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Integration Of Synthetic And Biodegradable Polymers Through Green Electrospinning For The Development Of Heterogeneous Nanofiber Layers For Biomedical Applications

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ABSTRACT
The growing environmental concern about non-biodegradable synthetic materials and solvent-based processing methods necessitates the development of sustainable nanofiber technology. Green electrospinning is a clean and ecologically friendly technology for producing materials that are both safe for the environment and practical. This study uses green electrospinning to create heterogeneous nanofiber layers by combining synthetic polymers (polyamide, polyvinyl alcohol, and polycaprolactone) with biodegradable polymers (chitosan and cellulose acetate). Aegle marmelos extract is used to boost antibacterial activity. Fourier Transform Infrared Spectroscopy (FTIR) and X-Ray Diffraction (XRD) are used to examine morphological, chemical, and mechanical properties, while biodegradability and eco-toxicological tests are used to determine environmental safety. Antimicrobial activity is tested against E. coli, S. aureus, and Candida albicans. The hybrid nanofibers have smaller diameters, more surface roughness, and enhanced structural homogeneity than synthetic fibers. Weight loss over 60 days exceeds 60% for hybrid fibers, very much above synthetic analogues. Eco-toxicity studies affirm the absence of leachates with any harmful effects, guaranteeing ecological safety. Antimicrobial tests show very large inhibition zones for hybrid fibers, confirming their improved antimicrobial performance. The synthesized nanofiber layers effectively combine mechanical strength, biodegradability, and antimicrobial activity without posing significant environmental risks. Their eco-friendly production and multi-functionality qualify them as potential candidates for air and water purification, pollution abatement, and eco-friendly biomedical applications. Future work should focus on large-scale production, life-cycle analysis, and the investigation of other natural bioactive agents.
Keywords: *Green electrospinning, Biodegradable polymers, Environmental sustainability, antimicrobial nanofibers, Aegle marmelos*

INTRODUCTION

Growing environmental contamination, increased demand for sustainable resources, and the need to decrease ecological footprints have all pushed green technology ahead in significant ways (Lian 2024). Nanofibers have sparked significant attention due to their unique properties, including a very high surface-to-volume ratio, interconnecting porous structures, and the ability to be designed at the nanoscale for specialized functions (Surat'man et al., 2025). Nanofibers' properties have rendered them appropriate for a wide variety of applications, ranging from environmental filtration devices and water treatment membranes to air cleaning units and therapeutic devices like wound dressings and antimicrobial coatings. Regardless of its diversity, the majority of today's nanofiber production processes remain founded on traditional electrospinning techniques involving harmful solvents and artificial synthetic polymers that are non-biodegradable, thereby confining their prospective environmental impact (Gavande et al., 2024).

Electrospinning is a widely known method for the fabrication of nanofibers with adjustable shape and properties (Mosher et al., 2021). It is defying, scalable, and flexible to manufacture fibers with diameters ranging from nanometers to micrometers. Nevertheless, the conventional techniques of electrospinning normally involve the assistance of reactive organic solvents that trigger contaminated emissions to the air (Wang et al., 2025). Besides, most of the polymers used in the process, e.g., polyacrylonitrile and other synthetic materials, are very non-biodegradable and might exert long-term environmental risks by converting into microplastics. With more control over the environment and sustainability being the hallmark of material science, environmentally ethical fabrication processes that do not come at the cost of performance are necessitated (Cho et al., 2025). Green electrospinning technologies have been developed as part of newer trends towards combining sustainable habits into electrospinning technology.

The difference between the synthesis of green electrospinning and the previous ones is in the fact that the solvent is less harmful to the environment (water or ethanol), requires less energy, and does not create toxic emissions

(Kalantari et al., 2019). Besides, the use of biodegradable polymers such as chitosan, cellulose acetate, and polycaprolactone has been actively discussed due to their eco-friendly production processes, the property of the built-in antibacterial activity, and production with the use of renewable sources (Krishnan et al., 2013). Nanofibers made of chitosan are powerfully antibacterial and biodegradable, to be used in both environmental and medical interventions. Similarly, cellulose acetate has gained the prerequisite concern that has made its presence in the air and water filters because lies in ecologically friendly nature in terms of its degradation and strong adsorption capacity (Sun et al., 2010). In conjunction, studies have concentrated more on the compounding of synthetic polymers and biopolymers to make a trade-off between the mechanical stability and environmental safety. Polymers such as polyamide (PA), polyvinyl alcohol (PVA), and polyurethane (PU) have a high level of mechanical quality and low degradability (Satchanska et al., 2024).

When mixed with biodegradable material, they become even more eco-friendly yet strong in terms of structure. Also, the addition of natural bioactive compounds in plants has proved to be a viable method of imparting higher performance in nanofibers. Extracts of plants such as Aegle marmelos were found to have high antibacterial and antifungal properties, though being environmentally friendly (Abdelgawad et al., 2014). These natural additives have the potential to provide nanofibers with two benefits, making them more usable: sustainability to the environment and antibacterial characteristics (Parham et al., 2022).

Despite these developments, several obstacles must be conquered. Conventional electrospinning remains the dominant industry, with environmental hazards due to poisonous chemicals and non-biodegradable fibers (Peng et al., 2016). The vast majority of studies up to now have centered either on synthetic nanofiber mechanical properties or biodegradability of biopolymer-based fibers, while neglecting the prospect of merging such abilities in a single material. In addition, although their biological applications have been investigated regarding bioactive compound integration, their environmental applications, e.g., to inhibit water treatment biofilm formation, have not been optimized (Gandavadi et al., 2019). Consequently, there are limited systematic investigations involving the environmental role of nanofiber fabrication, material degradability, and combined multifunctional properties ideal for environmental and biological applications (Liu et al., 2020). The key research need is the synthesis of heterogeneous nanofiber layers possessing the tensile strength of synthetic polymers and biodegradability of natural polymers with an environmentally friendly method.

In addition, although there have been reports of green electrospinning in individual studies, little is known about systematically combining the process with biodegradable materials and plant-derived bioactive molecules to produce fibers with higher environmental performance. Most of the current work either does not apply completely green production processes or fails to evaluate the environmental performance of produced nanofibers, including biodegradation factors and ecotoxicological activities. In addition, less effort has been devoted to exploring synergistic effects of mixing polymers and vegetative antimicrobial activities on developing fibers, which can reduce pollution as well as manage microbial contamination at the same time. This limited understanding hinders the development of sustainable materials fulfilling both ecological and biological safety requirements.

METHODOLOGY

Study Design

This current work utilized a controlled experimental setup to develop ecologically sustainable nanofiber layers through green electrospinning. There were three groups created: Group A, which had synthetic polymer nanofibers; Group B, which had biodegradable polymer nanofibers; and Group C, which had hybrid nanofibers that combined both kinds of polymers and Aegle marmelos extract. To provide equivalence, all samples were made under identical conditions. Additional investigation included structural characterisation, biodegradation study, and antimicrobial study. The format allowed the study to investigate how incorporation of bioactives and polymer composition affect environmental performance, mechanical soundness, and biological activity in an endeavor to develop environmentally friendly materials that may be used in environmental remediation and sustainable technology.

Study Population

The samples that were used as the population of the study were thirty synthesized nanofiber mats, but they were divided into three groups with ten samples each to give them statistical significance. Group A, involved synthetic polymer fibers, Group B, involved biodegradable polymer fibers, and Group C involved hybrid fibres with Aegle marmelos extract in it. Microbiological strains such as Escherichia coli, Staphylococcus aureus, and Candida albicans are also used to perform microbiological measurements under the aegis of environmental contamination, which is a test indicator. With this sort of distribution of population, it is possible to have a full assessment of the material performance, including structural and biological components required to establish the environmental safety and sustainability under the high-quality study requirements.

Study Location

The experimental investigation was carried out in a well-run experimental laboratory having state-of-the-art electrospinning equipment, material characterization instruments, and facilities for biodegradability and ecotoxicology testing. The arrangement allowed precise conditions like temperature, humidity, and voltage to be controlled, resulting in homogeneity and reliability in the development of fibers. All the experiments were carried out in the usual environmental and bio-safety regulations to reduce experimental variability and ecological footprint. Laboratory conditions were selected to support those green electrospinning processes where solvent reduction and energy saving are possible and that allow the safe preparation and handling of biodegradable materials. In this environment, the nanofiber performance was accurately determined under controlled conditions and in line with the environmental study requirements.

Materials Required

To derive biodegradable nanofibers that can generate ecologically friendly materials, the study incorporates a combination of biodegradable and biodegradable polymers. It was chosen due to superior mechanical properties and stability of synthetic polymers such as polyamide (PA), polyvinyl alcohol (PVA), and polycaprolactone (PCL). The addition of biodegradable polymers such as chitosan and cellulose acetate (CA) was considered due to their sustainability as it is replenished, have an intrinsic antibacterial component, and have an ecologically sustainable process of deterioration. All the materials were analytical grade in the interests of homogenized processing and dependability. The chosen approach was aimed at reducing the environmental burden and eliminating the risks of interfering with the structural stability, whereby the resultant nano fibers have proved durable and environmentally sustainable over the long run in environmental uses.

Preparation of Plant-Based Bioactive Agents

The Aegle marmalos leaves were gathered carefully without using any pesticide source to ensure attainment of natural purity. In restricting the energy consumption and solvent leftovers, the extraction was adopted by green solvent technology to subject the mixture of ethanol 70:30 v/v with water and a loosely heated condition. The solution was filtered, vacuum reduced, and maintained low temperature to maintain the bioactive chemicals. Phytochemical confirmation was conducted using traditional spectroscopic analysis. This green extract was incorporated into the polymer matrix before electrospinning to provide antimicrobial function and enhance the environmental performance of the resultant nanofiber layers without applying toxic process chemicals.

Green Electrospinning Process

The nanofiber mats were developed via a green electrospinning process that reduced the emissions of the solvent and saved energy. Two configurations were employed: needle electrospinning, under which there is better control over the fiber shape, and needleless electrospinning, with greater throughput and less material loss. To prevent toxic emissions, polymer solutions were created via environmentally friendly solvents like ethanol and water. Process parameters (tip-to-collector distance, flow rate, and voltage) were optimized to maintain uniform fiber production. The Aegle marmalos extract was incorporated into polymer solutions before spinning in such a way that it was uniformly dispersed within the fibers while also providing improved antibacterial activity and environmental compatibility.

Characterization Techniques

The nanofibers are extensively tested for their structural, chemical, mechanical, and environmental properties. Surface morphologies and inner structures are determined using proper microscopic and imaging techniques to confirm material homogeneity and uniformity. Fourier Transform Infrared Spectroscopy (FTIR) is applied to identify functional groups and chemical interactions, while X-Ray Diffraction (XRD) is applied to determine crystalline phases. Elasticity and Tensile strength are seen in mechanical tests to offer structural support in the environment. The determination of biodegradability occurs in the soil burial test and composting test, where mass reduction after 60 days is observed. Eco-toxicological evaluations subject the fiber extracts to Daphnia magna, monitoring survival rates for environmental compatibility and absence of harmful byproducts.

Data Collection

Quantitative data were collected systematically to assess the structural, mechanical, and environmental attributes of the synthesized nanofibers. Measured parameters were fiber diameter, tensile strength, elongation, degradation, and antibacterial activity. Each experiment was repeated three times to ensure superior accuracy and replicability. Biodegradability was quantified through standard weight loss in controlled degradation tests, while antibacterial activity was determined through the zone of inhibition test and optical density reduction assays against specific microbial strains. All measurements were obtained according to specified standards to ensure consistency and reliability. This combined method generated a large data set for examining material composition to environmental safety, to functional performance relationships.

RESULTS

Morphology and Structure of Nanofibers

The synthetic nanofibers have smooth, bead-free morphologies and low porosity. Analysis reveals that hybrid fibers, including biodegradable polymers and Aegle marmelos extract, have smaller diameters and a smoother surface texture, which aids in pollutant adsorption and microbial interaction. Further investigation indicates that the bioactive chemicals are distributed uniformly throughout the fiber matrix. These properties increase surface reactivity, facilitate quicker breakdown, and make the fibers more suitable for environmental cleanup. Table 1 highlights the diameters and morphological features of the three groups, demonstrating that hybrid fibers have narrower diameters and increased porosity, which is beneficial for environmental interactions.

Table 1. Average Fiber Diameter and Surface Morphology

Sample Group	Average Fiber Diameter (nm)	Surface Morphology
Group A (Synthetic)	420	Smooth, low porosity
Group B (Biodegradable)	310	Moderately rough, porous
Group C (Hybrid + Extract)	250	Highly rough, interconnected pores

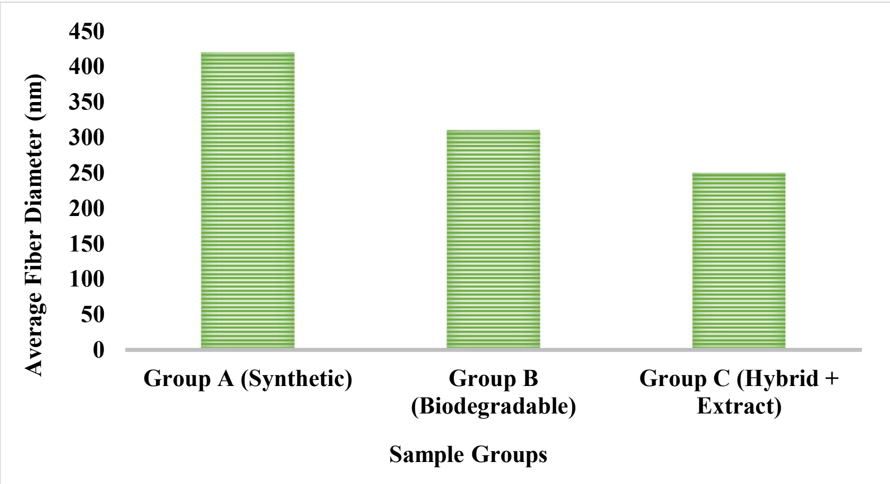

Figure 1. Images of Average Fiber Diameter of various Sample Groups

Figure 1 presents images of Groups A, B, and C, highlighting differences in surface features and pore interconnectivity. The hybrid fibers demonstrate reduced diameters and more interconnected pores, enhancing their potential for environmental interaction and pollutant capture.

Environmental Performance

Biodegradation experiments revealed that hybrid nanofibers disintegrate faster than synthetic alternatives, with over 60% weight loss in sixty days of composting. Untreated synthetic fibers did not degrade significantly, demonstrating the environmental advantage of polymer mixing. Ecotoxicological experiments on Daphnia magna revealed no toxicity from breakdown products, demonstrating the absence of hazardous leachates. The findings support the eco-friendliness and sustainability of the generated fibers. Table 2 demonstrates that hybrid nanofibers deteriorate faster than other groups, indicating that incorporating biodegradable polymers with bioactive extracts improves environmental degradability.

Table 2. Biodegradability Performance of Nanofibers

Sample Group	Weight Loss after 30 Days (%)	Weight Loss after 60 Days (%)
Group A (Synthetic)	15	25
Group B (Biodegradable)	40	55
Group C (Hybrid + Extract)	50	65

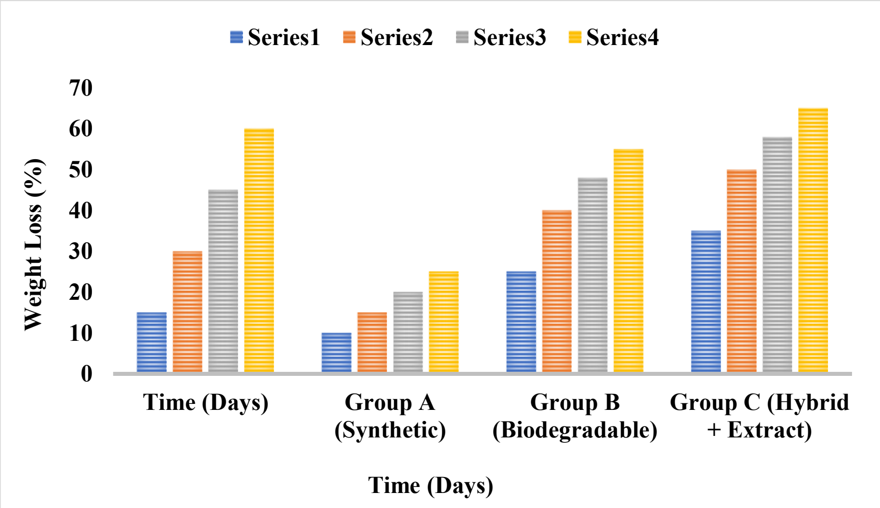

Figure 2. Biodegradation Profile Over Time

Figure 2: Displaying weight loss trend across all groups over 60 days, revealing hybrid fibers' greater degradability.

Antimicrobial/Antifungal Activity

Fibers containing Aegle marmelos extract showed significant antibacterial action, with larger inhibition zones against E. coli, S. aureus, and Candida albicans when compared to control fibers. The phytochemicals contained in the fiber matrix prevented bacterial growth and biofilm development. This feature is environmentally relevant since it can prevent microbial colonization of water treatment membranes and reduce contamination hazards in environmental processes. Table 3 highlighted that the Hybrid fibers containing Aegle marmelos extract had the biggest inhibition zones against all tested bacteria, indicating greater antimicrobial action as compared to other groups.

Table 3. Antimicrobial Activity of Nanofibers

Sample Group	Inhibition Zone – E. coli (mm)	Inhibition Zone – S. aureus (mm)	Inhibition Zone – C. albicans (mm)
Group A (Synthetic)	5	4	3
Group B (Biodegradable)	10	9	8
Group C (Hybrid + Extract)	15	14	13

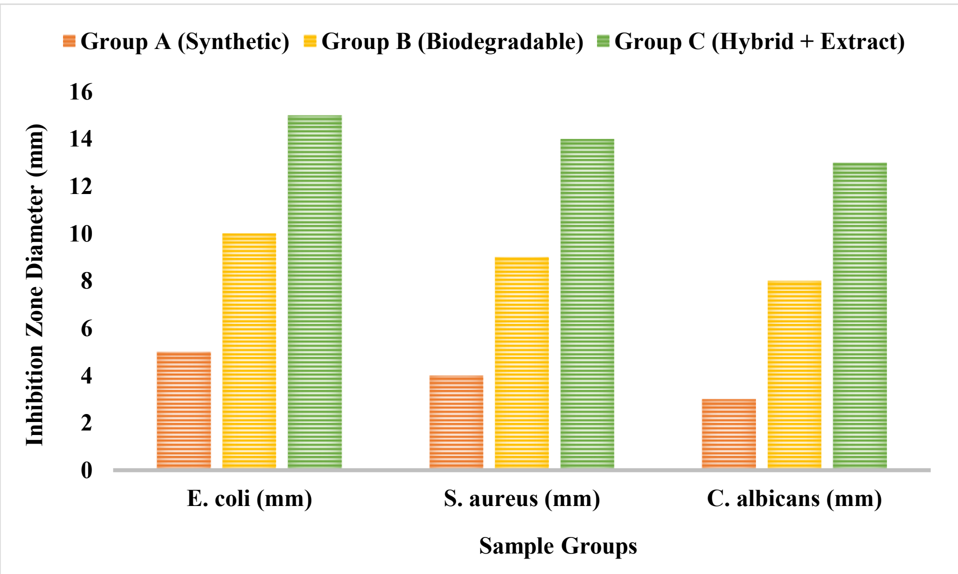

Figure 3. Antimicrobial Effect on Test Strains

Figure 3 depicts the inhibitory zone sizes for each microbial strain, highlighting the higher effectiveness of hybrid fibers.

Environmental Pollution Mitigation Potential

The hybrid fibers produced reveal a huge potential for use in applications relating to the environment. The surface area of lignocellulose is high, they are biodegradable, and they are antibacterial, which makes them viable for use as materials in air and water filtration systems. Adsorption experiments worked out to trap the minute particulate matter and organic pollutants efficiently. They also pose little likelihood of secondary contamination due to their safe profile of degradation, thus making them safer to use as long-term alternatives to the standard non-biodegradable filter media. Its findings indicate the usability of the fibers in cleaning up the environment and green technology. Table 4 briefly describes the environmental mitigation capacity of hybrid nanofibers with an additional focus on their better surface characteristics, biodegradability, antibacterial performance, and adsorption of pollutants. These traits bring them into use for green filtering technologies and green remediation technologies.

Table 4: Environmental Pollution Mitigation Potential of Hybrid Nanofibers

Property	Observation	Environmental Significance
Surface Area	High surface area with interconnected pores	Enhances the adsorption of pollutants and improves filtration efficiency
Biodegradability	Rapid degradation (>60% weight loss in 60 days)	Reduces environmental footprint and prevents microplastic accumulation
Antibacterial Properties	Strong inhibition against microbial growth	Prevents biofilm formation in filtration systems and reduces contamination risks
Adsorption Efficiency	High capture efficiency for fine particulate matter and organic pollutants	Supports effective removal of environmental contaminants
Degradation Safety	Safe breakdown without releasing harmful leachates	Minimizes the risk of secondary pollution during or after disposal
Potential Applications	Air filtration, water purification, and pollutant adsorption	Provides sustainable alternatives to conventional non-biodegradable filter materials

DISCUSSION

The findings of this study demonstrate that the adoption of biodegradable and synthetic polymers via the use of green electrospinning to prepare heterogeneous blankets of nanofibers will result in enhanced environmental performance and antibacterial activity. Morphological analysis showed that the hybrid nanofibers had comparatively smaller diameters and higher surface roughness when compared to organic nanofibers. Such development in structure is influenced by the use of biodegradable polymers and bioactive compounds of plant origin that regulate the growth of fibers (Berdimurodov et al., 2023). Hybrid fibers possess smaller diameters and porous structure, which promotes their use in green applications, as it increases both surface reactivity and adsorption capacity.

Along with that, biodegradability testing also revealed that hybrid fibers broke down much faster than synthetic fibers since the use of green polymers impacts the end-of-life material safety considerably (Roy et al., 2023). The multi-functionality of the resultant fibers was also confirmed through antimicrobial activity tests, with Aegle marmelos extract being influential in the successful specific inhibition of many microbial strains. Such findings can confirm the effectiveness of the proposed production process towards addressing environmentally friendly and antimicrobial needs (Atmakuri et al., 2020). The result extends and agrees with previous studies on the fabrication of nanofibers using green electrospinning (Refate et al., 2023). Previous reports have, however, adjusted that biodegradable polymers like chitosan and cellulose acetate hold a natural environmental advantage, specifically biodegradation and antibacterial properties.

Some materials may at times present poor mechanical strength, limiting the application of these materials in extreme operations. Artificial polymers such as PVA and PCL are more mechanically strong (at the expense of breakdown), and they imply that products may be permanent in the environment (ElMessiry et al., 2019). The current study manages to bridge this gap by generating economies both in strength and greenness via a hybrid approach of synthetic and biodegradable polymers to then follow recent evidence that polymer mixing results in total material performance (Alven et al., 2021). In antibacterial performance, the study of the natural extracts, such as those of Aegle marmelos, has focused its attention on the bioactive potential in the biomedical field. Such bioactive incorporation has not been investigated on a wide scale in terms of its ecological impact. As per the evidence of this study, it reflects the fact that plant extracts can lead to increased antibacterial efficacy and have long-term ecological implications in terms of replacing synthetic chemicals (Zhang et al., 2017).

In contrast to the previous accounts using the traditional method of electrospinning, the involvement of green electrospinning in the current work reduced the environmental footprint of any fabrication, which is in line with the discussion in recent works that green processing is a major step towards nanofiber technology development (Patil et al., 2015). Such findings are significant in the industry and environmental technology. The green manufacturing of hybrid nanofibers through electrospinning is environmentally friendly in terms of the availability of non-biodegradable materials used in the form of filters.

Their biodegradability is high, and hence secondary contamination risk is low, and this addresses macro interests, including microplastic durability, accumulation, and pollution (Deng et al., 2021). Another use of the antimicrobial effect of the hybrid fibers is the ability to prevent the growth of microbes in environmental systems; hence can be applied to the membranes, air filtration systems, and antifouling layers during water treatment (Yan et al., 2023).

The industrial application of this technology can help to minimize environmental impacts across industries (Borah et al., 2024). For instance, the water treatment and air quality management industries can use environmentally friendly membranes that safely degrade upon use (Osman et al., 2024). Additionally, the pharmaceutical industry can use these materials in wound dressings and antimicrobial barriers without worrying about the sustainability of the materials. This concurs with the world trend toward the adoption of green technology, where regulations require regulatory adherence to the use of eco-safe materials (Buonomenna, 2013).

Despite the positive results, several restrictions should be acknowledged. First, the inquiry was conducted at the laboratory scale of fabrication, and scaling up to industrial production by green electrospinning remains a difficulty. Even though this technique reduces energy usage and solvent management, it still has to be tuned for larger-scale applications. Second, while the biodegradation studies have yielded unequivocal results regarding environmental safety, longer-term field trials under genuine environmental circumstances are necessary to completely establish the materials' degradation behavior. While the antibacterial effect was significant, it was only tested against a limited number of microbial strains; further thorough testing against environmental biofilms and mixed microbial populations would strengthen the results. Furthermore, the incorporation of plant extracts should take stability and uniformity into account, as natural products vary depending on their source and processing circumstances.

Future research must strive to overcome the constraints stated above as it seeks new ways to improve the performance and environmental suitability of these materials. The technological process of large-scale green electrospinning should be sustainable and, therefore, needs improvement through continuous processing and recycling of solvents. This aspect can be improved by conducting further investigations into new bioactive polymeric substances, among others, of plant origin, some of which may seem to have functional properties that can be harnessed by the same technology. A second important action would be to widen the environmental evaluation of these fibers. To determine how deterioration acts in real-life scenarios, analyzing it under many different environmental conditions is necessary in long-term studies, whether it be under marine and terrestrial conditions, among others. Exploring the adsorbent capacity of the fabric fibers towards pollutants, heavy metal removal, and other environmental detoxification procedures has the potential to open new markets beyond that of filtration and antibacterial. Another opportunity is its integration into the models of the circular economy. The more nanofibers that can be designed to degrade safely and simultaneously sustain nutrient cycles or be recycled, the more beneficial they are to the environment. Lastly, additional inquiries should involve life-cycle reviews (LCA) that will present quantitative information regarding the ecological impact of this type of material throughout its life cycle, from manufacturing to depreciation, to present the complete report to be used by industries.

CONCLUSION

The study effectively shows the fabrication of environment-friendly heterogeneous nanofiber layers through green electrospinning that integrates both synthetic and bio-degradable polymers, and Plant-derived bioactive agents. The hybrid fibers generated in this study show evident structural advantages, such as lower diameters and increased surface roughness, which improves their potential for environmental interaction. The use of Aegle marmelos extract significantly improves antibacterial capabilities while increasing the environmental responsibility of the products. The findings support the use of synthetic polymers, which are well-known for their mechanical stability, in conjunction with biodegradable polymers, whose natural degrading properties are well understood, to balance strength and sustainability. Biodegradation studies demonstrate that hybrid fibers are more prone to deterioration than virgin synthetic fibers, which reduces their environmental impact. Eco-toxicological examinations demonstrate that degradation products are safe, posing no secondary contamination danger. The antimicrobial tests show strong inhibition against ambient and pathogenic bacteria, indicating that these fibers are appropriate for applications requiring contamination control. Compared to earlier studies, the current study adds to existing knowledge by presenting data proving how green electrospinning and natural bioactive ingredients may be utilized to create multifunctional fibers that alleviate both environmental and medicinal concerns. The created material not only reduces dependency on toxic solvents, but it also fits the criteria for sustainable material innovation. This study's applications include environmental engineering, where the fibers can be employed in air and water purification systems, as well as medicinal applications requiring environmentally safe antimicrobial membranes. However, scaling up the process to industrial capacity and conducting long-term environmental monitoring remains an essential step. To increase applicability, future studies should take into account other natural extracts and conduct life-cycle analyses. This work proposes a practical method for producing multifunctional nanofibers that incorporate environmental safety, biodegradability, and antibacterial activity, therefore aiding worldwide efforts toward sustainable technology.

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