essential resources, which attracted several workers to focus on them and this is the main motivation for this review. These resources used nanofibers in their activities to produce the needed water, energy, and food for human life. This potential is great in biomedicine applications, which do not need to be proven as they are very common in our lives. The integration production of energy, water, and food at the same time can be achieved when these nanofibers can be applied for using agro-wastes for producing nanofibers for energy/water treatments. What about the limitations of this study? This study still needs more experiments on field plant tissue culture to know how and when can we use the nanofibers in such fields. What about the research gaps/future perspectives that should be identified based on this review? The main aim of this study was to identify to what extent can nanofibers be applied in the field of plant biotechnology. However, this was not the only aim of this study. The green application of nanofibers and microbial nanofibers is a great area for the society of researchers to find a sustainable solution on the farm and industry level as well.

Author Contributions: Conceptualization, N.A., H.E.-R. and J.P.; methodology, D.S.; software, A.M.; validation, J.D. and J.P.; formal analysis, A.N.; investigation, N.A.; resources, D.S. and J.P.; data curation, H.E-R. and J.P.; writing—original draft preparation, N.A. and H.E.-R.; writing—review and editing, N.A., H.E.-R. and J.D.; visualization, H.E.-R. and N.A.; supervision, J.P.; project administration, J.P.; funding acquisition, J.P. All authors have read and agreed to the published version of the manuscript.

Funding: The authors thank the financial support of the 2020-1.1.2-PIACI-KFI-2020-00100 Project "Development of innovative food raw materials based on Maillard reaction by functional transformation of traditional and exotic mushrooms for food and medicinal purposes".

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to acknowledge the technical support of this research from "Project no. TKP2021-EGA-20 has been implemented with the support provided by the Ministry of Culture and Innovation of Hungary from the National Research, Development and Innovation Fund, financed under the TKP2021-EGA funding scheme". Neama Abdalla greatly thanks Zsuzsa Cseh and Ivett Novák-Hermann; Plant Biotechnological Laboratory, Centre for Agricultural Genomics and Biotechnology, Faculty of the Agricultural and Food Science and Environmental Management (FAFSEM), University of Debrecen, 4400 Nyíregyháza, Hungary; for technical helping in performing trials mentioned in the review article.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Kurien, R.A.; Anil, M.M.; Mohan, S.L.S.; Thomas, J.A. Natural fiber composites as sustainable resources for emerging applications—A review. *Mater. Today Proc.* 2023; *in press*. [CrossRef]
2. Dimple Singh, G.P.; Mangal, R. A comprehensive review of natural fiber reinforced composite and their modern application. *Mater. Today Proc.* 2023; *in press*. [CrossRef]
3. Mohammed, M.; Oleiwi, J.K.; Mohammed, A.M.; Jawad, M.A.; Osman, A.F.; Adam, T.; Betar, B.O.; Gopinath, S.C.B.; Dahham, O.S.; Jaafar, M. Comprehensive Insights on Mechanical Attributes of Natural-Synthetic Fibres in Polymer Composites. *J. Mater. Res. Technol.* **2023**, *25*, 4960–4988. [CrossRef]
4. Kishore, S.R.; Sridharan, A.P.; Chadha, U.; Narayanan, D.; Mishra, M.; Selvaraj, S.K.; Patterson, A.E. Natural fiber biocomposites via 4D printing technologies: A review of possibilities for agricultural bio-mulching and related sustainable applications. *Prog. Addit. Manuf.* **2023**. [CrossRef]
5. Bhadra, D.; Dhar, N.R. Selection of the natural fiber for sustainable applications in aerospace cabin interior using fuzzy MCDM model. *Materialia* **2022**, *21*, 101270. [CrossRef]
6. Badgar, K.; Abdalla, N.; El-Ramady, H.; Prokisch, J. Sustainable Applications of Nanofibers in Agriculture and Water Treatment: A Review. *Sustainability* **2022**, *14*, 464. [CrossRef]
7. De Vos, B.; De Souza, M.F.; Michels, E. Industrial hemp (*Cannabis sativa* L.) field cultivation in a phytoattenuation strategy and valorization potential of the fibers for textile production. *Environ. Sci. Pollut. Res.* **2023**, *30*, 41665–41681. [CrossRef] [PubMed]
8. Adapa, S.K. Jagadish Prospects of Natural Fiber-Reinforced Polymer Composites for Additive Manufacturing Applications: A Review. *J. Miner.* **2023**, *75*, 920–940.
9. Akter, M.; Uddin, M.H.; Anik, H.R. Plant fiber-reinforced polymer composites: A review on modification, fabrication, properties, and applications. *Polym. Bull.* **2023**. [CrossRef]
10. Dua, S.; Khatri, H.; Naveen, J.; Jawaid, M.; Jayakrishna, K.; Norrrahim, M.N.F.; Rashedi, A. Potential of natural fiber based polymeric composites for cleaner automotive component production—A comprehensive review. *J. Mater. Res. Technol.* **2023**, *25*, 1086–1104. [CrossRef]
11. Abdalla, J.A.; Hawileh, R.A.; Bahurudeen, A.; Jyothsna, G.; Sofi, A.; Shanmugam, V.; Thomas, B.S. A comprehensive review on the use of natural fibers in cement/geopolymer concrete: A step towards sustainability. *Case Stud. Constr. Mater.* **2023**, *19*, e02244. [CrossRef]
12. Sekhar, V.C.; Dasore, A.; Yalamasetti, B.; Madhuri, K.S.; Narendar, G. Flexural behavior of natural fiber epoxy composites. *Mater. Today Proc.* 2023; *in press*. [CrossRef]
13. Bangar, S.P.; Ilyas, R.A.; Chaudhary, N.; Dhull, S.B.; Chowdhury, A.; Lorenzo, J.M. Plant-Based Natural Fibers for Food Packaging: A Green Approach to The Reinforcement of Biopolymers. *J. Polym. Environ.* **2023**. [CrossRef]
14. Manjakkal, L.; Jain, A.; Nandy, S.; Goswami, S.; Carvalho, J.T.; Pereira, L.; See, C.H.; Pillai, S.C.; Hogg, R.A. Sustainable electrochemical energy storage devices using natural bast fibres. *Chem. Eng. J.* **2023**, *465*, 142845. [CrossRef]
15. Al-Gharrawi, M.Z.; Wang, J.; Bousfield, D.W. Improving water vapor barrier of cellulose based food packaging using double layer coatings and cellulose nanofibers. *Food Packag. Shelf Life* **2022**, *33*, 100895. [CrossRef]
16. Deerattrakul, V.; Sakulaue, P.; Bunpheng, A.; Kraithong, W.; Pengsawang, A.; Chakthranont, P.; Iamprasertkun, P.; Itthibenchapong, V. Introducing hydrophilic cellulose nanofiber as a bio-separator for "water-in-salt" based energy storage devices. *Electrochim. Acta* **2023**, *453*, 142355. [CrossRef]
17. Yu, M.; Jiang, G.; Demir, M.; Sun, Y.; Wang, R.; Liu, T. PTFE-based composite nanofiber membranes for solar-driven interfacial water evaporation. *Mater. Today Commun.* **2022**, *32*, 104019. [CrossRef]

18. Kandeh, S.H.; Amini, S.; Ebrahimzadeh, H. PVA/Stevia/MIL-88A@AuNPs composite nanofibers as a novel sorbent for simultaneous extraction of eight agricultural pesticides in food and vegetable samples followed by HPLC-UV analysis. *Food Chem.* **2022**, *386*, 132734. [CrossRef]
19. Ravindran, J.; Kumar, P.S.; Saravanan, A.; Lenin, N.; Baskaran, A. Fabrication and characterization of polyvinyl-alcohol-combined bromelain nanofiber and assessment of its antimicrobial potencies. *Appl. Nanosci.* **2023**, *13*, 4157–4165. [CrossRef]
20. Valachová, K.; Švík, K.; Jurčík, R.; Ondruška, L'.; Biró, C.; Šoltés, L. Enhanced healing of skin wounds in ischemic rabbits using chitosan/hyaluronan/edaravone composite membranes: Effects of laponite, carbon and silver-plated carbon nanofiber fillers. *Chem. Pap.* **2023**, *77*, 1835–1841. [CrossRef]
21. Bhuyan, C.; Konwar, A.; Bora, P.; Rajguru, P.; Hazarika, S. Cellulose nanofiber-poly(ethylene terephthalate) nanocomposite membrane from waste materials for treatment of petroleum industry wastewater. *J. Hazard. Mater.* **2023**, *442*, 129955. [CrossRef]
22. Khurana, D.; Sadashiva, S.; Dey, B.; Guruprasad, K.P.; Bhat, S.N.; Singh, B.N. Recent advancement in development and modification of nanofibrous matrix for the application in sensing and remediation of water pollutants. *Appl. Nanosci.* **2023**, *13*, 6115–6132. [CrossRef]
23. Xu, X.; Lv, H.; Zhang, M.; Wang, M.; Zhou, Y.; Liu, Y.; Yu, D.G. Recent progress in electrospun nanofibers and their applications in heavy metal wastewater treatment. *Front. Chem. Sci. Eng.* **2023**, *17*, 249–275. [CrossRef]
24. Venkatesan, M.; Chandrasekar, J.; Liang, F.C.; Lin, W.C.; Chen, W.C.; Cho, C.J.; Chen, Y.-T.; Lee, W.-Y.; Su, C.; Zhou, Y.; et al. Surface-enhanced fully nanofiber-based self-cleanable ultraviolet resistive triboelectric energy harvester for wearable smart garments. *Nano Energy* **2023**, *113*, 108556. [CrossRef]
25. Nkede, F.N.; Wardana, A.A.; Phuong, N.T.H.; Takahashi, M.; Koga, A.; Wardak, M.H.; Fanze, M.; Tanaka, F.; Tanaka, F. Preparation and Characterization of Chitosan/Lemongrass Oil/Cellulose Nanofiber Pickering Emulsions Active Packaging and Its Application on Tomato Preservation. *J. Polym. Environ.* **2023**, *31*, 4930–4945. [CrossRef]
26. El-Aassar, M.R.; Ibrahim, O.M.; Al-Oanzi, Z.H. Biotechnological Applications of Polymeric Nanofiber Platforms Loaded with Diverse Bioactive Materials. *Polymers* **2021**, *13*, 3734. [CrossRef]
27. Langwald, S.V.; Ehrmann, A.; Sabantina, L. Measuring Physical Properties of Electrospun Nanofiber Mats for Different Biomedical Applications. *Membranes* **2023**, *13*, 488. [CrossRef] [PubMed]
28. Shang, M.; Ma, B.; Hu, X.; Liu, L.; Wang, J.; Zhang, X. Biomimetic Core-Shell-Structured Nanofiber Membranes for Rapid and Portable Water Purification. *ACS Appl. Mater. Interfaces* **2022**, *14*, 44849–44858. [CrossRef] [PubMed]
29. Agrawal, S.; Ranjan, R.; Lal, B.; Rahman, A.; Singh, S.P.; Selvaratnam, T.; Nawaz, T. Synthesis and Water Treatment Applications of Nanofibers by Electrospinning. *Processes* **2021**, *9*, 1779. [CrossRef]
30. Vojoudi, E.; Babaloo, H. Application of Electrospun Nanofiber as Drug Delivery Systems: A Review. *Pharm. Nanotechnol.* **2023**, *11*, 10–24. [CrossRef] [PubMed]
31. Liu, T. Application of Carbon Nanofiber-Modified Concrete in Industrial Building Design. *Int. J. Anal. Chem.* **2023**, *2023*, 2587551. [CrossRef]
32. Abadi, B.; Goshtasbi, N.; Bolourian, S.; Tahsili, J.; Adeli-Sardou, M.; Forootanfar, H. Electrospun hybrid nanofibers: Fabrication, characterization, and biomedical applications. *Front. Bioeng. Biotechnol.* **2022**, *10*, 986975. [CrossRef]
33. El-Seedi, H.R.; Said, N.S.; Yosri, N.; Hawash, H.B.; El-Sherif, D.M.; Abouzid, M.; Abdel-Daim, M.M.; Yaseen, M.; Omar, H.; Shou, Q.; et al. Gelatin nanofibers: Recent insights in synthesis, bio-medical applications and limitations. *Heliyon* **2023**, *9*, e16228. [CrossRef]
34. Khalid, M.Y.; Arif, Z.; Noroozi, R.; Zolfagharian, A.; Bodaghi, M. 4D printing of shape memory polymer composites: A review on fabrication techniques, applications, and future perspectives. *J. Manuf. Process.* **2022**, *81*, 759–797. [CrossRef]
35. Mallakpour, S.; Radfar, Z.; Hussain, C.M. Current advances on polymer-layered double hydroxides/metal oxides nanocomposites and bionanocomposites: Fabrications and applications in the textile industry and nanofibers. *Appl. Clay Sci.* **2021**, *206*, 106054. [CrossRef]
36. Zheng, H.; Li, X.; Liu, L.; Bai, C.; Liu, B.; Liao, H.; Yan, M.; Liu, F.; Han, P.; Zhang, H.; et al. Preparation of nanofiber core-spun yarn based on cellulose nanowhiskers/quaternary ammonium salts nanocomposites for efficient and durable antibacterial textiles. *Compos. Commun.* **2022**, *36*, 101388. [CrossRef]
37. Tian, G.; Duan, C.; Zhou, B.; Tian, C.; Wang, Q.; Chen, J. Lignin-based electrospun nanofiber membrane decorated with photo-Fenton Ag@MIF-100(Fe) heterojunctions for complex wastewater remediation. *Front. Chem. Sci. Eng.* **2023**, *17*, 930–941. [CrossRef]
38. Fernandes, A.; Cruz-Lopes, L.; Esteves, B.; Evtuguin, D. Nanotechnology Applied to Cellulosic Materials. *Materials* **2023**, *16*, 3104. [CrossRef] [PubMed]
39. Wu, X.; Li, X.; Shi, Z.; Wang, X.; Wang, Z.; Li, C.M. Electrospinning Mo-Doped Carbon Nanofibers as an Anode to Simultaneously Boost Bioelectrocatalysis and Extracellular Electron Transfer in Microbial Fuel Cells. *Materials* **2023**, *16*, 2479. [CrossRef] [PubMed]
40. Bayer, I.S. Controlled Drug Release from Nanoengineered Polysaccharides. *Pharmaceutics* **2023**, *15*, 1364. [CrossRef] [PubMed]
41. Min, T.; Zhou, L.; Sun, X.; Du, H.; Bian, X.; Zhu, Z.; Wen, Y. Enzyme-responsive food packaging system based on pectin-coated poly (lactic acid) nanofiber films for controlled release of thymol. *Food Res. Int.* **2022**, *157*, 111256. [CrossRef] [PubMed]
42. Ozbey-Unal, B.; Gezmis-Yavuz, E.; Eryildiz, B.; Koseoglu-Imer, D.Y.; Keskinler, B.; Koyuncu, I. Boron removal from geothermal water by nanofiber-based membrane distillation membranes with significantly improved surface hydrophobicity. *J. Environ. Chem. Eng.* **2020**, *8*, 104113. [CrossRef]

43. Liu, Y.; Luo, B.; Liu, H.; He, M.; Wang, R.; Wang, L.; Quan, Z.; Yu, J.; Qin, X. 3D printed electrospun nanofiber-based pyramid-shaped solar vapor generator with hierarchical porous structure for efficient desalination. *Chem. Eng. J.* **2023**, *452*, 139402. [CrossRef]
44. Abdulhamid, M.A.; Muzamil, K. Recent progress on electrospun nanofibrous polymer membranes for water and air purification: A review. *Chemosphere* **2023**, *310*, 136886. [CrossRef] [PubMed]
45. Zumstein, M.; Battagliarin, G.; Kuenkel, A.; Sander, M. Environmental Biodegradation of Water-Soluble Polymers: Key Considerations and Ways Forward. *Acc. Chem. Res.* **2022**, *55*, 2163–2167. [CrossRef] [PubMed]
46. Zhang, Y.; Fang, K.; Wang, W.; Niu, H. A Water-Soluble Epoxy-Based Green Crosslinking System for Stabilizing PVA Nanofibers. *Molecules* **2022**, *27*, 4177. [CrossRef] [PubMed]
47. Liao, Q.; Liu, H.; Chen, Z.; Zhang, Y.; Xiong, R.; Cui, Z.; Wen, C.; Sa, B. Flexible and ultrathin dopamine modified MXene and cellulose nanofiber composite films with alternating multilayer structure for superior electromagnetic interference shielding performance. *Front. Phys.* **2023**, *18*, 33300. [CrossRef]
48. Guo, Y.; Wang, Y.; Jia, F.; Li, S.; Li, S.; Sarp, S.; Youravong, W.; Li, Z. Microbial fabrication of cellulose nanofiber-based ultrafiltration membrane: A sustainable strategy for membrane manufacture. *Cellulose* **2023**, *30*, 5001–5017. [CrossRef]
49. Zhang, J.; Wei, J.; Massey, I.Y.; Peng, T.; Yang, F. Immobilization of Microbes for Biodegradation of Microcystins: A Mini Review. *Toxins* **2022**, *14*, 573. [CrossRef]
50. Harun-Ur-Rashid, M.; Imran, A.B.; Susan, M.A.B.H. Green Polymer Nanocomposites in Automotive and Packaging Industries. *Curr. Pharm. Biotechnol.* **2023**, *24*, 145–163. [CrossRef]
51. Kishimoto, M.; Izawa, H.; Saimoto, H.; Ifuku, S. Dyeing of chitin nanofibers with reactive dyes and preparation of their sheets and nanofiber/resin composites. *Cellulose* **2022**, *29*, 2829–2837. [CrossRef]
52. Sanchez Ramirez, D.O.; Vineis, C.; Cruz-Maya, I.; Tonetti, C.; Guarino, V.; Varesano, A. Wool Keratin Nanofibers for Bioinspired and Sustainable Use in Biomedical Field. *J. Funct. Biomater.* **2022**, *14*, 5. [CrossRef]
53. Mathew, M.; Midhun Dominic, C.D.; Neenu, K.V.; Begum, P.M.S.; Dileep, P.; Kumar, T.G.A.; Sabu, A.A.; Nagane, D.; Parameswaranpillai, J.; Badawi, M. Carbon black and chitin nanofibers for green tyres: Preparation and property evaluation. *Carbohydr. Polym.* **2023**, *310*, 120700. [CrossRef]
54. Zheng, H.; Han, X.; Wei, Q.; Liu, X.; Li, Y.; Zhou, J. A green flexible and wearable biosensor based on carbon nanofibers for sensitive detection of uric acid in artificial urine. *J. Mater. Chem. B* **2022**, *10*, 8450–8461. [CrossRef]
55. Li, Z.; Wang, Y.; Fan, Z.; Sun, Y.; Sun, Y.; Yang, Y.; Zhang, Y.; Ma, J.; Wang, Z.; Zhu, Z. A Dual-Function Wearable Electrochemical Sensor for Uric Acid and Glucose Sensing in Sweat. *Biosensors* **2023**, *13*, 105. [CrossRef]
56. Jeencham, R.; Tawonsawatruk, T.; Numpaisal, P.O.; Ruksakulpiwat, Y. Reinforcement of Injectable Hydrogel for Meniscus Tissue Engineering by Using Cellulose Nanofiber from Cassava Pulp. *Polymers* **2023**, *15*, 2092. [CrossRef] [PubMed]
57. El-Wahab, R.M.A.; Fadel, S.M.; Abdel-Karim, A.M.; Eloui, S.M.; Hassan, M.L. Novel green flexible rice straw nanofibers/zinc oxide nanoparticles films with electrical properties. *Sci. Rep.* **2023**, *13*, 1927. [CrossRef] [PubMed]
58. Liu, C.; Li, Z.; Li, M.C.; Chen, W.; Xu, W.; Hong, S.; Wu, Q.; Mei, C. Lignin-containing cellulose nanofibers made with microwave-aid green solvent treatment for magnetic fluid stabilization. *Carbohydr. Polym.* **2022**, *291*, 119573. [CrossRef] [PubMed]
59. Du, Z.; Lv, H.; Wang, C.; He, D.; Xu, E.; Jin, Z.; Yuan, C.; Guo, L.; Wu, Z.; Liu, P.; et al. Organic solvent-free starch-based green electrospun nanofiber mats for curcumin encapsulation and delivery. *Int. J. Biol. Macromol.* **2023**, *232*, 123497. [CrossRef]
60. Namvari, M.; Inan, T.; Altan, A. MXene-cellulose nanofiber composites: Toward green, multi-functional, flexible, and highly efficient electromagnetic interference shielding materials. *Graphene 2D Mater.* **2023**, *8*, 5–26. [CrossRef]
61. Suzuki, A.; Nakamura, Y.; Asada, C. Production of polylactic acid biocomposite reinforced with environmentally friendly cellulose nanofiber derived from steam-treated bamboo. *Biomass Conv. Biorefin.* **2023**. [CrossRef]
62. Zhang, Y.; Zhu, B.; Cai, X.; Zhao, S.; Qiao, K.; Yuan, X.; Yu, J.; Sun, N.; Li, C.; Liang, X.; et al. Uniform doping of onion-like carbon nanofillers in carbon nanofibers via functionalization and in-situ polymerization for improved fiber graphitic structure and mechanical properties. *Colloids Surf. A Physicochem. Eng. Asp.* **2023**, *674*, 131874. [CrossRef]
63. Taha, R.H.; Refaat, D.; Yahia, M. Nanofiber Integrated Nanocomplex as Advanced Technology for the Treatment of Pathogens-Contaminated Water at Jouf Region. *J. Polym. Environ.* **2023**, *31*, 4714–4725. [CrossRef]
64. Rajati, H.; Alvandi, H.; Rahmatabadi, S.S.; Hosseinzadeh, L.; Arkan, E. A nanofiber-hydrogel composite from green synthesized AgNPs embedded to PEBAX/PVA hydrogel and PA/*Pistacia atlantica* gum nanofiber for wound dressing. *Int. J. Biol. Macromol.* **2023**, *226*, 1426–1443. [CrossRef] [PubMed]
65. Fadel, S.M.; Abou-Elseoud, W.S.; Hassan, E.A.; Ibrahim, S.; Hassan, M.L. Use of sugar beet cellulose nanofibers for paper coating. *Ind. Crops Prod.* **2022**, *180*, 114787. [CrossRef]
66. Lima, A.R.; Cristofoli, N.L.; da Costa, A.M.R.; Saraiva, J.A.; Vieira, M.C. Comparative study of the production of cellulose nanofibers from agro-industrial waste streams of *Salicornia ramosissima* by acid and enzymatic treatment. *Food Bioprod. Process.* **2023**, *137*, 214–225. [CrossRef]
67. Ratnawati; Septevani, A.A.; Nurul, A.; Arifin, Y.; Handayani, A.S.H. Synthesis and characterization of cellulose nanofiber/polyvinyl alcohol (CNF/PVA) nanocomposites for gas barrier applications in paper packaging. *Mater. Today Process.* 2023; *in press*. [CrossRef]

68. Wigati, L.P.; Wardana, A.A.; Tanaka, F.; Tanaka, F. Application of pregelatinized corn starch and basil essential oil edible coating with cellulose nanofiber as Pickering emulsion agent to prevent quality-quantity loss of mandarin orange. *Food Packag. Shelf Life* **2023**, *35*, 101010. [CrossRef]
69. Wardana, A.A.; Wigati, L.P.; Tanaka, F.; Tanaka, F. Incorporation of co-stabilizer cellulose nanofibers/chitosan nanoparticles into cajuput oil-emulsified chitosan coating film for fruit application. *Food Control* **2023**, *148*, 109633. [CrossRef]
70. Mannacharaju, M.; Ganesan, S.; Lee, J.K.; Rajagopal, R.; Chang, S.W.; Ravindran, B. Bacterial cell immobilized packed bed reactor for the elimination of dissolved organics from biologically treated post-tanning wastewater and its microbial community profile. *Chemosphere* **2023**, *320*, 138022. [CrossRef]
71. Zhao, Y.; Hussain, A.; Liu, Y.; Yang, Z.; Zhao, T.; Bamanu, B.; Su, D. Electrospinning micro-nanofibers immobilized aerobic denitrifying bacteria for efficient nitrogen removal in wastewater. *J. Environ. Manag.* **2023**, *343*, 118230. [CrossRef]
72. Bouabidi, Z.B.; El-Naas, M.H.; Zhang, Z. Immobilization of microbial cells for the biotreatment of wastewater: A review. *Environ. Chem. Lett.* **2019**, *17*, 241–257. [CrossRef]
73. Jatoi, A.S.; Ahmed, J.; Akhter, F.; Sultan, S.H.; Chandio, G.S.; Ahmed, S.; Hashmi, Z.; Usto, M.A.; Shaikh, M.S.; Siddique, M.; et al. Recent Advances and Treatment of Emerging Contaminants Through the Bio-assisted Method: A Comprehensive Review. *Water Air Soil. Pollut.* **2023**, *234*, 49. [CrossRef]
74. Malode, S.J.; Shanbhag, M.M.; Kumari, R.; Dkhar, D.S.; Chandra, P.; Shetti, N.P. Biomass-derived carbon nanomaterials for sensor applications. *J. Pharm. Biomed. Anal.* **2023**, *222*, 115102. [CrossRef]
75. Ramamurthy, P.C.; Singh, S.; Kapoor, D.; Parihar, P.; Samuel, J.; Prasad, R.; Kumar, A.; Singh, J. Microbial biotechnological approaches: Renewable bioprocessing for the future energy systems. *Microb. Cell Fact.* **2021**, *20*, 55. [CrossRef]
76. Jiang, H.; Yao, M.; Chen, J.; Zhang, M.; Hong, W. Advances in biomass-based nanofibers prepared by electrospinning for energy storage devices. *Fuel* **2024**, *355*, 129534. [CrossRef]
77. Liu, X.; Jiang, Y.; Song, X.; Qin, C.; Wang, S.; Li, K. A bio-mechanical process for cellulose nanofiber production—Towards a greener and energy conservation solution. *Carbohydr. Polym.* **2019**, *208*, 191–199. [CrossRef] [PubMed]
78. Dos Santos, A.E.A.; Cotta, T.; Santos, J.P.F.; Camargos, J.S.F.; do Carmo, A.C.C.; Alcântara, E.G.A.; Fleck, C.; Copola, A.G.L.; Nogueira, J.M.; Silva, G.A.B.; et al. Bioactive cellulose acetate nanofiber loaded with annatto support skeletal muscle cell attachment and proliferation. *Front. Bioeng. Biotechnol.* **2023**, *11*, 1116917. [CrossRef] [PubMed]
79. Chen, H.; Li, Y.; Liu, R.; Zhang, B.; Han, Z.; Lau, W.M.; Lu, Y.; Wang, X.; Wang, M.; Zhou, D. Novel porous CoS1.097@carbon nanofibers as flexible and binder-free anode material for sodium-ion batteries. *J. Alloys Compd.* **2023**, *956*, 170341. [CrossRef]
80. Huang, Y.; Zhao, H.; Bao, S.; Yin, Y.; Zhang, Y.; Lu, J. Hollow FeS_2 nanospheres encapsulated in N/S co-doped carbon nanofibers as electrode material for electrochemical energy storage. *J. Alloys Compd.* **2022**, *905*, 164184. [CrossRef]
81. Xing, L.; Chen, Y.; Yang, Y.; He, C.; Wu, T.; Xia, H.; Shen, K.; Tong, G.; Wu, W. Incorporation of Fe_xO_y nanoparticles into 3D interlinked porous carbon nanofiber networks to synergistically enhance the electrical insulation, electromagnetic wave absorbing/shielding performance and thermal conductivity. *Chem. Eng. J.* **2023**, *469*, 143952. [CrossRef]
82. Qin, Y.; Song, Z.; Miao, L.; Hu, C.; Chen, Y.; Liu, P.; Lv, Y.; Gan, L.; Liu, M. Hydrogen-bond-mediated micelle aggregating self-assembly towards carbon nanofiber networks for high-energy and long-life zinc ion capacitors. *Chem. Eng. J.* **2023**, *470*, 144256. [CrossRef]
83. Awang, N.; Nasir, A.M.; Yajid, M.A.M.; Jaafar, J. A review on advancement and future perspective of 3D hierarchical porous aerogels based on electrospun polymer nanofibers for electrochemical energy storage application. *J. Environ. Chem. Eng.* **2021**, *9*, 105437. [CrossRef]
84. Borah, S.; Saikia, L.; Guha, A.K.; Deka, M. SiO_2 nanofiber reinforced P(VdF-HFP) based microporous polymer electrolytes for advanced energy storage applications. *Colloids Surf. A Physicochem. Eng. Asp.* **2023**, *673*, 131819. [CrossRef]
85. Bai, Y.; Liu, Y.; Lv, H.; Shi, H.; Zhou, W.; Liu, Y.; Yu, D.G. Processes of Electrospun Polyvinylidene Fluoride-Based Nanofibers, Their Piezoelectric Properties, and Several Fantastic Applications. *Polymers* **2022**, *14*, 4311. [CrossRef]
86. Singh, M.; Gupta, A.; Saharan, P.; Kumar, C.; Sundriyal, S.; Padhye, R.; Daeneke, T.; Choudhary, N.R.; Dhakate, S.R. Rational designed Cu-MOF@1D carbon nanofibers as free-standing and flexible electrode for robust electrochemical energy storage. *J. Energy Storage* **2023**, *67*, 107617. [CrossRef]
87. Qin, R.; Tang, J.; Wu, C.; Zhang, Q.; Xiao, T.; Liu, Z.; Jin, Y.; Liu, J.; Wang, H. Nanofiber-reinforced clay-based 2D nanofluidics for highly efficient osmotic energy harvesting. *Nano Energy* **2022**, *100*, 107526. [CrossRef]
88. Wang, N.; Wang, B.; Wang, W.; Yang, H.; Wan, Y.; Zhang, Y.; Guan, L.; Yao, Y.; Teng, X.; Meng, C.; et al. Structural design of electrospun nanofibers for electrochemical energy storage and conversion. *J. Alloys Compd.* **2023**, *935*, 167920. [CrossRef]
89. Mukhiya, T.; Tiwari, A.P.; Chhetri, K.; Kim, T.; Dahal, B.; Muthurasu, A.; Kim, J.Y. A metal–organic framework derived cobalt oxide/nitrogen-doped carbon nanotube nanotentacles on electrospun carbon nanofiber for electrochemical energy storage. *Chem. Eng. J.* **2021**, *420*, 129679. [CrossRef]
90. Xi, B.; Wang, L.; Yang, B.; Xia, Y.; Chen, D.; Wang, X. Boosting output performance of triboelectric nanogenerator based on $BaTiO_3$:La embedded nanofiber membrane for energy harvesting and wireless power transmission. *Nano Energy* **2023**, *110*, 108385. [CrossRef]
91. Yu, S.; Tai, Y.; Milam-Guerrero, J.; Nam, J.; Myung, N.V. Electrospun organic piezoelectric nanofibers and their energy and bio applications. *Nano Energy* **2022**, *97*, 107174. [CrossRef]

92. Sun, Y.; Li, H.; Wang, J.; Liu, Y.; Guo, S.; Xie, H.; Li, C. Enhanced oxygen reduction upon Ag-Fe-doped polyacrylonitrile@UiO-66-NH_2 nanofibers to improve power-generation performance of microbial fuel cells. *J. Colloid. Interface Sci.* **2023**, *648*, 654–663. [CrossRef]
93. Lin, X.; Zheng, L.; Zhang, M.; Qin, Y.; Liu, Y.; Li, H.; Li, C. Simultaneous boost of anodic electron transfer and exoelectrogens enrichment by decorating electrospinning carbon nanofibers in microbial fuel cell. *Chemosphere* **2022**, *308*, 136434. [CrossRef]
94. Wang, X.; Xu, H.; Huang, S.; Zeng, X.; Li, L.; Zhao, X.; Zhang, W. CoFe alloy nanoparticles embedded in vertically grown nanosheets on N-doped carbon nanofibers as a trifunctional electrocatalyst for high-performance microbial fuel cells. *Appl. Surface Sci.* **2023**, *609*, 155452. [CrossRef]
95. Moradian, J.M.; Yang, F.Q.; Xu, N.; Wang, J.Y.; Wang, J.X.; Sha, C.; Ali, A.; Yong, Y.C. Enhancement of bioelectricity and hydrogen production from xylose by a nanofiber polyaniline modified anode with yeast microbial fuel cell. *Fuel* **2022**, *326*, 125056. [CrossRef]
96. Jiang, N.; Song, J.; Yan, M.; Hu, Y.; Wang, M.; Liu, Y.; Huang, M. Iron cobalt-doped carbon nanofibers anode to simultaneously boost bioelectrocatalysis and direct electron transfer in microbial fuel cells: Characterization, performance, and mechanism. *Bioresour. Technol.* **2023**, *367*, 128230. [CrossRef] [PubMed]
97. Qin, Y.; Li, H.; Sun, Y.; Guo, S.; Liu, Y.; Zhai, Z.; Li, C. Directional assembly of multi-catalytic sites CoCu-MOFs with porous carbon nanofiber templates as efficient catalyst for microbial fuel cells. *J. Environ. Chem. Eng.* **2023**, *11*, 109662. [CrossRef]
98. Guo, S.; Liu, Y.; Sun, Y.; Li, C. Heterostructure-induced enhanced oxygen catalysis behavior based on metal cobalt coupled with compound anchored on N-doped carbon nanofiber for microbial fuel cell. *J. Colloid. Interface Sci.* **2023**, *636*, 305–316. [CrossRef] [PubMed]
99. Sun, Y.; Li, H.; Wang, J.; Liu, Y.; Guo, S.; Li, C. One-piece adhesive-free molding polyvinylidene fluoride @Ag nanofiber membrane for efficient oxygen reduction reaction in microbial fuel cells. *J. Environ. Chem. Eng.* **2022**, *10*, 108898. [CrossRef]
100. Barakat, N.A.M.; Ali, R.H.; Kim, H.Y.; Nassar, M.M.; Fadali, O.A.; Tolba, G.M.K.; Moustafa, H.M.; Ali, M.A. Carbon Nanofibers-Sheathed Graphite Rod Anode and Hydrophobic Cathode for Improved Performance Industrial Wastewater-Driven Microbial Fuel Cells. *Nanomaterials* **2022**, *12*, 3961. [CrossRef]
101. Zhang, M.; Liu, Y.; Li, C. Enhanced performance of microbial fuel cells with a bacteria/shape-controllable aligned carbon nanofibers hybrid biofilm. *Int. J. Hydrogen Energy* **2023**, *48*, 1107–1119. [CrossRef]
102. Liu, Y.; Sun, Y.; Li, H.; Ren, T.; Li, C. Co-filtration of bacteria/electrospun oriented carbon nanofibers integrating with carbon nanotubes for microbial fuel cell. *J. Environ. Chem. Eng.* **2022**, *10*, 107664. [CrossRef]
103. Sameen, D.E.; Ahmed, S.; Lu, R.; Li, R.; Dai, J.; Qin, W.; Zhang, Q.; Li, S.; Liu, Y. Electrospun nanofibers food packaging: Trends and applications in food systems. *Crit. Rev. Food Sci. Nutr.* **2022**, *62*, 6238–6251. [CrossRef]
104. Huang, H.; Song, Y.; Zhang, Y.; Li, Y.; Li, J.; Lu, X.; Wang, C. Electrospun Nanofibers: Current Progress and Applications in Food Systems. *J. Agric. Food Chem.* **2022**, *70*, 1391–1409. [CrossRef]
105. Topuz, F.; Uyar, T. Antioxidant, antibacterial and antifungal electrospun nanofibers for food packaging applications. *Food Res. Int.* **2020**, *130*, 108927. [CrossRef]
106. Duan, M.; Sun, J.; Huang, Y.; Jiang, H.; Hu, Y.; Pang, J.; Wu, C. Electrospun gelatin/chitosan nanofibers containing curcumin for multifunctional food packaging. *Food Sci. Hum. Wellness* **2023**, *12*, 614–621. [CrossRef]
107. Maroufi, L.Y.; Norouzi, R.; Ramezani, S.; Ghorbani, M. Novel electrospun nanofibers based on gelatin/oxidized xanthan gum containing propolis reinforced by Schiff base cross-linking for food packaging. *Food Chem.* **2023**, *416*, 135806. [CrossRef] [PubMed]
108. Wu, X.; Liu, Z.; He, S.; Liu, J.; Shao, W. Development of an edible food packaging gelatin/zein based nanofiber film for the shelf-life extension of strawberries. *Food Chem.* **2023**, *426*, 136652. [CrossRef]
109. Ertan, K.; Celebioglu, A.; Chowdhury, R.; Sumnu, G.; Sahin, S.; Altier, C.; Uyar, T. Carvacrol/cyclodextrin inclusion complex loaded gelatin/pullulan nanofibers for active food packaging applications. *Food Hydrocoll.* **2023**, *142*, 108864. [CrossRef]
110. Duan, M.; Sun, J.; Yu, S.; Zhi, Z.; Pang, J.; Wu, C. Insights into electrospun pullulan-carboxymethyl chitosan/PEO core-shell nanofibers loaded with nanogels for food antibacterial packaging. *Int. J. Biol. Macromol.* **2023**, *233*, 123433. [CrossRef] [PubMed]
111. El-Nawasany, L.I.; Sundookh, A.; Kadoum, L.A.; Yasin, M.A.; AlSalem, H.S.; Binkadem, M.S.; Al-Goul, S.T.; Zidan, N.S.; Shoueir, K.R. Ameliorating characteristics of magnetically sensitive TPU nanofibers-based food packaging film for long-life cheese preservation. *Food Biosci.* **2023**, *53*, 102633. [CrossRef]
112. Zhang, Y.; Yang, Z.; Zou, Y.; Farooq, S.; Li, Y.; Zhang, H. Novel Ag-coated nanofibers prepared by electrospraying as a SERS platform for ultrasensitive and selective detection of nitrite in food. *Food Chem.* **2023**, *412*, 135563. [CrossRef]
113. Zhang, Y.; Yang, K.; Qin, Z.; Zou, Y.; Zhong, H.; Zhang, H. Cross-linked gluten/zein nanofibers via Maillard reaction with the loading of star anise essential oil/β-cyclodextrin inclusions for food-active packaging. *Food Packag. Shelf Life* **2022**, *34*, 100950. [CrossRef]
114. Bian, X.; Sun, X.; Min, T.; Zhou, L.; Du, H.; Zhu, Z.; Bian, Y.; Jiao, X.; Wen, Y. Functionalized polyvinyl alcohol nanofibers with visible light-triggered antibacterial and ethylene scavenging capabilities for food packaging. *Food Packag. Shelf Life* **2023**, *36*, 101056. [CrossRef]
115. Lin, L.; Luo, C.; Li, C.; Abdel-Samie, M.A.; Cui, H. Eugenol/silk fibroin nanoparticles embedded *Lycium barbarum* polysaccharide nanofibers for active food packaging. *Food Packag. Shelf Life* **2022**, *32*, 100841. [CrossRef]
116. Nixon, E.J.; Sakthivel, R.; ALOthman, Z.A.; Ganesh, P.S.; Chung, R.J. Lanthanum nickelate spheres embedded acid functionalized carbon nanofiber composite: An efficient electrocatalyst for electrochemical detection of food additive vanillin. *Food Chem.* **2023**, *409*, 135324. [CrossRef] [PubMed]

117. Wagh, R.V.; Khan, A.; Priyadarshi, R.; Ezati, P.; Rhim, J.W. Cellulose nanofiber-based multifunctional films integrated with carbon dots and anthocyanins from Brassica oleracea for active and intelligent food packaging applications. *Int. J. Biol. Macromol.* **2023**, *233*, 123567. [CrossRef]
118. Mendes, J.F.; Norcino, L.B.; Corrêa, T.Q.; Barbosa, T.V.; Paschoalin, R.T.; Mattoso, H.L.C. Obtaining poly (lactic acid) nanofibers encapsulated with peppermint essential oil as potential packaging via solution-blow-spinning. *Int. J. Biol. Macromol.* **2023**, *230*, 123424. [CrossRef] [PubMed]
119. Zhou, Y.; Liu, R.; Zhou, C.; Gao, Z.; Gu, Y.; Chen, S.; Yang, Q.; Yan, B. Dynamically crosslinked chitosan/cellulose nanofiber-based films integrated with γ-cyclodextrin/curcumin inclusion complex as multifunctional packaging materials for perishable fruit. *Food Hydrocoll.* **2023**, *144*, 108996. [CrossRef]
120. Hu, G.; Luo, F.; Han, J.; Li, J.; Zhou, C.; Yang, C.; Wang, Z.; Yang, W.; Hu, Y. EGCG/HP-β-CD inclusion complexes integrated into PCL/Chitosan oligosaccharide nanofiber membranes developed by ELS for fruit packaging. *Food Hydrocoll.* **2023**, *144*, 108992. [CrossRef]
121. Shen, C.; Yang, Z.; Wu, D.; Chen, K. The preparation, resources, applications, and future trends of nanofibers in active food packaging: A review. *Crit. Rev. Food Sci. Nutr.* **2023**, 1–16. [CrossRef]
122. Forghani, S.; Zeynali, F.; Almasi, H.; Hamishehkar, H. Accurate Monitoring of Shrimp Freshness via Cornflower Anthocyanins-Loaded Bio-based Nanofiber Mats and Casted Films. *J. Polym. Environ.* **2023**, *31*, 4258–4273. [CrossRef]
123. Singh, A.K.; Itkor, P.; Lee, Y.S. State-of-the-Art Insights and Potential Applications of Cellulose-Based Hydrogels in Food Packaging: Advances towards Sustainable Trends. *Gels* **2023**, *9*, 433. [CrossRef]
124. Castro-Muñoz, R.; Kharazmi, M.S.; Jafari, S.M. Chitosan-based electrospun nanofibers for encapsulating food bioactive ingredients: A review. *Int. J. Biol. Macromol.* **2023**, *245*, 125424. [CrossRef]
125. Yang, F.; Wang, F.; Mazahreh, J.; Hu, X. Ultrasound-assisted air-jet spinning of silk fibroin-soy protein nanofiber composite biomaterials. *Ultrason. Sonochem* **2023**, *94*, 106341. [CrossRef]
126. Das, P.P.; Kalyani, P.; Kumar, R.; Khandelwal, M. Cellulose-based natural nanofibers for fresh produce packaging: Current status, sustainability and future outlook. *Sustain. Food Technol.* **2023**, *1*, 528–544. [CrossRef]
127. Okonkwo, E.C.; Namany, S.; Fouladi, J.; Almanassra, I.W.; Mahmood, F.; Al-Ansari, T. A multi-level approach to the energy-water-food nexus: From molecule to governance. *Clean. Environ. Syst.* **2023**, *8*, 100110. [CrossRef]
128. Malakar, A.; Cooper, J.A. Nanotechnology at the Juncture of Water, Food, and Energy Nexus: Boon or Bane. In *Food, Energy, and Water Nexus*; Ray, C., Muddu, S., Sharma, S., Eds.; Springer: Cham, Switzerland, 2022; pp. 233–259. [CrossRef]
129. Abdelzaher, M.A.; Farahat, E.M.; Abdel-Ghafar, H.M.; Balboul, B.A.A.; Awad, M.M. Environmental Policy to Develop a Conceptual Design for the Water–Energy–Food Nexus: A Case Study in Wadi-Dara on the Red Sea Coast, Egypt. *Water* **2023**, *15*, 780. [CrossRef]
130. Lodge, J.W.; Dansie, A.P.; Johnson, F. A review of globally available data sources for modelling the Water-Energy-Food Nexus. *Earth-Sci. Rev.* **2023**, *243*, 104485. [CrossRef]
131. Herrera-Franco, G.; Bollmann, H.A.; Lofhagen, J.C.P.; Bravo-Montero, L.; Carrión-Mero, P. Approach on water-energy-food (WEF) nexus and climate change: A tool in decision-making processes. *Environ. Dev.* **2023**, *46*, 100858. [CrossRef]
132. Villicaña-García, E.; Cansino-Loeza, B.; Ponce-Ortega, J.M. Applying the "matching law" optimization approach to promote the sustainable use of resources in the water-energy-food nexus. *Sustain. Prod. Consum.* 2023; *in press*. [CrossRef]
133. Zolghadr-Asli, B.; McIntyre, N.; Djordjevic, S.; Farmani, R.; Pagliero, L. The sustainability of desalination as a remedy to the water crisis in the agriculture sector: An analysis from the climate-water-energy-food nexus perspective. *Agric. Water Manag.* **2023**, *286*, 108407. [CrossRef]
134. Sánchez-Zarco, X.G.; Ponce-Ortega, J.M. Water-energy-food-ecosystem nexus: An optimization approach incorporating life cycle, security and sustainability assessment. *J. Clean. Prod.* **2023**, *414*, 137534. [CrossRef]
135. Ye, W.; Ma, E.; Liao, L.; Hui, Y.; Liang, S.; Ji, Y.; Yu, S. Applicability of photovoltaic panel rainwater harvesting system in improving water-energy-food nexus performance in semi-arid areas. *Sci. Total Environ.* **2023**, *896*, 164938. [CrossRef]
136. Llanaj, X.; Törős, G.; Hajdú, P.; Abdalla, N.; El-Ramady, H.; Kiss, A.; Solberg, S.Ø.; Prokisch, J. Biotechnological Applications of Mushrooms under Water—Energy—Food Nexus: Crucial Aspects and Prospects from Farm to Pharmacy. *Foods* **2023**, *12*, 2671. [CrossRef]
137. El-Ramady, H.; Abdalla, N.; Sári, D.; Ferroudj, A.; Muthu, A.; Prokisch, J.; Fawzy, Z.F.; Brevik, E.C.; Solberg, S.Ø. Nanofarming: Promising Solutions for the Future of the Global Agricultural Industry. *Agronomy* **2023**, *13*, 1600. [CrossRef]
138. Massaglia, G.; Frascella, F.; Chiadò, A.; Sacco, A.; Marasso, S.L.; Cocuzza, M.; Pirri, C.F.; Quaglio, M. Electrospun Nanofibers: From Food to Energy by Engineered Electrodes in Microbial Fuel Cells. *Nanomaterials* **2020**, *10*, 523. [CrossRef]
139. Wahid, F.; Zhao, X.Q.; Cui, J.X.; Wang, Y.Y.; Wang, F.P.; Jia, S.R.; Zhong, C. Fabrication of bacterial cellulose with TiO_2-ZnO nanocomposites as a multifunctional membrane for water remediation. *J. Colloid. Interface Sci.* **2022**, *620*, 1–13. [CrossRef]
140. Diep, E.; Schiffman, J.D. Electrospinning Living Bacteria: A Review of Applications from Agriculture to Health Care. *ACS Appl. Bio Mater.* **2023**, *6*, 951–964. [CrossRef]
141. Hassoun, A.; Prieto, M.A.; Carpena, M.; Bouzembrak, Y.; Marvin, H.J.P.; Pallarés, N.; Barba, F.J.; Bangar, S.P.; Chaudhary, V.; Ibrahim, S.; et al. Exploring the role of green and Industry 4.0 technologies in achieving sustainable development goals in food sectors. *Food Res. Int.* **2022**, *162*, 112068. [CrossRef] [PubMed]

142. Zhuang, J.; Pan, M.; Zhang, Y.; Liu, F.; Xu, Z. Rapid adsorption of directional cellulose nanofibers/3-glycidoxypropyltrimethoxysilane/polyethyleneimine aerogels on microplastics in water. *Int. J. Biol. Macromol.* **2023**, *235*, 123884. [CrossRef]
143. Chausali, N.; Saxena, J.; Prasad, R. Nanotechnology as a sustainable approach for combating the environmental effects of climate change. *J. Agric. Food Res.* **2023**, *12*, 100541. [CrossRef]
144. Putnis, N.; Neilson, M. Environmental sustainability and quality care: Not one without the other. *Int. J. Qual. Health Care.* **2022**, *34*, mzac066. [CrossRef] [PubMed]
145. He, J.; Li, J.; Gao, Y.; He, X.; Hao, G. Nano-based smart formulations: A potential solution to the hazardous effects of pesticide on the environment. *J. Hazard. Mater.* **2023**, *456*, 131599. [CrossRef]
146. Premnath, S.; Selvamani, C.; Yadav, R.K.; Ahirwar, J.P.; Naidu, S.C.V.R.M.; Boopathi, B.; Sivaram, P. Effective utilization of biodiesel blends with nano additives on diesel engine towards eco-sustainability. *Mater. Today Proc.* 2023; *in press*. [CrossRef]
147. Roy, S.; Rautela, R.; Kumar, S. Towards a sustainable future: Nexus between the sustainable development goals and waste management in the built environment. *J. Clean. Prod.* **2023**, *415*, 137865. [CrossRef]
148. Pokhriyal, M.; Rakesh, P.K.; Rangappa, S.M.; Siengchin, S. Effect of alkali treatment on novel natural fiber extracted from *Himalayacalamus falconeri* culms for polymer composite applications. *Biomass Conv. Biorefin.* **2023**. [CrossRef]
149. Maguteeswaran, R.; Prathap, P.; Satheeshkumar, S.; Madhu, S. Effect of alkali treatment on novel natural fiber extracted from the stem of *Lankaran acacia* for polymer composite applications. *Biomass Conv. Biorefin.* **2023**. [CrossRef]
150. Joe, M.S.; Sudherson, D.P.S.; Suyambulingam, I.; Siengchin, S.; Rajeshkumar, G. Characterization of novel cellulosic plant fiber reinforced polymeric composite from *Ficus benjamina* L. stem for lightweight applications. *Biomass Conv. Biorefin.* **2023**, *13*, 14267–14280. [CrossRef]
151. Priyadharshini, G.S.; Velmurugan, T.; Suyambulingam, I.; Sanjay, M.R.; Siengchin, S.; Vishnu, R. Characterization of cellulosic plant fiber extracted from *Waltheria indica Linn. stem. Biomass Conv. Biorefin.* **2023**. [CrossRef]
152. Parida, P.K.; Pradhan, A.K.; Pandit, M.K. Characterization of Cellulose Fiber Extracted from Stems of *Myriostachya wightiana* (MW) Plants: A Viable Reinforcement for Polymer Composite. *Fibers Polym.* **2023**, *24*, 489–503. [CrossRef]
153. Bhunia, A.K.; Mondal, D.; Parui, S.M.; Mondal, A.K. Characterization of a new natural novel lignocellulose fiber resource from the stem of *Cyperus platystylis* R.Br. *Sci. Rep.* **2023**, *13*, 9699. [CrossRef]
154. Shazleen, S.S.; Sabaruddin, F.A.; Ando, Y.; Ariffin, H. Optimization of Cellulose Nanofiber Loading and Processing Conditions during Melt Extrusion of Poly(3-hydroxybutyrate-co-3-hydroxyhexanoate) Bionanocomposites. *Polymers* **2023**, *15*, 671. [CrossRef]
155. Ranamalla, S.R.; Porfire, A.S.; Tomuță, I.; Banciu, M. An Overview of the Supramolecular Systems for Gene and Drug Delivery in Tissue Regeneration. *Pharmaceutics* **2022**, *14*, 1733. [CrossRef]
156. Yan, X.; Yao, H.; Luo, J.; Li, Z.; Wei, J. Functionalization of Electrospun Nanofiber for Bone Tissue Engineering. *Polymers* **2022**, *14*, 2940. [CrossRef]
157. Zhu, S.; He, Z.; Ji, L.; Zhang, W.; Tong, Y.; Luo, J.; Zhang, Y.; Li, Y.; Meng, X.; Bi, Q. Advanced Nanofiber-Based Scaffolds for Achilles Tendon Regenerative Engineering. *Front. Bioeng. Biotechnol.* **2022**, *10*, 897010. [CrossRef]
158. Baran, E.T.; Tahmasebifar, A.; Yilmaz, B. Co-axial electrospinning of PLLA shell, collagen core nanofibers for skin tissue engineering. *J. Biomater. Appl.* **2023**, *37*, 1645–1666. [CrossRef]
159. Ju, Y.X.; Song, P.; Wang, P.Y.; Chen, X.X.; Chen, T.; Yao, X.H.; Zhao, W.G.; Zhang, D.Y. Cartilage structure-inspired elastic silk nanofiber network hydrogel for stretchable and high-performance supercapacitors. *Int. J. Biol. Macromol.* **2023**, *242 Pt 2*, 124912. [CrossRef] [PubMed]
160. Dorkhani, E.; Noorafkan, Y.; Salehi, Z.; Ghiass, M.A.; Tafti, S.H.A.; Heirani-Tabasi, A.; Tavafoghi, M. Design and fabrication of polyvinylidene fluoride-graphene oxide/gelatine nanofibrous scaffold for cardiac tissue engineering. *J. Biomater. Sci. Polym. Ed.* **2023**, *34*, 1195–1216. [CrossRef] [PubMed]
161. Jin, C.; Chen, D.; Zhu, T.; Chen, S.; Du, J.; Zhang, H.; Dong, W. Poly(ferulic acid)-hybrid nanofibers for reducing thrombosis and restraining intimal hyperplasia in vascular tissue engineering. *Biomater. Adv.* **2023**, *146*, 213278. [CrossRef]
162. Sahrayi, H.; Hosseini, E.; Ramazani Saadatabadi, A.; Atyabi, S.M.; Bakhshandeh, H.; Mohamadali, M.; Aidun, A.; Farasati Far, B. Cold atmospheric plasma modification and electrical conductivity induction in gelatin/polyvinylidene fluoride nanofibers for neural tissue engineering. *Artif. Organs.* **2022**, *46*, 1504–1521. [CrossRef] [PubMed]
163. Choe, J.A.; Uthamaraj, S.; Dragomir-Daescu, D.; Sandhu, G.S.; Tefft, B.J. Magnetic and Biocompatible Polyurethane Nanofiber Biomaterial for Tissue Engineering. *Tissue Eng. Part. A.* **2023**, *29*, 413–423. [CrossRef]
164. Hama, R.; Reinhardt, J.W.; Ulziibayar, A.; Watanabe, T.; Kelly, J.; Shinoka, T. Recent Tissue Engineering Approaches to Mimicking the Extracellular Matrix Structure for Skin Regeneration. *Biomimetics* **2023**, *8*, 130. [CrossRef]
165. Phutane, P.; Telange, D.; Agrawal, S.; Gunde, M.; Kotkar, K.; Pethe, A. Biofunctionalization and Applications of Polymeric Nanofibers in Tissue Engineering and Regenerative Medicine. *Polymers* **2023**, *15*, 1202. [CrossRef]
166. Kanjwal, M.A.; Ghaferi, A.A. Graphene Incorporated Electrospun Nanofiber for Electrochemical Sensing and Biomedical Applications: A Critical Review. *Sensors* **2022**, *22*, 8661. [CrossRef]
167. Huang, C.; Xu, X.; Fu, J.; Yu, D.G.; Liu, Y. Recent Progress in Electrospun Polyacrylonitrile Nanofiber-Based Wound Dressing. *Polymers* **2022**, *14*, 3266. [CrossRef]
168. Tahir, R.; Albargi, H.B.; Ahmad, A.; Qadir, M.B.; Khaliq, Z.; Nazir, A.; Khalid, T.; Batool, M.; Arshad, S.N.; Jalalah, M.; et al. Development of Sustainable Hydrophilic *Azadirachta indica* Loaded PVA Nanomembranes for Cosmetic Facemask Applications. *Membranes* **2023**, *13*, 156. [CrossRef] [PubMed]

169. Ghajarieh, A.; Habibi, S.; Talebian, A. Biomedical Applications of Nanofibers. *Russ. J. Appl. Chem.* **2021**, *94*, 847–872. [CrossRef]
170. Al-Mayahi, A.M.W. The effect of humic acid (HA) and zinc oxide nanoparticles (ZnO-NPS) on in vitro regeneration of date palm (*Phoenix dactylifera* L.) cv. Quntar. *Plant Cell Tissue Organ. Cult.* **2021**, *145*, 445–456. [CrossRef]
171. El-Bialy, S.M.; El-Mahrouk, M.E.; Elesawy, T.; Alaa El-Dein Omara, A.E.D.; Elbehiry, F.; El-Ramady, H.; Áron, B.; Prokisch, J.; Brevik, E.C.; Solberg, S.Ø. Biological Nanofertilizers to Enhance Growth Potential of Strawberry Seedlings by Boosting Photosynthetic Pigments, Plant Enzymatic Antioxidants, and Nutritional Status. *Plants* **2023**, *12*, 302. [CrossRef] [PubMed]
172. Nalci, O.B.; Nadaroglu, H.; Pour, A.H.; Gungor, A.A.; Haliloglu, K. Effects of ZnO, CuO and γ-Fe_3O_4 nanoparticles on mature embryo culture of wheat (*Triticum aestivum* L.). *Plant Cell Tissue Organ. Cult.* **2019**, *136*, 269–277. [CrossRef]
173. Dağlioğlu, Y.; Açikgöz, M.A.; Özcan, M.M.; Kara, S.M. Impact of Al_2O_3 NPs on Callus Induction, Pigment Content, Cell Damage and Enzyme Activities in *Ocimum basilicum* Linn. *J. Int. Environ. Appl. Sci.* **2022**, *17*, 22–33.
174. Mazaheri-Tirani, M.; Dayani, S. In vitro effect of zinc oxide nanoparticles on *Nicotiana tabacum* callus compared to ZnO micro particles and zinc sulfate ($ZnSO_4$). *Plant Cell Tissue Organ. Cult.* **2020**, *140*, 279–289. [CrossRef]
175. Yoshihara, S.; Yamamoto, K.; Nakajima, Y.; Takeda, S.; Kurahashi, K.; Tokumoto, H. Absorption of zinc ions dissolved from zinc oxide nanoparticles in the tobacco callus improves plant productivity. *Plant Cell Tissue Organ. Cult.* **2019**, *138*, 377–385. [CrossRef]
176. Hasanin, M.; El-Henawy, A.; Eisa, W.H.; El-Saied, H.; Sameeh, M.J. Nano-amino acid cellulose derivatives: Eco-synthesis, characterization, and antimicrobial properties. *Int. J. Biol. Macromol.* **2019**, *132*, 963–969. [CrossRef]
177. Kim, D.H.; Gopal, J.; Sivanesan, I. Nanomaterials in plant tissue culture: The disclosed and undisclosed. *RSC Adv.* **2017**, *7*, 36492–36505. [CrossRef]
178. Kulus, D.; Tymoszuk, A. Gold nanoparticles affect the cryopreservation efficiency of in vitro-derived shoot tips of bleeding heart. *Plant Cell Tissue Organ. Cult.* **2021**, *146*, 297–311. [CrossRef]
179. Ibrahim, A.S.; Fahmy, A.H.; Ahmed, S.S. Copper nanoparticles elevate regeneration capacity of (*Ocimum basilicum* L.) plant via somatic embryogenesis. *Plant Cell Tissue Organ. Cult.* **2019**, *136*, 41–50. [CrossRef]
180. Cuong, D.M.; Du, P.C.; Tung, H.T.T.; Ngan, H.T.M.; Luan, V.Q.; Phong, T.H.; Khai, H.D.; Phuong, T.T.B.; Nhut, D.T. Silver nanoparticles as an effective stimulant in micropropagation of *Panax vietnamensis*—A valuable medicinal plant. *Plant Cell Tissue Organ. Cult.* **2021**, *146*, 577–588. [CrossRef]
181. Venkatachalam, P.; Malar, S.; Thiyagarajan, M. Effect of phycochemical coated silver nanocomplexes as novel growth stimulating compounds for plant regeneration of *Alternanthera sessilis* L. *J. Appl. Phycol.* **2017**, *29*, 1095–1106. [CrossRef]
182. Ha, N.T.M.; Do, C.M.; Hoang, T.T.; Ngo, N.D.; Bui, L.V.; Nhut, D.T. The effect of cobalt and silver nanoparticles on overcoming leaf abscission and enhanced growth of rose (*Rosa hybrida* L. 'Baby Love') plantlets cultured in vitro. *Plant Cell Tissue Organ. Cult.* **2020**, *141*, 393–405. [CrossRef]
183. Jadczak, P.; Kulpa, D.; Bihun, M.; Przewodowski, W. Positive effect of AgNPs and AuNPs in in vitro cultures of *Lavandula angustifolia* Mill. *Plant Cell Tissue Organ. Cult.* **2019**, *139*, 191–197. [CrossRef]
184. Abbas, H.K.; Abdulhussein, M.A.A. Improving Shoot Multiplication of Strawberry (*Fragaria ananassa* L. Cv. Roby Gem) In Vitro By Using AgNPs and Iron Nanoparticles. *Nat. Volatiles Essent. Oils* **2021**, *8*, 2521–2530.
185. Dehkourdi, E.H.; Mosavi, M. Effect of Anatase Nanoparticles (TiO_2) on Parsley Seed Germination (*Petroselinum crispum*) In Vitro. *Biol. Trace Elem. Res.* **2013**, *155*, 283–286. [CrossRef]
186. Hasanin, M.; Hashem, ·A.H.; Lashin, I.; Hassan, S.A.M. In Vitro improvement and rooting of banana plantlets using antifungal nanocomposite based on myco-synthesized copper oxide nanoparticles and starch. *Biomass Convers. Biorefin.* **2023**, *13*, 8865–8875. [CrossRef]
187. Elakkiya, T.V.; Meenakshi, R.V.; Kumar, S.P.; Karthik, V.; Shankar, R.K.; Sureshkumar, P.; Hanan, A. Green synthesis of copper nanoparticles using *Sesbania aculeata* to enhance the plant growth and antimicrobial activities. *Int. J. Environ. Sci. Technol.* **2022**, *19*, 1313–1322. [CrossRef]
188. Mozafari, A.; Havas, F.; Ghaderi, N. Application of iron nanoparticles and salicylic acid in in vitro culture of strawberries (*Fragaria* × *ananassa* Duch.) to cope with drought stress. *Plant Cell Tiss. Organ. Cult.* **2018**, *132*, 511–523. [CrossRef]
189. Ghanti, F.; Somayeh, B. Effect of methyl jasmonate and silver nanoparticles on production of secondary metabolites by *Calendula officinalis* L. (Asteraceae). *Trop. J. Pharm. Res.* **2014**, *13*, 1783–1789. [CrossRef]
190. Javed, R.; Mohamed, A.; Yücesan, B.; Gürel, E.; Kausar, R.; Zia, M. CuO nanoparticles significantly influence in vitro culture, steviol glycosides, and antioxidant activities of *Stevia rebaudiana* Bertoni. *Plant Cell Tissue Organ. Cult.* **2017**, *131*, 611–620. [CrossRef]
191. Chung, M.; Rekha, K.; Rajakumar, G.; Thiruvengadam, M. Production of bioactive compounds and gene expression alterations in hairy root cultures of Chinese cabbage elicited by copper oxide nanoparticles. *Plant Cell Tissue Organ. Cult.* **2018**, *134*, 95–106. [CrossRef]
192. Khan, A.K.; Kousar, S.; Tungmunnithum, D.; Hano, C.; Abbasi, B.H.; Anjum, S. Nano-Elicitation as an Effective and Emerging Strategy for In Vitro Production of Industrially Important Flavonoids. *Appl. Sci.* **2021**, *11*, 1694. [CrossRef]
193. Iqbal, Z.; Javad, S.; Naz, S.; Shah, A.A.; Shah, A.N.; Paray, B.A.; Gulnaz, A.; Abdelsalam, N.R. Elicitation of the in vitro Cultures of Selected Varieties of Vigna radiata L. With Zinc Oxide and Copper Oxide Nanoparticles for Enhanced Phytochemicals Production. *Front. Plant Sci.* **2022**, *13*, 908532. [CrossRef]
194. Rahmawati, M.; Mahfud, C.; Risuleo, G.; Jadid, N. Nanotechnology in Plant Metabolite Improvement and in Animal Welfare. *Appl. Sci.* **2022**, *12*, 838. [CrossRef]

195. Tymoszuk, A.; Kulus, D. Silver nanoparticles induce genetic, biochemical, and phenotype variation in chrysanthemum. *Plant Cell Tissue Organ. Cult.* **2020**, *143*, 331–344. [CrossRef]
196. Niazian, M.; Nalousi, A.M.; Azadi, P.; Ma'mani, L.; Chandler, S.F. Perspectives on new opportunities for nano-enabled strategies for gene delivery to plants using nanoporous materials. *Planta* **2021**, *254*, 83. [CrossRef]
197. Sarmast, M.K.; Salehi, H. Silver Nanoparticles: An Influential Element in Plant Nanobiotechnology. *Mol. Biotechnol.* **2016**, *58*, 441–449. [CrossRef]
198. Sreelekshmi, R.; Siril, E.A.; Muthukrishnan, S. Role of Biogenic Silver Nanoparticles on Hyperhydricity Reversion in *Dianthus chinensis* L. an In Vitro Model Culture. *J. Plant Growth Regul.* **2021**, *41*, 23–39. [CrossRef]
199. Mozafari, A.; Dedejani, S.; Ghaderi, N. Positive responses of strawberry (*Fragaria* × *ananassa* Duch.) explants to salicylic and iron nanoparticle application under salinity conditions. *Plant Cell Tiss. Organ. Cult.* **2018**, *134*, 267–275. [CrossRef]
200. Asl, A.G.; Mozafari, A.; Ghaderi, N. Iron nanoparticles and potassium silicate interaction effect on salt-stressed grape cuttings under in vitro conditions: A morphophysiological and biochemical evaluation. *Cell Dev. Biol—Plant* **2019**, *55*, 510–518.
201. Ramirez-Mosqueda, M.A.; Sanchez-Segura, L.; Hernandez-Valladolid, S.L.; Bello-Bello, E.; Bello-Bello, J.J. Influence of silver nanoparticles on a common contaminant isolated during the establishment of *Stevia rebaudiana* Bertoni culture. *Plant Cell Tissue Organ. Cult.* **2020**, *143*, 609–618. [CrossRef]
202. Timoteo, C.O.; Paiva, R.; dos Reis, M.V.; Claro, P.I.C.; da Silva, D.P.C.; Marconcini, J.M.; de Oliveira, J.E. Silver nanoparticles in the micropropagation of *Campomanesia rufa* (O. Berg) Nied. *Plant Cell Tissue Organ. Cult.* **2019**, *137*, 359–368. [CrossRef]
203. Tung, H.T.; Thuong, T.T.; Cuong, D.M.; Luan, V.Q.; Hien, V.T.; Hieu, T.; Nam, N.B.; Phuong, H.T.N.; Vinh, B.V.T.; Khai, H.D.; et al. Silver nanoparticles improved explant disinfection, in vitro growth, runner formation and limited ethylene accumulation during micropropagation of strawberry (*Fragaria* × *ananassa*). *Plant Cell Tissue Organ. Cult.* **2021**, *145*, 393–403. [CrossRef]
204. Safavi, K. Effect of Titanium Dioxide Nanoparticles in Plant Tissue Culture Media for Enhance Resistance to Bacterial Activity. *Bull. Env. Pharmacol. Life Sci.* **2014**, *3*, 163–166.
205. Wang, W.; Yang, R.; Li, T.; Komarneni, S.; Liu, B. Advances in recyclable and superior photocatalytic fibers: Material, construction, application and future perspective. *Compos. Part. B Eng.* **2021**, *205*, 108512. [CrossRef]
206. Wang, W.; Li, T.; Komarneni, S.; Lu, X.; Liu, B. Recent advances in Co-based co-catalysts for efficient photocatalytic hydrogen generation. *J. Colloid. Interface Sci.* **2022**, *608*, 1553–1575. [CrossRef]
207. Xiang, W.; Yuan, J.; Wu, Y.; Luo, H.; Xiao, C.; Zhong, N.; Zhao, M.; Zhong, D.; He, Y. Working principle and application of photocatalytic optical fibers for the degradation and conversion of gaseous pollutants. *Chin. Chem. Lett.* **2022**, *33*, 3632–3640. [CrossRef]
208. Azmoon, P.; Farhadian, M.; Pendashteh, A.; Navarchian, A.H. Synergistic effect of adsorption and photocatalytic degradation of oilfield-produced water by electrospun photocatalytic fibers of Polystyrene/Nanorod-Graphitic carbon nitride. *J. Environ. Sci.* 2023; *in press*. [CrossRef]
209. Gallegos-Cerda, S.D.; Hernández-Varela, J.D.; Chanona Pérez, J.J.; Huerta-Aguilar, C.A.; Victoriano, L.G.; Arredondo-Tamayo, B.; Hernández, O.R. Development of a low-cost photocatalytic aerogel based on cellulose, carbon nanotubes, and TiO_2 nanoparticles for the degradation of organic dyes. *Carbohydr. Polym.* **2024**, *324*, 121476. [CrossRef]
210. Yang, J.; Song, H.; Wu, J.; Zhu, X. Preparation of SiO_2@CN/BTO membrane and its enhanced photocatalytic performance. *Mater. Res. Bull.* **2024**, *169*, 112546. [CrossRef]
211. Seo, H.J.; Im, E.; Myung, Y.; Min, Y.; Hyun, D.C.; Moon, G.D. Flexible, cuttable, origami-enabling ceramic nanofiber mat for visible light-driven catalysts. *Appl. Surf. Sci.* **2024**, *643*, 158711. [CrossRef]
212. Pathak, D.; Sharma, A.; Sharma, D.P.; Kumar, V. A review on electrospun nanofibers for photocatalysis: Upcoming technology for energy and environmental remediation applications. *Appl. Surf. Sci. Adv.* **2023**, *18*, 100471. [CrossRef]
213. Xing, W.; Wang, Y.; Mao, X.; Gao, Z.; Yan, X.; Yuan, Y.; Huang, L.; Tang, J. Improvement strategies for oil/water separation based on electrospun SiO_2 nanofibers. *J. Colloid. Interface Sci.* **2024**, *653*, 1600–1619. [CrossRef]
214. Kenry; Lim, C.T. Nanofiber technology: Current status and emerging developments. *Prog. Polym. Sci.* **2017**, *70*, 1–17. [CrossRef]
215. Shi, H.; Liu, Y.; Bai, Y.; Lv, H.; Zhou, W.; Liu, Y.; Yu, D.G. Progress in defect engineering strategies to enhance piezoelectric catalysis for efficient water treatment and energy regeneration. *Sep. Purif. Technol.* **2024**, *330*, 125247. [CrossRef]
216. Varun, S.; George, N.M.; Chandran, A.M.; Varghese, L.A.; Mural, P.K.S. Multifaceted PVDF nanofibers in energy, water and sensors: A contemporary review (2018 to 2022) and future perspective. *J. Fluor. Chem.* **2023**, *265*, 110064. [CrossRef]
217. Hiwrale, A.; Bharati, S.; Pingale, P.; Rajput, A. Nanofibers: A current era in drug delivery system. *Heliyon* **2023**, *9*, e18917. [CrossRef] [PubMed]
218. Solangi, N.H.; Karri, R.R.; Mubarak, N.M.; Mazari, S.A. Mechanism of polymer composite-based nanomaterial for biomedical applications. *Adv. Ind. Eng. Polym. Res.* 2023; *in press*. [CrossRef]