

Regulatory Frameworks for Polymeric Nanofiber-Based Drug Delivery Systems: Current Status, Challenges, and Future Perspectives

Nidhi Sharma

Chandigarh College of Pharmacy, Chandigarh Group of College, Landran, Mohali, 140307, India

Abstract

Nanofibers are increasingly recognized as adaptable nanostructured materials with significant promise across biomedical, pharmaceutical, environmental, filtration, energy, and industrial fields. Their nanoscale size, large surface-area-to-volume ratio, flexibility, porosity, and adjustable properties render them especially appealing for advanced drug delivery, wound healing, tissue engineering, cancer therapy, gene delivery, and biosensing. A range of fabrication methods—such as electrospinning, centrifugal spinning, solution blow spinning, phase separation, self-assembly, and nanofiber printing—have been established to create nanofibrous structures. Of these, electrospinning continues to be one of the most extensively studied techniques, owing to its adaptability and capacity to produce fibers with controlled morphology. The characteristics of the resulting nanofibers are heavily affected by material choice and processing parameters, including polymer concentration, viscosity, molecular weight, solvent properties, applied voltage, and environmental conditions.

Natural and biodegradable polymers have attracted growing interest as substitutes for conventional synthetic polymers, thanks to their biocompatibility, biodegradability, and environmental benefits. Nevertheless, difficulties concerning mechanical strength, stability, solvent toxicity, reproducibility, production cost, and large-scale manufacturing still limit broader application. Nanofiber-based systems also demand thorough assessment of toxicity, stability, drug-release behavior, characterization, and long-term biological effects prior to clinical and commercial translation.

From a regulatory standpoint, nanofiber-based pharmaceutical products pose added challenges involving standardized characterization, quality control, manufacturing consistency, safety assessment, environmental impact, and regulatory harmonization. Differences in fiber diameter, morphology, porosity, composition, and processing conditions can influence product performance and make quality and regulatory assessment more complex. Consequently, future progress in nanofiber technology should emphasize sustainable materials, safer solvents, solvent-recovery systems, scalable manufacturing, advanced process monitoring, artificial intelligence-assisted optimization, and harmonized regulatory approaches. Cooperation among researchers, industry, and regulatory authorities will be crucial for moving nanofiber technologies from laboratory research into safe, effective, reproducible, and commercially viable applications.

Keywords: Nanofiber, Electrospinning; Drug delivery, Biopolymers, Biomedical applications, Sustainability, Regulatory challenges.

1. Introduction

Nanofibers have turned into a point of interest because of their properties including elevated surface zone, nanoscale width and flexibility that make them suitably supportive in healthcare, filtration, pressing, electronics and garment ventures. In general, the diameter of nanofibers is less than 100 nm, which increases its performance in many advanced applications. The global nanofiber market is expected to grow rapidly — expanding from approx. USD 9.87 billion in 2022 to USD 53.54 billion by end of the forecast year — with polymers and composite materials anticipated to lead the industry throughout this timeframe. Nanofibers have some advantages, however producing nanofibers at scale faces several road-blocks including scalability of production routes resulting in non-uniform fiber properties and cost of production being high [1].

Moreover, the synthetic process usually employs toxic organic solvents and non-biodegradable conventional polymers that bring about several environmental and health issues [2]. To overcome these problems, researchers are now directing their attention toward the development of plant-, animal- and microorganism-based biopolymer nanofibers from renewable resources [3]. These biopolymer molecules offer a cost-effective and biodegradable, stable and environmentally friendly methodology for the production of safer nanofibers [4]. All these bio-fabricated/biopolymers are sustainable, biodegradable and compatible for in vivo application.

The type of polymer chosen and the technique used to fabricate nanofibers plays a significant role in determining the yield of polymeric nano-fibers [5]. At present, electrospinning, centrifugal spinning, solution blow spinning, electro-blown spinning, wet spinning and melt spinning techniques have been developed for the preparation of nanofibers over the years [6]. These approaches have their own strengths and weaknesses in terms of production efficiency, cost, operational complexity and material properties [7]. Electrospinning continues to be the most widely studied and employed technique for nanofiber fabrication among all of the existing techniques [8]. It has the ability to prepare ultrafine fibers with nanoscale diameter by using electrostatic force that stretches polymer solution or polymer melt into a fiber [9]. On the other hand, in non-electrospinning methods nanofibers are formed from mechanical or aerodynamic forces rather than electrical energy [10].

Nanofibers are strongly affected by several processing and environmental parameters [11]. Significantly polymer concentration, molecular weight and viscosity of the polymer solution, the type of solvent used, feed rate (ml/h) and distance between nozzle and collector [12]. In electrospinning and similar methods, polymer morphology and fiber performance is influenced to a large extent by parameters such as voltage and air pressure [13]. In electrospinning, various setups adjust the electric field and flow to regulate jet formation, thinning, and fiber arrangement [14]. Organic solvent nanofiltration (OSN) refers to the membrane technology created to carry out precise molecular separations and recover solvents within the chemical and pharmaceutical sectors [15]. Centrifugal spinning is one effective technique for producing nanofibers from a range of materials [16]. Practical effectiveness is frequently undermined by their strong tendency to degrade [17]. Electrospinning is an effective technique for producing micro- and nanofibers that are applied in areas including biomedical engineering, filtration, and energy storage. One crucial element in successful electrospinning is selecting the right solvent, since it influences how

effectively the polymer dissolves, the characteristics of the solution, the quality of the fibres, and how efficient the process is overall [18].

One of the main problems correlated with nanofiber technology is using common synthetic polymers and organic solvents. [19] However, a large number of conventional polymers are persistent and have low biocompatibility services, limiting their utility for biological engineering and bioscience [20]. Further, commonly used toxic volatile organic solvents in processing may present risks to human health and the environment [21]. These difficulties have stimulated researchers to prioritize the use of biodegradable biopolymers and eco-friendly solvents as environmentally friendly substitutes [22]. Due to their renewable nature and source, biopolymers are attractive because they yield biodegradable and environmentally benign nanofibers [23]. However, they also exhibit certain processing challenges in spite of their benefits [24]. Extraction and purification processes usually required for these are complex, expensive, and require long periods of time [25]. Moreover, it is known that many biopolymers are more heat sensitive than conventional poly(s) and may degrade at high processing temperature during recycling [26]. As an example, polycaprolactone has a melting temperature of about 58 °C, polylactic and polyglycolic acid is about 175 °C and 228 °C respectively [27]. Processing conditions and eventual application are governed by their thermal properties [28].

Sustainability and safety in terms of nanofiber technology is another important factor [29]. Recycling nanofibers can be considered as a viable option that could contribute to minimizing the harmful effect on the environment and increasing the efficiency of recycling [30]. However, despite the promising features, there might be some negative aspects related to the development and operation of nanofibers [31]. First of all, the presence of highly charged equipment at the stage of electrospinning makes the process rather dangerous and leads to an increased risk of electrocution [32]. Secondly, toxic solvents and nanosized fibers can cause some health problems when animals are exposed to these elements and such problems are possible in case of people as well [33]. As a result, the process of further improvement of nanofiber technology involves not only production improvement but also sustainability and safety issues as well [34].

2. Classification of nanofiber by key characteristics- Material-based nanofibers

Natural polymer nanofibers

Due to their physicochemical similarities to the extracellular matrix, natural polymers have emerged as excellent biomaterials for biomedical and tissue engineering purposes [35]. Natural polymers consist of naturally existing molecules such as proteins, lipids, nucleic acids, and polysaccharides [36]. They are better biocompatible and less immunogenic than synthetic polymers, which mean that they are less likely to cause any biological reactions in the body [37]. Being rich in proteins, which include amino acids like glycine and aspartic acid, they provide effective adhesion of cells and their proliferation, growth, and differentiation [38].

Various types of natural polymers have been studied in order to synthesize nanofibers; these include silk fibroin, collagen, elastin, gelatin, chitosan, chitin, cellulose acetate, casein, and fibrinogen [39]. There are a number of approaches to producing nanofibers, such as melt-blowing, template synthesis, self-assembly, direct stretching, wet spinning, electrospinning, centrifugal jet spinning, plasma-induced synthesis, pressurized spinning, and solution blow spinning [40]. Nevertheless, most of the above-mentioned techniques have certain disadvantages [41]. Thus, for instance, melt-blowing is applicable only to thermoplastic polymers, template synthesis results in the formation of short fibers that cannot

easily be separated from the template, direct stretching is characterized by poor productivity and inability to obtain nanofibers smaller than 100 nm, and self-assembly requires rather expensive amphiphilic materials [42]. Electrospinning is among the most successful fabricating technologies due to its simplicity, reproducibility, versatility, and economic feasibility [43]. This method allows for creating nano and microfibers using polymer solutions or melts of either natural or synthetic origin [44].

Natural polymers have a number of advantages, including biodegradability, bioactivity, low level of toxicity, and good tissue compatibility [45]. Natural polymers usually degrade without producing toxic materials; besides, they cause only a minimal response from the immune system [46]. Moreover, natural polymers are generally available and inexpensive [47]. However, natural polymers have a number of drawbacks as well [48]. For instance, they usually have low mechanical strength, high hygroscopicity, low solubility, and high solution viscosity; all this makes fabrication of materials more difficult (including electrospinning) [49]. To enhance nanofibers stability and mechanical properties, cross-linking of natural polymers is necessary [50]. In addition, proteins can change their structure under high voltage; besides, there can be differences in composition because of possible contamination during their extraction [51].

Inorganic nanofibers

Inorganic biomaterials have attracted significant research interest as carriers for drug delivery owing to their good biocompatibility, ease of functionalization, and ability to increase the bioavailability of the drug [52]. Many inorganic nanoparticles such as halloysite, laponite, nano-hydroxyapatite, attapulgite, carbon nanotubes, and graphene have been used in the fabrication of nanofibers in order to increase the efficiency of drug delivery systems [53]. The main characteristics of the inorganic nanoparticles are that they have high surface area and are able to be tailored on the surface and thus can provide controlled and sustained drug release [54]. In combination with electro spun polymer nanofibers, inorganic nanoparticles are able to control the release rate of drugs and reduce the chance of burst release [55]

Carbon-Based nanofibers-

Carbon nanofibers (CNFs) are carbon-based materials with unique physical and chemical properties that are of great interest to scientists and technologists [56]. In contrast to regular carbon fibers with diameter sizes of micrometers, CNFs have very small dimensions and range in size from 3 to 200 nm. CNFs are often obtained by catalytic pyrolysis of carbon-containing precursors or electrospinning and then carbonizing polymers [57]. CNFs may be synthesized by the methods of catalytic chemical vapor deposition (CVD) as well as electrospinning and then carbonizing of polymer precursors [58]. Such properties are useful for different areas of application like energy-storage electrodes, reinforcement for carbon-fiber composites, and bone tissue engineering [59]. Due to increasing commercial production and academic interest, CNFs will likely become more significant in development of green technologies, especially by using with other types of carbon fibers and carbon nanotubes [60].

Peptide and protein nanofibers

In recent years, new developments in the field of nanotechnology have improved the delivery of drugs by means of nanoparticles, nanospheres, nanogels, and nanofibers, which help to resolve problems related to poor solubility and low bioavailability and provide for targeted drug delivery [61]. Nanofibers produced by electrospinning show great interest among drug delivery systems because of high specific surface area, porosity, flexibility of pore size regulation, increased permeability and possibility of loading different kinds of molecules [62]. There are various polymers that could be used in order to create nanofibers. Proteins and peptides represent one of the most promising candidates owing to their

biocompatibility and biological properties [63]. Peptide is the name for a short chain of amino acids, while protein is a complex molecule that serves certain biological purposes, like catalyzing reactions, hormones' regulation, protection against diseases, molecular transportation [64]. Large size and complex organization of proteins make them very vulnerable to physical and chemical damages, affecting absorption and delivery of the protein molecule across different biological barriers [65]. As a result, new nanofiber drug delivery system could serve as an effective way of increasing stability, controlled release and efficiency of protein- and peptide-based drugs [66].

Comparison of peptides/proteins with other materials

Unlike manufactured and natural chemicals, peptides and proteins are macromolecules that are important in the structure of the body, hence showing great biocompatibility. The ability of peptides and proteins to be easily biodegraded means that surgery and other invasive measures do not have to be adopted to get rid of the peptide and protein-containing substance from the body [67]. Therefore, peptide and protein-containing nanofibers show more benefits than nanofibers made from natural and artificial polymers because the artificial polymers can endanger living beings [68]. Since nanofibers are fibrous just like the extracellular matrix, it is always favorable to have them as a form of drug delivery system [69]. Different drugs can be embedded within nanofibers through dissolution of the drug within the polymer solution prior to fabrication, ensuring that the drugs are well-loaded [70]. The uniform loading of the drug into the nanofibers is crucial, making it necessary to have cross-linkers and co-solvents [71].

3. Methods for manufacturing of nanofibres-

Fabrication methods

Nano-fibers are fibers having diameter less than 100 nm [72]. Nanofibers are fabricated using several methods that operate on different principles for their preparation and application [73]. Some of the commonly employed methods for the fabrication of nanofibers are electrospinning, self-assembly, phase separation, template-based preparation, and nanofiber printing [74].

Electrospinning

Among various methods that can be used to fabricate ultrafine nanofibers, electrospinning is regarded as one of the most widespread ones [75]. The principle of this technique is to apply an electrical field onto a solution or melt of the selected material, which results in jet generation followed by its solidification due to solvent evaporation prior to collecting on the ground collector [76]. Electrospinning equipment includes several key elements such as a high-voltage power source, syringe pump, capillary needle, and grounded collector [77]. The procedure starts with forming of a Taylor cone on the needle tip, where electrostatic forces overcome surface tension of the polymer solution [78]. Further increase in the applied voltage leads to jet generation by the thin polymer solution, which stretches, elongates, and experiences solvent evaporation until nanofibers are formed on the collector [79].

The features of electrospun nanofibers significantly depend on certain parameters that are usually characterized as solution, processing, and ambient parameters [80]. Such solution parameters as concentration, viscosity, conductivity, surface tension, and molecular weight of the polymer solution affect greatly fiber morphology and stability [81]. It is very important to use adequate concentrations and viscosity to receive smooth beads-free fibers, while conductivity influences fiber diameter and jet formation [82].

Phase separation

By causing polymer phase separation by gelation, phase separation is a straightforward and economical technique for creating nanofibers. The technique facilitates the immediate formation of porous nanofibrous matrices, wherein polymer concentration governs fiber attributes such as porosity and mechanical resilience [83]. The ultimate nanofiber configuration is achieved through the extraction and freeze-drying of the solvent post gel formation [84]. Nonetheless, the extensive commercial and biomedical applications of the approach are constrained by its failure to produce continuous fibers, its laborious process, and its limitation to polymers with appropriate gelation properties [85]. To enhance practical utility, current investigations seek to improve process efficiency, broaden polymer compatibility, and refine control over nanofiber morphology [86].

Nanofiber printing method

Nanofibrillated cellulose (NFC) preparation is the first step in the sequential process of nanofiber printing, which concludes with the creation of structures using 3D printing methods [87].

Material selection

Because it determines the end product's structural and functional characteristics, material selection is crucial to the creation of nanofibers [88]. Because of their superior biocompatibility, biodegradability, and capacity to promote tissue regeneration, natural polymers like chitosan, collagen, gelatin, alginate, cellulose, hyaluronic acid, and silk fibroin are widely used in drug delivery and other biomedical applications [89].

4. Biomedical applications

Textiles, automotive, construction, civil engineering, solar energy, environmental management, transportation, agriculture, and food processing are just a few of the many industries where nanotechnology is widely used to improve performance, efficiency, and creativity [90]. The use of nanofibers in wound healing, targeted drug administration, cancer therapy, gene delivery, tissue engineering, and biosensing technologies has increased due to recent developments in nanofiber synthesis techniques, particularly electrospinning [91].

Nanofibers are useful for a variety of therapeutic applications because they can control drug-release behavior, enhance biocompatibility, and closely resemble the structure of the natural extracellular matrix [92]. In order to improve treatment effectiveness and functionality, current research is increasingly concentrated on novel strategies such as nanoparticle-loaded nanofibers, stimuli-responsive nanofiber systems, and the coupling of nanofibers with 3D printing technologies [93].

Large-scale production challenges, expensive manufacturing, long-term biocompatibility issues, and complicated regulatory approval procedures are some of the main drawbacks [94]. Therefore, overcoming these obstacles and optimizing the potential of nanofibers in contemporary biological applications would require future advancements in precise fabrication techniques, sustainable production methods, and interdisciplinary research collaboration [95].

Because of their special mechanical characteristics, high surface-area-to-volume ratio, and versatility in drug delivery systems, nanofibers have drawn a lot of attention in the rapidly developing field of nanotechnology in biomedicine [96]. The use of nanofibers in wound healing, targeted drug administration, gene therapy, cancer treatment, tissue engineering, and biosensing has increased due to recent developments in fabrication techniques, especially electrospinning [97].

Their relevance in therapeutic applications has increased due to their capacity to deliver regulated drug release, improve biocompatibility, and mimic the extracellular matrix [98]. Innovative strategies including stimuli-responsive drug delivery systems, nanofibers loaded with nanoparticles, and integrating nanofibers with 3D printing technologies are becoming more and more the focus of current research [99]. However, issues with long-term safety, manufacturing costs, large-scale manufacture, and regulatory approval still prevent them from being widely used in clinical settings [100].

5. Commercialization and Regulatory Aspects

The use of toxic solvents and synthetic compounds in many reported electrospinning processes has created substantial regulatory and safety issues, as several of these ingredients are not allowed under current pharmaceutical regulations [101]. Therefore, great emphasis is being put into developing safer electrospinning technologies, optimal processing conditions, and environmentally benign materials for nanofiber production [102].

Research in this sector focuses on increasing electrospinning parameters, characterisation techniques, and safety evaluation methodologies to generate high-quality and repeatable nanofibers [103]. The characterisation of nanofibers, particularly those containing entrapped pharmacological molecules, plays a critical role in determining their performance, stability, and regulatory acceptance [104]. However, poor comprehension of nanofiber characterisation techniques can result in problems with repeatability, reproducibility, and incorrect result interpretation [105].

The final characteristics and electrospinning behavior of drug-loaded nanofibers are significantly influenced by their composition [106]. Toxic solvents and unapproved crosslinking agents have been used in numerous prior researches, which restricts their direct medicinal applicability [107]. In order to increase the compatibility and regulatory acceptance of nanofiber-based drug delivery systems, researchers are currently investigating safer biopolymers and non-toxic solvents [108]. Standards and recommendations for the manufacturing and assessment of nanofibers are also being developed by regulatory bodies in a number of nations [109]. Future commercialization and wider pharmaceutical use of drug-loaded nanofibers are anticipated to be supported by emerging trends including innovative biopolymers and sustainable nanofiber technology [110].

6. Regulatory issues in nanofiber-

Significant prospects for scientific and technological improvements have been made possible by nanotechnology, which manipulates materials at the microscopic level [111]. However, a number of regulatory issues pertaining to environmental safety, human health, and ethical issues have also been brought about by its quick development [112]. Risk and toxicity assessment of nanomaterials, appropriate definition and characterization, product labeling, environmental impact assessment, international regulatory harmonization, intellectual property protection, and ethical considerations are important regulatory issues in nanotechnology [113].

Nanomaterials may have unanticipated biological and environmental consequences because they frequently have distinct physical and chemical characteristics that set them apart from their bulk forms [114]. Because of this, regulatory bodies have a hard time assessing their toxicity and possible risks. Therefore, it is crucial to establish standardized testing procedures and efficient risk assessment frameworks for nanomaterials [115].

Furthermore, because elements like particle size, shape, and surface characteristics have a significant impact on their behavior and safety profile, identifying and describing nanomaterials is still difficult [116].

To guarantee consumer knowledge and well-informed decision-making, nano-enabled products must be properly labeled [118]. Because nanoparticles can build up in ecosystems and have a detrimental impact on wildlife and natural resources, environmental issues also arise [119]. The necessity for stringent environmental monitoring and safety requirements is further highlighted by the release of nanoparticles during manufacture, usage, or disposal activities [120].

For nanotechnology-based goods to be safely commercialized and accepted worldwide, international harmonization of regulatory standards is required [121]. Furthermore, because nanotechnology is multidisciplinary, it poses special intellectual property issues that complicate patent evaluation and protection [122].

Regulatory decision-making must also take into account ethical and societal issues, such as privacy, technological abuse, and fair access to the advantages of nanotechnology [123]. Global regulatory bodies are actively creating safety frameworks, standards, and cooperative research projects to address these issues and encourage the ethical development and manufacture [124]. Because of their distinct structural and functional characteristics, nanofibers have garnered significant attention in the domains of environmental research, pharmaceuticals, and biomedical engineering [125]. Despite their enormous promise, a number of manufacturing, technical, and regulatory obstacles make it difficult for nanofiber-based products to be successfully commercialized [126]. While there are clear benefits to a variety of manufacturing methods, including as electrospinning, centrifugal spinning, solution spinning, and self-assembly, there are also issues with process standardization, validation, and regulatory compliance [127].

Consistent quality, safety, and efficacy are requirements set by regulatory bodies like the Food and Drug Administration (FDA) and the European Medicines Agency (EMA), which can be challenging to meet with existing nanofiber production techniques [128].

The scalability of manufacturing processes is a significant issue [129]. While other techniques like melt-electrospinning writing and rotary jet spinning exhibit better scalability, they still need to be further optimized to guarantee reliable and repeatable industrial production [130]. Another crucial issue is maintaining reproducibility because fiber diameter, morphology, porosity, and overall performance can be greatly impacted by variables such polymer concentration, solution viscosity, humidity, temperature, surface tension, and collection settings [131]. Complying with strict regulatory standards can be made more difficult by even little changes in these conditions, which can lead to significant deviations in product quality [132].

The absence of widely recognized techniques for characterizing nanofibers is another significant problem [133]. Researchers and manufacturers currently employ a wide range of methods to evaluate structural homogeneity, mechanical characteristics, stability, drug release behavior, and biological interactions [134]. The regulatory approval procedure is slowed down and standardized quality criteria are difficult to develop due to this lack of harmonization [135]. Nanofiber-based systems must also exhibit biocompatibility, long-term stability, the absence of impurities, repeatable drug release profiles, and uniform performance across production batches in pharmaceutical and tissue engineering applications [136]. Comprehensive preclinical and clinical evaluation is also crucial for regulatory approval [137]. Although some nanofiber formulations have demonstrated promising outcomes in

laboratory and animal experiments, thorough information on toxicity, biodistribution, pharmacokinetics, immunogenicity, and long-term biological effects is necessary for successful translation into clinical application [139].

Rather than poor therapeutic effectiveness, promising treatments frequently fail to advance due to a lack of adequate regulatory proof [140]. Additionally, developers frequently have to prepare separate regulatory applications to meet the criteria of various jurisdictions due to the lack of globally unified rules for nanotechnology [141]. This raises the cost of development and lengthens the time it takes for approval, especially for new businesses and academic institutions [142].

7. Challenges in Spinning Process Engineering

The manufacturing process has a significant impact on the quality of nanofibers. Despite being the most popular industrial processes, centrifugal spinning and electrospinning nevertheless have a number of technical drawbacks [143]. The diameter, pore size, and fiber shape of nanofibers made using these methods often vary, resulting in uneven product quality. Mechanical characteristics and filtering effectiveness may also be negatively impacted by structural flaws including beads, drops, and uneven fiber alignment [144].

Numerous operational factors, including as polymer concentration, solution viscosity, electrical conductivity, applied voltage, spinning distance, nozzle geometry, and collector design, must be optimized in order to improve process consistency [145]. High-speed cameras, optical sensors, and real-time imaging systems are examples of advanced monitoring technologies that help researchers better comprehend jet generation and fiber deposition during spinning [146].

In order to anticipate process behavior, optimize operating conditions, and enhance product repeatability, artificial intelligence, machine learning, and computational modeling are being increasingly used into nanofiber manufacturing [147]. These intelligent manufacturing techniques have the ability to improve process standardization and drastically cut down on experimental trial-and-error [148]. Additionally, hybrid electro-centrifugal spinning technologies have garnered a lot of attention lately since they combine the benefits of centrifugal and electrospinning, leading to increased production and better fiber quality [149].

8. How to overcome issue-

Nanofiber Stability in Various Environments-

One of the most important elements influencing the practical use of polymeric nanofibers is their long-term durability [150]. The nature of the polymer, the surrounding environment, and the intended usage all affect their physical and chemical stability [151]. Nanofibrous membranes must sustain their structural integrity and filtration effectiveness over extended operation in applications like water and air filtration [152]. Their performance can be greatly diminished by any deterioration, dissolution, or loss of mechanical strength [153]. However, because they are resistant to environmental deterioration and typically need to be burned after use, very stable nanofibers [154].

On the other hand, a number of biomedical applications benefit from regulated biodegradation. After their therapeutic purpose is fulfilled, nanofibers intended for tissue engineering, wound dressings, drug delivery, and regenerative medicine are anticipated to progressively break down [155].

Many modification techniques have been studied to increase the durability of water-soluble nanofibers without sacrificing their biodegradability [156]. One of the best methods for decreasing water solubility

while maintaining the fibers' structural properties is chemical cross-linking [157]. Additionally, a number of physical and chemical post-treatment methods have been used to improve the durability of nanofibrous structures, such as heat treatment UV curing [158].

The utility of nanofibers has been further extended by recent developments in surface engineering [159]. Mechanical strength, chemical resistance, and environmental stability are greatly enhanced by the addition of inorganic oxides and ultrathin protective coatings [160]. Additional biological activities like improved biocompatibility, regulated medication release, and antibacterial activity are also introduced by these surface alterations [161].

While maintaining the nanofibrous architecture, advanced deposition methods like as Atomic Layer Deposition (ALD), Vapour Phase Infiltration (VPI), and Physical Vapour Deposition (PVD) allow for exact control over coating thickness and surface chemistry [162].

The development of biodegradable polymeric and composite nanofibers with adjustable degradation profiles and multipurpose surface characteristics is a growing focus of current research [163]. These materials are especially promising for biomedical applications requiring transient structural support, such as wound healing, tissue regeneration, and cosmetic formulations [164]. Future research is therefore anticipated to concentrate on creating ecologically friendly nanofibers that combine controlled biodegradability with good performance [165].

Polymer–Solvent Interactions and suitable material Selection-

Choosing the right polymers and solvents is one of the main issues in the production of nanofibers [166]. Since most traditional polymers used in electrospinning, such as polyamide and polyacrylonitrile, are insoluble in water, organic solvents like formic acid or dimethylformamide are needed [167]. These solvents are costly, poisonous, and environmentally dangerous even if they successfully breakdown polymers and create high-quality nanofibers [168].

Water-soluble polymers, on the other hand, offer a more secure and eco-friendly processing method [169]. However, when exposed to watery environments, these materials frequently show poor moisture resistance and quickly lose their structural integrity [170]. As a result, its direct use is restricted in applications that call for extended contact to water or humid environments [171].

As a result, scientists are creating new biodegradable polymers, smart polymers, and conjugated polymer systems that combine superior process capability with improved environmental stability [172]. Despite these developments, many naturally occurring polymers have complicated branched molecular structures and high molecular weights, which make it challenging to electrospin them because electrostatic forces are not enough to stretch the polymer solution into continuous[173].

Solvent management is still a significant economic and environmental issue, in addition to polymer selection [174]. A significant amount of solvent is lost during processing and evaporates into the atmosphere during the manufacture of nanofibers [175]. One efficient way to reduce solvent waste is to develop solvent recovery systems, such as adsorption, condensation, and closed-loop recycling technologies [176].

Production Rate and Industrial Scale-Up

Industrial-scale manufacturing of nanofibers is still difficult, despite the fact that laboratory-scale production has established itself [177]. Instead of using continuous manufacturing, the majority of current production systems use batch mode, which limits productivity and costs [178]. Because water evaporates more slowly and residual moisture frequently necessitates additional drying steps, water-based spinning systems typically show lower production rates than organic solvent-based

processes [179]. Optimizing solution preparation, polymer feeding, solvent evaporation, nanofiber collection, and quality assurance is necessary to increase efficiency [180]. To boost manufacturing capacity, a number of engineering strategies have been put forth [181]. Production rates can be significantly increased by automated fiber collection, enhanced airflow control, optimal spinneret layouts, and multi-nozzle electrospinning systems [182]. Furthermore, rheological modeling, artificial intelligence, and computational fluid dynamics can be used to improve process factors and lower production variability [183].

Close cooperation between university researchers and commercial manufacturers will be necessary for the effective commercialization of nanofiber technology [184]. These collaborations can enhance equipment design, speed up process optimization, and ease the shift from laboratory-scale research to large-scale industrial production [185].

9. Safety Considerations

The commercial acceptability of nanofibers is still influenced by safety concerns, despite tremendous scientific advancements [186]. Misconceptions about the possible health dangers of fibrous nanomaterials have been caused by historical links with asbestos fibers [187]. Because of this, despite the proven benefits of nanofiber-based technologies [188].

Standardized testing procedures, transparent regulatory frameworks, thorough toxicological evaluation, and efficient dissemination of scientific data are all necessary to address these issues [189].

Toxicological Assessment

The safety of tailored nanofibers has been positively demonstrated by recent toxicological studies [190]. Inorganic nanofibers are often not more harmful than nanoparticles made of the same chemical substance, according to comparative research [191]. Nanofibers are less likely to penetrate intact skin or reach the deepest parts of the respiratory tract due to their greater size [192].

When compared to equivalent nanoparticles, experimental research using ceramic nanofibers has shown little detrimental effects on lung cells [193]. These results imply that many nanoscale particle materials may provide greater health risks than well-designed nanofibers [194]. To create thorough safety standards for upcoming clinical and industrial uses, however, more study into long-term exposure, inhalation toxicity, biodegradation behavior, and occupational safety is still necessary [195].

10. Conclusion-

In the fields of biomedicine, the environment, energy, filtration, and industry, nanofiber technology has shown great promise [196]. Its widespread commercialization is nevertheless constrained by a number of manufacturing and technical issues, despite notable progress [197]. Enhancing nanofiber stability, lowering manufacturing costs, optimizing polymer-solvent systems, increasing production efficiency, and putting sustainable solvent recovery techniques into practice are some of the main concerns [198]. The performance and economic viability of nanofibers will be greatly enhanced by addressing these constraints through creative material design, cutting-edge production processes, and efficient post-processing procedures [199].

Strong cooperation between academic researchers, industry manufacturers, and regulatory agencies is necessary for the successful transfer of nanofiber technology from laboratory research to industrial applications [200]. These collaborations can guarantee product quality, safety, and regulatory compliance, standardize production procedures, and quicken technical innovation [201].

Additionally, it is anticipated that further research into intelligent manufacturing, green processing technologies, biodegradable materials, and multifunctional surface changes will expand the range of nanofiber uses while promoting sustainable development [202].

All things considered, nanofibers continue to be among the most useful and adaptable nanomaterials on the market today [203]. To overcome current obstacles and fully realize their potential in next clinical, environmental, and industrial applications, ongoing scientific innovation, interdisciplinary research, and technology breakthroughs will be crucial [204].

Future Perspectives

The development of environmentally friendly polymers, green solvent systems, effective solvent recovery techniques, intelligent process control, and continuous large-scale manufacturing should be the main goals of future developments in nanofiber technology [205]. Concurrently, advances in surface fictionalization, biodegradable composites, and multifunctional nanofibers will increase their use in enhanced healthcare, filtration, energy storage, environmental remediation, and medicine [206]. While maintaining product quality, safety, and environmental sustainability, it is anticipated that the combination of automation, artificial intelligence, and uniform regulatory frameworks will speed up commercialization [207].

References-

1. Maduna L, Patnaik A. Challenges associated with the production of nanofibers. *Processes*. 2024 Sep 27;12(10):2100.
2. Gupta A. Adoption of biodegradable polymers as an Eco-friendly substitute for conventional plastics. *Journal of Advanced Education and Sciences*. 2026 Jun 1;6(3):126-33.
3. Esakkimuthu S, Ganga VS, Subramaniam S. Exploration and Utilization of Nanotechnology in the Modifications and Sustainable Utilizations of Plant-Based Biopolymers. In *Biopolymers from Plant Origin for Environmental Sustainability* 2026 Feb 7 (pp. 599-629). Cham: Springer Nature Switzerland.
4. Rawat R, Prasad B, Luo WJ, Thapliyal A, Negi P. Biopolymers for a sustainable future: advanced nanoarchitectonics and multifunctional applications. *Materials Research Express*. 2026 Mar 13;13(5):052001.
5. Patel S, Patil Y, Chaudhari S, Mundada A, Chalikwar SS, Patil JS. Polymer-based nanofibers in biomedicine: Fabrication to therapeutic applications. *Letters in Drug Design & Discovery*. 2026 Feb 3:100298.
6. Kanaan AF, de Oliveira WA, Boaron CK, Sauer H, Santana MA, Piedade AP, Vidotti M. Electrospinning technology applied for building up electrochemical platforms—a review. *Journal of Solid State Electrochemistry*. 2026 Jun 15:1-38.
7. Chaanaoui M, Byiringiro J, Hammouti B. Cost modeling of innovative metal 3D printed solar absorber tubes for high-efficiency parabolic trough collector. *The International Journal of Advanced Manufacturing Technology*. 2026 Jan 12:1-5.
8. Wu T, Hao R, Su Q, Sun L, Zhang T, Du J, Fu M, Wang Y, Xue J, Li X. Fabrication of Tissue Constructs and Organoids Using Electrospun Micro/Nanofibers. *Chemical Reviews*. 2026 Apr 8;126(10):5961-6014.
9. Maji S, Pradhan J, Mehra NK, Baldi A. Polymeric nanofibers: Quality by design: Perspectives and prospects. *Letters in Drug Design & Discovery*. 2026 Feb 12:100291.

10. Kumar P, Jain A, Sharma M, Garg A, Ganguly SC, Patel A, Khan Y, Debnath B, Ashique S, Hussain MS. Nanofibres: a promising approach in drug delivery systems. *International Journal of Polymeric Materials and Polymeric Biomaterials*. 2026 Jan 2;1-35.
11. Mhalshekar K, Krishan A, Gaydhane M, Sontakke S, Pawar V. Advanced electrospun nanofibers for photocatalytic degradation: sustainable solutions for wastewater remediation. *ACS omega*. 2026 Jan 29;11(5):6954-85.
12. Negi J, Rawat A, Rawat M, Sharma H, Dwivedi C. Electrospinning for advanced textiles: optimizing fibre morphology and improving stability by post-treatment methods. *Journal of Polymer Research*. 2026 Jun;33(6):267.
13. Evran S, Ekren N, Yılmaz M, Sarkın AS, Duta L, Gündüz O. Experimental and Numerical Analysis of Electrospun Polylactic Acid Fiber Deposition: Effects of Processing Parameters on Morphology and Coating Uniformity. *Fibers*. 2026 Jun 18;14(6):75.
14. Rabbi MF, Ahn JH, Vu DL, Ahn KK. Recent Advances in Electrospun Nanofibers for Triboelectric Nanogenerators: Performance Enhancement Strategies and Emerging Applications. *Advanced Materials*. 2026 Jun;38(31):e22834.
15. Wang Z, Tang Y, Wang Y, Huang Q, Chen L, Wang Z, Wu T, Jiang Z, Li Z, Zhu Z. Spinning, Functionalizing, and Assembling of Flexible Fiber Electronics and Their Applications. *Small*. 2026 Mar;22(18):e14279.
16. Chowdhury N, Rahman A, Parvinzadeh Gashti M. A Review About Centrifugal Spun Polymer and Polymer Composites Nanofibers in Filtration Process: Mechanism, Efficiency and Applications. *Journal of Composites Science*. 2026 Apr 7;10(4):199.
17. Botia Carreño EO, Elghandour MM, De Palo P, Maggiolino A, De Angelis M, Salem AZ. Nano/microencapsulation of feed additives for ruminal microbiome modulation and enteric methane mitigation in ruminants: a critical review. *Frontiers in Veterinary Science*. 2026 May 5;13:1798669.
18. Pan CT, Ghosh S, Wu CM, Shiue YL, Rahim MS. solvent systems in electrospinning—polymer compatibility, toxicological risks, and environmental considerations. *Journal of Materials Science*. 2026 Mar;61(11):7390-417.
19. Trucillo P. Biomaterials for drug delivery and human applications. *Materials*. 2024 Jan 18;17(2):456.
20. Ikeda M. Public health problems of organic solvents. *Toxicology letters*. 1992 Dec 1;64:191-201.
21. Aleksandrovna SN. TRENDS IN ECO-FRIENDLY NAIL COATINGS AND BIOPOLYMER FORMULATIONS. *Вестник науки и образования*. 2026(1 (168)-2):15-21.
22. Esakkimuthu S, Ganga VS, Subramaniam S. Exploration and Utilization of Nanotechnology in the Modifications and Sustainable Utilizations of Plant-Based Biopolymers. In *Biopolymers from Plant Origin for Environmental Sustainability* 2026 Feb 7 (pp. 599-629). Cham: Springer Nature Switzerland.
23. Faria C, Reis D, Dias D, Reis R, Cruz S. Material Limitations and Processing Challenges of Bio-Based Thermoplastics: A Review. *Journal of Applied Polymer Science*. 2026:e70436.
24. Bhardwaj A, Srivastava A, Chakraborty S, Mishra AK. Extraction, purification, and identification strategies. In *Secondary Metabolites in Stress and Disease Management* 2026 Jan 1 (pp. 163-193). Academic Press.

25. Tayyab H, Liu S, Zhang H, Shen R, Liu Y, Jiang J, Li B. A Comprehensive Review on Chemical Process and Catalytic Mechanism in Conversion of Biomass to Carbon Materials. *Journal of Materials Chemistry A*. 2026.
26. de Simão de Sousa G, Latras A, Fernández C, Mínguez Enkovaara LF, Jiménez-Quero A. Polyhydroxyalkanoates as Sustainable Agricultural Plastics: Processing Strategies, Performance, and Environmental Perspectives. *Macromolecular Materials and Engineering*. 2026 May;311(5):e70236.
27. Kaya H, Alp E, Sabet S, Buonomo B, Fedele L, Rossi S, Manca O. Experimental investigation of thermal performance of NanoEncapsulated-PCM emulsions in parallel plate thermal energy storage system. *International Communications in Heat and Mass Transfer*. 2026 Jan 1;170:110009.
28. Saleh AM, Selim RN, El-Morsy MT, Mansour SA, Elhady R, Ismail SF, Gamal M, Kenawy ER. A review of nanofiber-based drug delivery systems: fabrication, characterization, advances, and future prospects. *Journal of Materials Science: Polymers*. 2026 Dec;1(1):10.
29. Arunkumar P, Alqahtani MD, Al Ghamdi MS, Elgarahy AM. Integrating additive manufacturing with biodegradable polymers for sustainable biomedical engineering: a state-of-the-art review. *International Journal of Polymeric Materials and Polymeric Biomaterials*. 2026 Jun 22:1-38.
30. Xu M, Wang Y, Zuo T, Xie H, Zhang S, Zhang Y, Chen R. Exposure and risk assessment in the nanotechnology industry: health and environmental challenges from nanomaterial properties. *Journal of Environmental Exposure Assessment*. 2026 May 19;5(2):N-A.
31. Tören E. Advancements in portable electrospinning technology for wound healing applications: a comprehensive review. *Biomedical Materials & Devices*. 2026 Jun;4(2):2548-71.
32. Sharma R, Agrawal P, Dadhich M, Dutta G, Ambwani S, Mundra V, Kumar T. Tiny Particles, Major Risks: An Integrative Review of Micro-and Nanoplastics Exposure and Its Medical Significance.
33. Arunkumar P, Alqahtani MD, Al Ghamdi MS, Elgarahy AM. Integrating additive manufacturing with biodegradable polymers for sustainable biomedical engineering: a state-of-the-art review. *International Journal of Polymeric Materials and Polymeric Biomaterials*. 2026 Jun 22:1-38.
34. Jo H, Kang S, Yang JE, Kim I, Lee SS. Biodegradable Natural Polymer-Based Drug Delivery Systems for Bone Tissue Engineering. *Medicinal Research Reviews*. 2026 Mar 25.
35. Sharma A, Ashique S, Kaushik M, Jha SK, Gupta G, Puri V, Kesharwani P. Polysaccharides and carbohydrate polymers: Innovations from nature to industry. *Journal of the Science of Food and Agriculture*. 2026 Feb 27.
36. Barbary BG, Lukesh NR, Bachelder EM, Ainslie KM. Biodegradable polymers for application as robust immunomodulatory biomaterial carrier systems. *Small*. 2026 Mar;22(16):2409422.
37. Liu H, Zhang H, Yang W, Chen H, Wang J, Chang F. Natural Biomaterials for Osteochondral Repair: From Source to Strategy. *Advanced Healthcare Materials*. 2026 Jun 16:e71344.
38. Saleh AM, Selim RN, El-Morsy MT, Mansour SA, Elhady R, Ismail SF, Gamal M, Kenawy ER. A review of nanofiber-based drug delivery systems: fabrication, characterization, advances, and future prospects. *Journal of Materials Science: Polymers*. 2026 Dec;1(1):10.
39. Saleh AM, Selim RN, El-Morsy MT, Mansour SA, Elhady R, Ismail SF, Gamal M, Kenawy ER. A review of nanofiber-based drug delivery systems: fabrication, characterization, advances, and future prospects. *Journal of Materials Science: Polymers*. 2026 Dec;1(1):10.

40. Salehi M, Arabpour Z, Zamani S, Alizadeh M, Gharibshahiyan M, Rezvani M, Aldaghi N, Yekesadat SM, R Djalilian A. Corneal bioengineering via electrospun nanofibers and nanoparticles. *Journal of Biomaterials Applications*. 2026 Apr;40(9):1094-140.
41. Banerji A. *Developing New Strategies Based on Melt Blowing for High Performance Nonwoven Fiber Production* (Doctoral dissertation, University of Minnesota).
42. Xue J, Wu T, Dai Y, Xia Y. Electrospinning and electrospun nanofibers: methods, materials, and applications. *Chemical reviews*. 2019 Mar 27;119(8):5298-415.
43. Scaffaro R, Maio A, Lopresti F, Botta L. Nanocarbons in electrospun polymeric nanomats for tissue engineering: a review. *Polymers*. 2017 Feb 21;9(2):76.
44. Jo H, Kang S, Yang JE, Kim I, Lee SS. Biodegradable Natural Polymer-Based Drug Delivery Systems for Bone Tissue Engineering. *Medicinal Research Reviews*. 2026 Mar 25.
45. Das H, Kashyap M, Rahman A. Toxicological, Safety, and Regulatory Considerations. *Magnetic Particles for Targeted Drug Delivery and Biomedical Applications*. 2026;4:167.
46. Ghorbanpoor H, Soykan MN, Benzait Z, Altuğ B, Ekenel EQ, Ebrahimi A, Kilic A, Uysal O, Avci H. Biomedical applications of functional nanofibres. In *Electrospun Nanofibers* 2026 Jan 1 (pp. 495-517). Woodhead Publishing.
47. Tang X, Li Y, He X, Zhang S. A Comprehensive Review of Natural Polymer-Based Adsorbents for Microplastic Removal. *Journal of Polymer Science*. 2026.
48. Wang X, Jiang L, Li Y, Xie X, Lin Y, Chen Z, Zhao S. Research progress of plant protein-based electrospun nanofibers as wound dressings. *Journal of Materials Chemistry B*. 2026.
49. Vaseashta A, Salel S, Bölgen N. Biopolymer-Based Electrospun Nanofibers for Wound Healing, Regeneration, and Therapeutics. *Materials*. 2026 Apr 3;19(7):1443.
50. Zamani S, Najafi R, Emiola-Sadiq T, Zhang L, Meda V. Dry Fractionation of Plant Proteins and Starches By Tribo-Electrostatic Separation: A Review on Functional and Nutritional Properties. *Food and Bioprocess Technology*. 2026 Feb;19(2):53.
51. Daneshgar H, Ahmadi S, Abbariki N, Rabiee N, Bencherif SA. Surface-Coated Inorganic Nanomaterials for Drug Delivery: Chemical Design, Biomedical Applications, and Mechanistic Insights. *Advanced NanoBiomed Research*. 2026 Feb;6(2):e202500144.
52. Tazwar MF, Muhtasim ST, Reza T, Autul YS, Hoque ME. Inorganic Nanofiller-Incorporated Polymeric Nanocomposites for Biomedical Applications. In *Nanofillers* 2023 Aug 30 (pp. 117-152). CRC Press.
53. Muthu Y, Sankar P, Srinivasan J, Mohana MS, Elumalai K. Nanoparticles, hydrogels, and stimuli-responsive systems: controlled release strategies for growth factor delivery. *Biomedical Materials & Devices*. 2026 Jun;4(2):1980-97.
54. Xing J, Feng J, Wang Q, Yu DG, Annie Bligh SW. Recent advances in electrospun nanofiber-based implantable drug delivery systems for breast cancer therapy. *RSC Pharmaceutics*. 2026 Mar 24;3(2):276-304.
55. Vijayakumar V, Rathinam T. Nanofibers in biomedical applications: recent developments and challenges. *Biomedical Materials & Devices*. 2026 Sep;4(3):2983-3000.
56. Flores-Lasluisa JX, Navlani-García M, Berenguer-Murcia Á, Morallón E, Cazorla-Amorós D. 10 years of frontiers in carbon-based materials: carbon, the “newest and oldest” material. The story so far. *Frontiers in Materials*. 2024 Apr 9;11:1381363.

57. Guo C. Fabrication strategies for fiber-shaped carbon architectures and their functional integration into flexible sensing platforms. In International Conference on Electronic Devices and Intelligent Control (EDIC 2026) 2026 Jul 9 (Vol. 14300, pp. 390-400). SPIE.
58. Kim YA, Hayashi T, Endo M, Dresselhaus MS. Carbon nanofibers. In Springer handbook of nanomaterials 2013 (pp. 233-262). Berlin, Heidelberg: Springer Berlin Heidelberg.
59. Vafaeva KM, Zegait R. Carbon nanotubes: revolutionizing construction materials for a sustainable future: A review. Research on Engineering Structures and Materials. 2023;10(2):559-621.
60. Rathour A, Yadav S, Sharma P, Vashist Y, Singh M, Kumar V. Recent Developments in Polymer-Derived Nanomaterials: Advanced Strategies for Drug Delivery and Therapy. ChemistrySelect. 2026 Apr;11(15):e00005.
61. Kumar S, Rathaur S, Maity D, Varshney P, Gayen JR. Nanotechnology based targeted drug delivery systems for breast cancer: challenges, recent advancement and future perspectives. Nanomedicine. 2026 Apr 3;21(7):1027-48.
62. Hiwrale A, Bharati S, Pingale P, Rajput A. Nanofibers: A current era in drug delivery system. Heliyon. 2023 Sep 1;9(9).
63. Sewald N, Jakubke HD. Peptides: chemistry and biology. John Wiley & Sons; 2015 Nov 19.
64. Emadi R, Amiri Z, Mortazavi Moghadam F, Raoufi S, Zargar Moradi M, Asadi S, Cho W, Park JH, Voosough A, Ramezani Farani M, Hwang SK. Self-assembling nanocomposites for smart drug delivery: towards personalized and stimuli-responsive therapeutics. RSC advances. 2026 Jan 23;16(6):5088-127.
65. Alfadhel M. Nanofiber-based drug delivery systems: a review on its applications, challenges, and envisioning future perspectives. Current drug delivery. 2026 Jan;23(1):44-55.
66. Saleh AM, Selim RN, El-Morsy MT, Mansour SA, Elhady R, Ismail SF, Gamal M, Kenawy ER. A review of nanofiber-based drug delivery systems: fabrication, characterization, advances, and future prospects. Journal of Materials Science: Polymers. 2026 Dec;1(1):10.
67. Consequently, peptide and protein-based nanofibers offer more advantages to living organisms compared to those derived from natural and synthetic polymers, since synthetic polymers may pose risks to living entities.
68. Alfadhel M. Nanofiber-based drug delivery systems: a review on its applications, challenges, and envisioning future perspectives. Current drug delivery. 2026 Jan;23(1):44-55.
69. Abdul Hameed MM, Mohamed Khan SA, Thamer BM, Rajkumar N, El-Hamshary H, El-Newehy M. Electrospun nanofibers for drug delivery applications: Methods and mechanism. Polymers for Advanced Technologies. 2023 Jan;34(1):6-23.
- 70. Saleh AM, Selim RN, El-Morsy MT, Mansour SA, Elhady R, Ismail SF, Gamal M, Kenawy ER. A review of nanofiber-based drug delivery systems: fabrication, characterization, advances, and future prospects. Journal of Materials Science: Polymers. 2026 Dec;1(1):10.**
71. Maji S, Pradhan J, Mehra NK, Baldi A. Polymeric nanofibers: Quality by design: Perspectives and prospects. Letters in Drug Design & Discovery. 2026 Feb 12:100291.
72. So SH, Lee SY, Kang H, Min H, Jung HT, Lee KH, Kim DW. Metal-organic frameworks for gas sensors: comprehensive review from principal, fabrication to application. International Journal of Extreme Manufacturing. 2026 Feb 1;8(1):012001.

73. Ke J, Han B, Wang W, Tao Z, Li Z, Lian H, Meng Z. Three-Dimensional Electrospun Nanofiber Scaffolds: Fabrication Methods and Biomedical Applications. *Macromolecular Bioscience*. 2026 Jan;26(1):e00573.
74. Vijayakumar V, Rathinam T. Nanofibers in biomedical applications: recent developments and challenges. *Biomedical Materials & Devices*. 2026 Sep;4(3):2983-3000.
75. Ahn H, Kim H, Park M, Lee BS. Recent Advances in Melt Electrospinning and Melt Electrowriting: Jet Taming, Fiber Diameter Control, and Emerging Applications. *Fibers and Polymers*. 2026 Apr 15:1-25.
76. Shaban M, Mosa TM, Abdel-Hamid H, Abdalfarg N, Hashim G. Advancements in electrospinning: a comprehensive review of historical development, key parameters, applications, and challenges. *Discover Chemistry*. 2026 Feb 20;3(1):82.
77. Mokhova E, Menshutina N. Investigation of the Influence of the Physicochemical Properties of PVP and PAN Solutions on the Structural Characteristics of Fiber Materials Formed During Electrospinning. *Journal of Polymer Science*. 2026 May 15.
78. Kanaan AF, de Oliveira WA, Boaron CK, Sauer H, Santana MA, Piedade AP, Vidotti M. Electrospinning technology applied for building up electrochemical platforms—a review. *Journal of Solid State Electrochemistry*. 2026 Jun 15:1-38.
79. Negi J, Rawat A, Rawat M, Sharma H, Dwivedi C. Electrospinning for advanced textiles: optimizing fibre morphology and improving stability by post-treatment methods. *Journal of Polymer Research*. 2026 Jun;33(6):267.
80. Ye HY, Shangguan WJ, Wu H, Zhao J, Xiao LB, Xu DJ, Xu GC, Huang QL, Zhang GH, Cao LD, Tan YA. In-site fabrication of pheromone-loaded core-sheath fibers via handheld emulsion electrospinning with natural surfactants for *Apolygus lucorum* attraction. *Chemical Engineering Journal*. 2026 Apr 1:175731.
81. Thorat AS, Bardelli A, Pettineo S, Castellano M, Alloisio M, Vicini S. Fabrication and characterization of cellulose derivatives electrospun nonwoven mats. *Cellulose*. 2026 Jun 18:1-3.
82. Saleh AM, Selim RN, El-Morsy MT, Mansour SA, Elhady R, Ismail SF, Gamal M, Kenawy ER. A review of nanofiber-based drug delivery systems: fabrication, characterization, advances, and future prospects. *Journal of Materials Science: Polymers*. 2026 Dec;1(1):10.
83. Feng C, Wen Z, Ou J, Jin Z, Li J, Yan X. Cellulose nanofiber/sodium alginate/chitosan aerogel spheres for adsorbing cationic dyes. *Carbohydrate Research*. 2026 Apr 30:109942.
84. Arunkumar P, Alqahtani MD, Al Ghamdi MS, Elgarahy AM. Integrating additive manufacturing with biodegradable polymers for sustainable biomedical engineering: a state-of-the-art review. *International Journal of Polymeric Materials and Polymeric Biomaterials*. 2026 Jun 22:1-38.
85. Hjiri M, Mustapha N, Benamara M. Structure–Property Relationships in Polymer–Perovskite Hybrid Materials. *Journal of Inorganic and Organometallic Polymers and Materials*. 2026 Feb 19:1-28.
86. Khoda B, Habib A. 3D Bioprinting with Cellulose-Derived Bio-ink and Precursors. In *Biodegradable 3D-Printing* 2026 Apr 1 (pp. 71-98). Singapore: Springer Nature Singapore.
87. Farahani AH, Moghadam RZ, Marandi M. Electrospinning of nanofibers and the functional potential of starch: a comprehensive review. *Discover Nano*. 2026 Feb 2;21(1):24.
88. Zhao L, Zhou Y, Zhang J, Liang H, Chen X, Tan H. Natural polymer-based hydrogels: from polymer to biomedical applications. *Pharmaceutics*. 2023 Oct 23;15(10):2514.

89. Saxena T, Chawla VK, Yadav S. Nano-Technology-Based Natural Fiber Composite Materials for Smart Technology Applications. In *Handbook of Electronic Devices and Materials* 2026 Apr 18 (pp. 1-34). Singapore: Springer Nature Singapore.
90. Vaseashta A, Salel S, Bölgen N. Biopolymer-Based Electrospun Nanofibers for Wound Healing, Regeneration, and Therapeutics. *Materials*. 2026 Apr 3;19(7):1443.
91. Goldberg M, Langer R, Jia X. Nanostructured materials for applications in drug delivery and tissue engineering. *Journal of Biomaterials Science, Polymer Edition*. 2007 Jan 1;18(3):241-68.
92. Jayaprakash N, Michael B. Stimuli-responsive electrospun nanofibrous membranes for drug delivery: a comprehensive review. *Biomedical Materials & Devices*. 2026 Mar 10;1:32.
93. Dhurandhar Y, Prajapati JL, Singh AP, Chauhan NS, Namdeo KP. Industrial Scale-up and Commercialization Challenges of Redox-Responsive Drug Delivery Systems. In *Redox-Responsive Delivery Systems* 2026 (pp. 261-278). CRC Press.
94. Muñoz-Silva M, García-Álvarez R, Pérez E, Jiménez-Jiménez C, Esteban-Arranz A. Biopolymer—Nanoparticle Interactions in 3D-Printing for Biomedical Applications: Advantages, Limitations and Future Perspectives. *Polymers*. 2026 Apr 24;18(9):1038.
95. Saleh AM, Selim RN, El-Morsy MT, Mansour SA, Elhady R, Ismail SF, Gamal M, Kenawy ER. A review of nanofiber-based drug delivery systems: fabrication, characterization, advances, and future prospects. *Journal of Materials Science: Polymers*. 2026 Dec;1(1):10.
96. Alfadhel M. Nanofiber-based drug delivery systems: a review on its applications, challenges, and envisioning future perspectives. *Current drug delivery*. 2026 Jan;23(1):44-55.
97. Zhao X, Liu Q, Xu Z, Yang F, Li Z, Bai X, Zhu H, Liu Y, Wang Y. Cell membrane-coated nanoparticles: advanced drug delivery systems for chronic wound healing therapy. *International Journal of Nanomedicine*. 2026 Dec 31:563555.
98. Ujjwal RR, Sutar AD, Shukla R, Slaughter G. Nanofibrous Materials and Nanoparticles for Combating Antimicrobial Resistance: Synthesis, Integration, and Translational Perspectives. *ACS Biomaterials Science & Engineering*. 2026 Jul 16.
99. Zhou G, Liu H. Commercial translation of electrochemical biosensors: supply chain strategy, scale-up manufacturing, and regulatory–quality considerations. *Biosensors*. 2026 Feb 9;16(2):112.
100. Pan CT, Ghosh S, Wu CM, Shiue YL, Rahim MS. solvent systems in electrospinning—polymer compatibility, toxicological risks, and environmental considerations. *Journal of Materials Science*. 2026 Mar;61(11):7390-417.
101. Mhalshekar K, Krishan A, Gaydhane M, Sontakke S, Pawar V. Advanced electrospun nanofibers for photocatalytic degradation: sustainable solutions for wastewater remediation. *ACS omega*. 2026 Jan 29;11(5):6954-85.
102. Abodunrin OD, Atoyebi EO, Bricha M, Mabrouk KE. Innovative wound nanofiber mats: revolutionizing wound care through quality by design and artificial intelligence. *Biomedical Materials Science*. 2026 May 8;1(1):4.
103. Alfadhel M. Nanofiber-based drug delivery systems: a review on its applications, challenges, and envisioning future perspectives. *Current drug delivery*. 2026 Jan;23(1):44-55.
104. Basu P. On-Line Characterization Techniques in Nanofabrication. In *NANOFABRICATION IN THE ERA OF MACHINE LEARNING: Advances and Emerging Frontiers* 2026 (pp. 514-590).

105. Fan J, Bu Y, Huang L, Chen X, Yan H, Lin Q. Electrospun multilayer nanofibers with modified antibacterial alginate derivative for enhanced spinnability and drug sustained release. *Colloids and Surfaces B: Biointerfaces*. 2026 Feb 24;115:566.
106. Sossah J. *Interaction of layer-by-layer coated hemoglobin microparticles with blood cells—An in-vitro study* (Doctoral dissertation).
107. Saleh AM, Selim RN, El-Morsy MT, Mansour SA, Elhady R, Ismail SF, Gamal M, Kenawy ER. A review of nanofiber-based drug delivery systems: fabrication, characterization, advances, and future prospects. *Journal of Materials Science: Polymers*. 2026 Dec;1(1):10.
108. Amponsah LA, Oduro KO, Aboagye SA, Arthur M. Patents, Regulatory Issues, and Future Prospects of Biopolymers. In *Biopolymers: Green and Sustainable Approaches for Drug Delivery, Food Products and Packaging* 2026 Jan 2 (pp. 525-543). Singapore: Springer Nature Singapore.
109. Alfadhel M. Nanofiber-based drug delivery systems: a review on its applications, challenges, and envisioning future perspectives. *Current drug delivery*. 2026 Jan;23(1):44-55.
110. Abdulraheem MI, Barwant MM, Gourkhede PH, Elnor RO, Hashem M, Dawood MF, Hu J. Converging nanotechnology and biotechnology: innovations at the interface of engineering and biology. *Polymer Bulletin*. 2026 Apr;83(4):168.
111. Negut I, Visan AI. Regulatory compliance and ethical considerations in integration artificial intelligence. *Artificial Intelligence in Chemical Engineering*. 2026 Jan 1:627-50.
112. ALLAN J. Global Summit on Regulatory Science 2019 Nanotechnology and Nanoplastics.
113. Kirubakaran D, Wahid JB, Karmegam N, Jeevika R, Sellapillai L, Rajkumar M, SenthilKumar KJ. A comprehensive review on the green synthesis of nanoparticles: advancements in biomedical and environmental applications. *Biomedical Materials & Devices*. 2026 Mar;4(1):388-413.
114. Atofarati EO, Ajuka LO, Enweremadu CC. Life cycle assessment of nanomaterials and laboratory consumables: toward safer and sustainable nanotechnology. *Journal of Nanoparticle Research*. 2026 Apr;28(4):94.
115. Syed SM, Kulkarni S, Patil M, Satpute K. A comprehensive review of green synthesis methods and applications of nanoparticles derived from plant extracts and microorganisms. *Discover Green Chemistry*. 2026 Mar 2;1(1):6.
116. Kamboj A, Kaur G, Jain H, Singh L. A review on consumer acceptance and psychological barriers to nano-enhanced functional foods. *Nutrire*. 2026 Jun;51(1):15.
117. Kirubakaran D, Wahid JB, Karmegam N, Jeevika R, Sellapillai L, Rajkumar M, SenthilKumar KJ. A comprehensive review on the green synthesis of nanoparticles: advancements in biomedical and environmental applications. *Biomedical Materials & Devices*. 2026 Mar;4(1):388-413.
118. Nadanathangam V. Life cycle analysis of nanoparticles. In *Metal and Metal Oxide Nanoparticles in Textile Applications* 2026 Jan 1 (pp. 477-494). Woodhead Publishing.
119. Bawankar DL, Rajurkar SP, Shirbhate S, Mankar SV, Nikose KA. Nanotechnology-Based Drug Delivery Systems: Quality By Design Approaches And Regulatory Perspectives. *Int. J. Sci. R. Tech*. 2026;3(5).
120. Murthyappa H, Goudanavar P, Juturi RK, Konasuru Puttaraju HP, Boregowda H, Thippeswamy M. Regulatory intelligence-driven oversight of nanomedicines: gaps in US, EU, and India. *Nanomedicine Journal*. 2026 Jul 14:e28092.
121. Foisal RA, Susan AB, Imran AB. Ethical, Legal, and Societal Aspects of Nanomaterials. In *Nanomaterials Revolution* 2026 (pp. 499-541). Jenny Stanford Publishing.

122. Thakur A, Mir BA, Kapoor P, Niyaz S, Parrey Z, Wani AK, Wani AW, Shah MA, Parihar P, Rakhra G, Ahmad Z. Ethical considerations and regulations in nano-agrobiotechnology. In *Nano-Delivering Plant Biostimulants and Anti-Pathogenic Agents* 2026 Jan 1 (pp. 561-577). Elsevier.
123. Kaur S, Sahu V, Yadav S, Shukla VK. Ethical and regulatory considerations in nanodermatology. In *Nanodermatology* 2026 Jan 1 (pp. 499-522). Elsevier.
124. Ke J, Han B, Wang W, Tao Z, Li Z, Lian H, Meng Z. Three-Dimensional Electrospun Nanofiber Scaffolds: Fabrication Methods and Biomedical Applications. *Macromolecular Bioscience*. 2026 Jan;26(1):e00573.
125. Shokoya MM, Szabó E, Nagy ZK, Sebe I, Zelkó R. Therapeutic nanofibrous scaffolds in precision drug delivery: formulation design, challenges and regulatory frameworks. *Expert Opinion on Drug Delivery*. 2026 May 4.
126. Saleh AM, Selim RN, El-Morsy MT, Mansour SA, Elhady R, Ismail SF, Gamal M, Kenawy ER. A review of nanofiber-based drug delivery systems: fabrication, characterization, advances, and future prospects. *Journal of Materials Science: Polymers*. 2026 Dec;1(1):10.
127. Sanyal GC, Sanyal V. Navigating regulatory landscapes in green antibacterial materials. In *Green Antibacterial Materials* 2026 Jan 1 (pp. 471-505). Woodhead Publishing.
128. Nantoi V, Nantoi D. Streamlining organizational manageability through scalable decision making. *Вадим Нантой, Vadim Nantoi*; 2026 Jan 4.
129. Gusmão RD, Maciel EM, Frattini WC, Medeiros ES, Fonseca FA, Bianco HT. Advances and challenges in nanofiber production: techniques and applications in nanotechnology. *Polímeros*. 2025 Nov 17;35(4):e20250039.
130. Chinnappan BA, Krishnaswamy M, Xu H, Hoque ME. Electrospinning of biomedical nanofibers/nanomembranes: effects of process parameters. *Polymers*. 2022 Sep 6;14(18):3719.
131. Kabir M, Rana MR, Debnath A. The role of quality assurance in accelerating pharmaceutical research and development: strategies for ensuring regulatory compliance and product integrity. *Journal of Angiotherapy*. 2024 Dec 8;8(12):1-1.
132. Saleh AM, Selim RN, El-Morsy MT, Mansour SA, Elhady R, Ismail SF, Gamal M, Kenawy ER. A review of nanofiber-based drug delivery systems: fabrication, characterization, advances, and future prospects. *Journal of Materials Science: Polymers*. 2026 Dec;1(1):10.
133. Shadab A, Haider MF, Abohassan M. Liposome-based drug delivery systems: mechanisms, preparation strategies, clinical status, and therapeutic applications. *AAPS PharmSciTech*. 2026 Apr 23;27(4):190.
134. Sah H, Lomash V, Sharma D, Shingatgeri VM. One world, one forum: Harmonizing the medical device regulatory framework. *Future Health*. 2026 Jan 24.
135. Soares GO, Santi VH, Soares AC, Sousa DF, de Souza SO, Oliveira Jr ON. Machine learning-enhanced nanofiber systems: a new frontier in controlled drug release. *Nanotechnology*. 2026 Feb 6;37(5):052001.
136. Bode G, Starck-Lantova P, Kramer PJ. Future of regulatory safety assessment: how to improve drug development? Focus on preclinical strategies. In *Drug Discovery and Evaluation: Safety and Pharmacokinetic Assays* 2023 Jul 28 (pp. 1-26). Cham: Springer International Publishing.
137. Tu Y, Li B, Zheng S, Qu G, Li M, Li S, Shao C. Growth factor applications and clinical translation: advances and challenges. *Annals of Medicine*. 2026 Dec 31;58(1):2642893.

138. Niazi SK. Oral delivery of peptides and proteins: pharmacokinetic boundaries, negative selection, and route triage. *Frontiers in Drug Delivery*. 2026 Mar 20;6:1776167.
139. Ong AY, Kale AU, Antoun J, Hogg HD, Hammond B, Keane PA, Pearson R, Harvey H, Denniston AK. Current challenges and the way forwards for regulatory databases of artificial intelligence as a medical device. *NPJ digital medicine*. 2026 Feb 11;9(1):235.
140. Murthyappa H, Goudanavar P, Juturi RK, Konasuru Puttaraju HP, Boregowda H, Thippeswamy M. Regulatory intelligence-driven oversight of nanomedicines: gaps in US, EU, and India. *Nanomedicine Journal*. 2026 Jul 14:e28092.
141. Halligan-Avery E, Eager B, Palanski M. Using Academic Side Hustles to Support Leadership Scholars and Research. *Journal of Leadership & Organizational Studies*. 2026:15480518261419918.
142. Song J, Kim M, Lee H. Recent advances on nanofiber fabrications: Unconventional state-of-the-art spinning techniques. *Polymers*. 2020 Jun 20;12(6):1386.
143. Shaban M, Mosa TM, Abdel-Hamid H, Abdalfarg N, Hashim G. Advancements in electrospinning: a comprehensive review of historical development, key parameters, applications, and challenges. *Discover Chemistry*. 2026 Feb 20;3(1):82.
144. Chinnappan BA, Krishnaswamy M, Xu H, Hoque ME. Electrospinning of biomedical nanofibers/nanomembranes: effects of process parameters. *Polymers*. 2022 Sep 6;14(18):3719.
145. Tian Y, Zhou J, Zhu H, Huo K, Xie X, Zhang W, Zheng H. Electrohydrodynamic printing technology: mechanisms, control, and applications. *Microsystems & Nanoengineering*. 2026 Mar 10;12(1):83.
146. Subeshan B, Asmatulu E. Computational precision control of electrospun polymer nanofiber morphology using machine learning and genetic algorithm optimization. *Journal of Materials Science*. 2026 Jun;61(23):16424-68.
147. Zaman S, Mahmud MS, Mollick AA, Lhaden T, Dantzler J, Arroyo S, Goona NK, Mesbah M, Ahsan MA, Lin Y. Artificial intelligence in additive Manufacturing: Advances in smart materials, lattice optimization, and process intelligence. *The International Journal of Advanced Manufacturing Technology*. 2026 Apr 18:1-55.
148. Dopirak M, Dopirak M, Gendrich O, Wang Y, Zhang W. Advances in electrospinning approaches for the fabrication of therapeutically relevant nanofibers. *Nanomedicine*. 2026 May 19;21(10):1503-27.
149. Zuo M, Song J, Hu H, Zheng L, Zhang L, Lawrie CH. Chemically doped conductive polymers for wearable health monitoring. *Advanced Materials Technologies*. 2026 Jun;11(12):e02209.
150. Kook M, Peterson C, Bhat AS, Nefedova A, Vanetsev A, Ivask A, Kisand V. Artificial aging induced changes in ZnO-and TiO₂-based polyacrylic surface coatings. *npj Materials Degradation*. 2026 Jan 17.
151. Liu C, Wu W, Li X, Jiao T. Electrospun MOFs-based nanofibrous membranes for water and air purification: a review. *Science China Materials*. 2026 Jan;69(1):44-72.
152. Belmahi S, Benfrid A, Djedid IK, Guergour R, Djakhdane N. Influence of acidic and alkaline environments on the mechanical properties of cement mortars. *Periodica Polytechnica Civil Engineering*. 2026 Mar 23;70(1):315-26.
153. Mubarak MF, Metwally BS, Bendary HI, Hosny R, Nassar MY, Alfurayj I, Taha A, Bakir EM. Green valorization of cotton–acrylic fabric blends into magnetic nanofiber adsorbents for PFAS and

- organic dye remediation in complex wastewater streams. *Scientific Reports*. 2026 Jul 4;16(1):20561.
154. Vijayakumar V, Rathinam T. Nanofibers in biomedical applications: recent developments and challenges. *Biomedical Materials & Devices*. 2026 Sep;4(3):2983-3000.
155. Zhou D, Zhang C, Yuan F, Li L, Li L, Ye J, Luan K, Zhang Z, Jing L, Xue R, Zhang T. Imparting polyvinyl alcohol enhanced biodegradability, tunable water-solubility, melt processability, and antibacterial activity simultaneously. *Polymer Degradation and Stability*. 2026 Feb 9;111998.
156. Jiang G, Ramachandraiah K, Feng X, Wang X, Zhang W. Valorization of Panax ginseng residues: Functional fiber development through cross-linking combined with ultrasonication. *Ultrasonics Sonochemistry*. 2026 Apr 2;107845.
157. Kowalczyk T. Functional micro-and nanofibers obtained by nonwoven post-modification. *Polymers*. 2020 May 10;12(5):1087.
158. Chen X, Cao H, He Y, Zhou Q, Li Z, Wang W, He Y, Tao G, Hou C. Advanced functional nanofibers: strategies to improve performance and expand functions. *Frontiers of optoelectronics*. 2022 Dec;15(1):50.
159. Vinodhini SP, Xavier JR. Recent progress in graphene-based nanocomposites for enhanced energy storage and corrosion protection. *Journal of Materials Science*. 2025 Sep;60(34):14837-79.
160. Liu Z, Liu X, Ramakrishna S. Surface engineering of biomaterials in orthopedic and dental implants: Strategies to improve osteointegration, bacteriostatic and bactericidal activities. *Biotechnology journal*. 2021 Jul;16(7):2000116.
161. Arun AP, Sreenivasan N, Patil JH, Kusanur R, Ramachandraiah HL, Ramakrishna M. Thin Films for Next Generation Technologies: A Comprehensive Review of Fundamentals, Growth, Deposition Strategies, Applications, and Emerging Frontiers. *Processes*. 2025 Nov 28;13(12):3846.
162. Ullah A, Rehman N, Ullah R, Ullah H, Khan A, Sadiq M, Ullah B, Khan N, Ghani F. Recent advances in the biodegradable polymers for environmental and biomedical applications. *Polymer Bulletin*. 2026 Jul;83(7):353.
163. Rathee G, Singh NK, Kohli S, Deshmukh K, Rathee J, Puertas A, Solanki P, Kaushik A. Tailored injectable nanocomposite hydrogels for high-performance biomedical applications. *Biomaterials Science*. 2026 Jul 3.
164. Olivos-Ramírez MA, González-Morones P, Flores-Silva PC, Sifuentes-Nieves I, García-Hernández Z, Mendoza-Tolentino Y, Hernández-Gámez JF, Hernández-Hernández E. Sustainable Biodegradable Biocomposites Reinforced With Natural Fibers: A Review on Processing, Properties, and Degradation. *Journal of Applied Polymer Science*. 2026 Apr 20;143(16):e70536.
165. Alfadhel M. Nanofiber-based drug delivery systems: a review on its applications, challenges, and envisioning future perspectives. *Current drug delivery*. 2026 Jan;23(1):44-55.
166. Mitchell GR, editor. *Electrospinning: Principle, Practice and Possibilities*. Royal Society of Chemistry; 2026 Mar 11.
167. Mustafa MA. Recent progress in nanomaterials for air quality improvement. *Discover Environment*. 2026 Apr 30;4(1):196.
168. Ahmed I, Iqbal Y, Hussain I, Dilbraiz MA, Zulfiqar H, Chatha SA, Ullah S. Recent Developments on Natural Polymers as Viable Alternatives to Conventional Materials for Sustainable Packaging. *Materials Circular Economy*. 2026 Dec;8(1):18.

169. Lan D, Wang J, Wang Y, Guo X, Du D, Zhang C, Wu G. Environmentally adaptable hydrogels with highly entangled interpenetrating networks for efficient electromagnetic wave absorption. *Carbon*. 2026 Mar 4;121416.
170. Nam J, Jin D, Kim S. Multiscale coupled hygrothermal performance of PCM-integrated timber building envelope. *Energy and Buildings*. 2026 May 9;117610.
171. Kanaan AF, de Oliveira WA, Boaron CK, Sauer H, Santana MA, Piedade AP, Vidotti M. Electrospinning technology applied for building up electrochemical platforms—a review. *Journal of Solid State Electrochemistry*. 2026 Jun 15;1-38.
172. Wang Z, Fang E, Chen L, Fan Z, Song S. Recent developments in recycling technologies for polymeric plastics. *Polymer Chemistry*. 2026 Feb 10;17(6):601-32.
173. Liu Y, Wang Q, Shangguan Z, Deng C, Yan H, Shao Z, Zheng G. Fully bio-based triboelectric bimodal nanofiber membrane for high-performance air filtration and respiratory monitoring. *Separation and Purification Technology*. 2026 Mar 6;137511.
174. Lee SG, Cho DW, Oh TH. Reinforcement learning control of pilot-scale solvent recovery for battery manufacturing: Surrogate-assisted optimization with techno-economic analysis and life-cycle assessment. *Journal of Cleaner Production*. 2026 Jul 19;572:148885.
175. Kiskira K, Plakantonaki S, Gerolimos N, Kalkanis K, Sfyroera E, Coelho F, Priniotakis G. Life Cycle Optimization of Circular Industrial Processes: Advances in By-Product Recovery for Renewable Energy Applications. *Clean Technologies*. 2026 Jan 5;8(1):5.
176. Yusro M, Hacker V. Controlling electrospun nanofiber geometry as an advanced energy catalyst: patterning methods and scale-up. *Energy Advances*. 2026 Jul 13.
177. Metya S, Prakash P, Rathore AS. Continuous Processing for Manufacturing of Antibody–Drug Conjugates (ADCs). *Bioconjugate Chemistry*. 2026 Feb 1.
178. Kim HJ, Chen W, Lee JM, Jung HS. AI-driven green processing and life cycle assessment for sustainable perovskite solar cells. *Nature Communications*. 2026 May 20;17(1):4512.
179. Abodunrin OD, Atoyebi EO, Bricha M, Mabrouk KE. Innovative wound nanofiber mats: revolutionizing wound care through quality by design and artificial intelligence. *Biomedical Materials Science*. 2026 May 8;1(1):4.
180. Tuli NT, Rashid AB, Hoque ME. Artificial intelligence in additive manufacturing for biomedical engineering. In *3D Printing for Biomedical Engineering* 2026 Jan 1 (pp. 561-594). Elsevier.
181. Muthusamy S, Mohamad EN, Muhamad MR, Razlan ZB. From Single-Nozzle to Multi-Nozzle Electrospinning: A Comparative Manufacturability Perspective on 3D Electrospun Structures. *International Journal of Precision Engineering and Manufacturing*. 2026 May;27(5):2199-245.
182. Jha A, Kalaiselvi K, Nandhini RS, Raj AS, Karthik P. Advancements in computational fluid dynamics-aided artificial intelligence and machine learning in food processing. In *Artificial Intelligence in Food Science* 2026 Jan 1 (pp. 359-376). Academic Press.
183. Singh S, Kumari R, Kamble Z. Bridging the Gap Between Laboratory Research and Industrial Implementation of Green Composite Technologies: A Review. *Polymer Composites*. 2026 Jan 5.
184. Rathod S, Rai A, Yadav B, Vishwakarma G. Pilot Plant: Bridging the Gap from Lab to Industrial Scale. *Int. J. Sci. R. Tech*. 2026;3(4).
185. Vijayakumar V, Rathinam T. Nanofibers in biomedical applications: recent developments and challenges. *Biomedical Materials & Devices*. 2026 Sep;4(3):2983-3000.

186. Usmani A, Singh P, Chauhan SB, Singh I. Toxicology and Safety Issues of Nanomaterials in Drug Delivery. In *Nanotechnology and Phytopharmaceuticals: Applications in Drug Discovery and Delivery* 2026 Mar 4 (pp. 1-31). Cham: Springer Nature Switzerland.
187. Sharma A, Verma S. Additive manufacturing of 3D-printed carbon nanofiber-based materials for versatile applications: a comprehensive review. *Journal of Materials Science: Materials in Electronics*. 2026 May;37(15):1161.
188. Thakur A, Kumar A. Global Perspectives on Regulatory Landscape for Low-Dimensional Biosensors: Standardized Testing, Privacy, and Safety. In *Evolution of Low-Dimensional Biosensors in Food Safety, Agriculture, and Healthcare* (pp. 389-421). CRC Press.
189. Jitpibull J, Ratanavaraporn J. Silk Fibroin in Medicine: A Review on ISO10993 Biocompatibility, Preclinical Evidence, and Clinical Perspectives. *Advanced Therapeutics*. 2026 Feb;9(2):e00483.
190. Priyadarshi R, Khan A, Riahi Z, Rhim JW. Toxicity and Safety of Nanomaterials in Food Packaging Applications: A Dimension-Based Review. *Comprehensive Reviews in Food Science and Food Safety*. 2026 Jan;25(1):e70374.
191. Priyadarshi R, Khan A, Riahi Z, Rhim JW. Toxicity and Safety of Nanomaterials in Food Packaging Applications: A Dimension-Based Review. *Comprehensive Reviews in Food Science and Food Safety*. 2026 Jan;25(1):e70374.
192. He J, Wu Y, Cheng M, Gao H, Lu H, Lin Z, Jiang Y, Zou Z, Pan Y, Gong W, Wang K. Piezoelectric ceramic nanofiber aerogels direct neutrophil fate for diabetic tissue regeneration. *Advanced Materials*. 2026 Apr;38(19):e20475.
193. Kim KO, Mayakrishnan G, Ullah A, Kim IS. Inhalation toxicity and skin irritation assessment of PVDF nanofiber-based breath mask filters. *Fashion and Textiles*. 2026 Feb 11;13(1):7.
194. Rawat A, Khanna A, Butola BS, Sharma N. Safety, Toxicity, and Regulation of Biomaterials: A Systematic Review of Global Frameworks and Emerging Challenges. *Journal of Biomedical Materials Research Part B: Applied Biomaterials*. 2026 May;114(5):e70064.
195. Vijayakumar V, Rathinam T. Nanofibers in biomedical applications: recent developments and challenges. *Biomedical Materials & Devices*. 2026 Sep;4(3):2983-3000.