INTERNATIONAL JOURNAL OF MULTIDISCIPLINARY: APPLIED BUSINESS AND EDUCATION RESEARCH
2025, Vol. 6, No. 8, 3826 – 3840
http://dx.doi.org/10.11594/ijmaber.06.08.08

Research Article

Nanocellulose and Phycocyanin as Viable Additives for Electrospun Fibers: A Review of Functional Properties, Electrospinning Parameters, and Physicochemical Characterization

Tabitha P. Vergel de Dios[1], Mia A. Luares[1], Myiesha Dane C. Calibara[1], Samuel Nelson G. Arboleda[1], John Ray C. Estrellado[1,2,3*]

[1]Department of Science, Technology, Engineering, and Mathematics, The Academy, De La Salle University Integrated School, Laguna Boulevard, LTI Spine Road, Barangays Biñan and Malamig, Biñan City, Laguna
[2]Department of Chemical Engineering, Gokongwei College of Engineering, De La Salle University, 2401 Taft Ave., Malate, Manila
[3]Center for Engineering and Sustainable Development Research, De La Salle University, 2401 Taft Ave., Malate, Manila

Article history:
Submission 06 July 2025
Revised 14 August 2025
Accepted 23 August 2025

**Corresponding author:*
E-mail:
john.ray.estrellado@dlsu.edu.ph

ABSTRACT

This literature review aims to highlight the developments and future directions in the use of nanocellulose and phycocyanin as electrospinning additives for biomedical applications, specifically in wound healing. Nanocellulose, a cellulose derivative known for its surface area, mechanical strength, and biocompatibility, is proposed as a sustainable alternative to enhancers of mechanical properties. Phycocyanin, a blue pigment from cyanobacteria, possesses anti-inflammatory, antioxidant, and antimicrobial properties, which may potentially enhance the performance of nanocellulose. The combination of the two components in electrospun fibers demonstrates significant promise for effective wound healing applications. However, progress is limited by the scarcity of experimental studies integrating both materials. One of the future directions of the study is improving the stability and shelf-life of phycocyanin within nanofibers, including approaches such as encapsulation and protective coatings. Scaling and manufacturing challenges, including high energy consumption and harsh chemical treatments in nanocellulose extraction, as well as the parameters of electrospinning, need to be addressed to enable mainstream commercialization. Further exploration of sustainable and purely physical extraction methods for nanocellulose is also critical for environmentally friendly alternatives to process scale-up and intensification.

How to cite:
de Dios, T. P. V., Luares, M. A., Calibara, M. D. C., Arboleda, S. N. G., & Estrellado, J. R. C. (2025). Nanocellulose and Phycocyanin as Viable Additives for Electrospun Fibers: A Review of Functional Properties, Electrospinning Parameters, and Physicochemical Characterization. *International Journal of Multidisciplinary: Applied Business and Education Research. 6*(8), 3826 – 3840. doi: 10.11594/ijmaber.06.08.08

***Keywords**: Cyanobacteria, Electrospinning, Nanocellulose, Parameters, Phycocyanin, Tensile Strength, Wound healing*

Introduction

Affordable and accessible disposable wooden utensils are one of the most common forms of waste produced, especially in Asian countries with booming street-food and restaurant businesses (Fu & Zhu, 2023). In China alone, 80 billion pairs of single-use chopsticks are consumed annually, leading to the deforestation of 20 million trees (Jodnok et al., 2021; Luo, 2013). Most disposable chopsticks are not recycled and end up in landfills, which also leads to the release of preservation chemicals such as paraffin, hydrogen peroxide, and sulphur (The Economist, 2014). To combat the waste and chemical pollution produced, nanocellulose is extracted from a variety of disposed wood, such as hardwood, processed wood, and fiberboards, for further conversion (Kumar, 2022; Suzuki, 2018; Singh, 2023).

Nanocellulose is a renewable bio-based nanomaterial notable for its large surface area, strong mechanical properties, and biocompatibility while being cost-effective (Goswami et al., 2024). Wound dressings made of nanocellulose are a promising alternative to traditional dressings due to their wound care properties, such as biodegradability, antimicrobial properties, and customizability with compound additions (Resch et al., 2021). Moreover, recent reviews emphasize nanocellulose's intrinsic hydrophilicity and high porosity, which enable moisture retention and oxygen permeability—key factors that actively promote cell proliferation and accelerate wound healing (Abazari et al., 2021; Applied Sciences)

One possible addition to nanocellulose is phycocyanin, a pigment found in algae with anti-inflammatory, antioxidant, and antibacterial properties that can aid wound closure (Meng et al., 2025). While other bioactive compounds (i.e., plant extracts, essential oils, etc.) have been explored, phycocyanin stands out with its observed bioactive properties and sourcing from sustainable microalgae (Mouro et al., 2023; Fernandes et al., 2023). A leading method of synthesizing nanocellulose and other compounds into medical composites is electrospinning (Ahmed et al., 2025). Mimicking the extracellular matrix, electrospinning creates a high porosity environment that promotes cell growth and tissue regeneration (Chen et al., 2022). However, despite recent advancements, nanocellulose wound dressings are still in development and have yet to hit mainstream commercialization.

The objective of this review paper is to evaluate the current state of electrospun nanocellulose and phycocyanin for medical applications by compiling recent developments and addressing the gaps for further improvement. While there have been previous papers exploring nanocellulose-based wound dressings and the integration of bioactive compounds, the potential of phycocyanin, a sustainable and algae-derived pigment with wound-healing properties, as an additive has been greatly overlooked. Moreover, only a few studies have utilized disposable wooden utensils as a source for nanocellulose, despite their abundance, especially in Asian countries. This review aims to simultaneously address these gaps by integrating phycocyanin and wood-waste-derived nanocellulose dressing.

In this review, a preliminary search was conducted using the keywords nanocellulose, nanocellulose extraction, nanocellulose characterization, electrospinning, and phycocyanin within research databases such as Scopus, Elsevier, Google Scholar, etc. This review focuses on existing methods for nanocellulose extraction from disposable wooden utensils and conversion of nanocellulose into wound dressings via electrospinning. Studies were selected based on recognition, relevancy, and commonly repeated techniques. Each method's results and limitations were examined to provide a balanced analysis.

Functional Properties for Wound Healing Patches

Table 1. Properties observed from wound patches

Author & Year	Material Used	Property Tested	Outcome	Conclusion
Zaman et al. (2011)	Gelatin-based bio-adhesive membrane	Tensile strength	12.7 MPa tensile strength; 40.4% elongation at break	Demonstrated good mechanical properties for wound protection
Bülbül et al. (2022)	Various synthetic and natural dressings (review)	Tensile strength (review)	Ideal range: 2.5–35 MPa; elongation 70–78%	Set baseline values for effective mechanical properties
Kaya & Derman (2023)	Nanofiber and hydrogel dressings	Swelling ratio	Hydrogel: higher swelling; nanofiber: lower swelling	Hydrogels more suitable for highly exuding wounds
Mutlu et al. (2017)	PHBV nanofibers + Curcumin	Swelling ratio	Swelling ratio increased from 50% to 332% with curcumin addition	Curcumin enhances fluid absorption capability
Khandual et al. (2021)	Drug-loaded polymer composites	Loading efficiency	High loading efficiency with minimal active compound loss	Improved delivery system with optimized bioactive compound retention
Trushina et al. (2022)	General reference (review on drug delivery systems)	Loading efficiency (def.)	Defined loading efficiency as % of entrapped compound	Provided theoretical framework for evaluating loading in drug delivery systems

Wound dressings are essential materials for the promotion of wound healing and the prevention of further infection and injury (Wcw-Admin-Support, 2023). Several characteristics of an ideal wound dressing include the ability to: control moisture around the wound, protect the wound from infections and microorganisms, decrease the surface necrosis of the wound, and give mechanical protection (Ghomi et al., 2019). To evaluate and assess the effectiveness of wound dressings, several methods for testing different properties have been created. Three of these include the testing of tensile strength, which was done in the study of Zaman et al. (2011), swelling ratio, which was done by Kaya & Derman (2023), and loading efficiency, which was performed by Khandual et al. (2021).

Tensile strength, elongation at break, and Young's modulus are measurements of the mechanical properties of wound dressings (Bülbül et al., 2022). Tensile strength is the amount of force a material can withstand before breaking. It is one of the most important properties to be considered in assessing the effectiveness of wound dressings, as those that possess good tensile strength have the ability to withstand mechanical stresses, allowing wounds to be properly protected. According to Bülbül et al. (2022), the ideal tensile strength of wound dressings ranges from 2.5 to 35 MPa and has a breaking elongation ranging from 70% to 78% in healthy conditions. A study that made use of tensile testing was the experiment of Zaman et al. (2011), wherein a gelatin-based bioadhesive wound dressing was produced and characterized. The membranes resulted in a tensile strength of 12.7 MPa and a 40.4% elongation at break.

Swelling capacity and swelling ratio are two ways to quantify a material's ability to absorb and retain liquid. These are measured to observe the moisture balance in wound dressings. An ideal wound dressing has a high swelling capacity and swelling ratio to absorb exudates from the wound to keep the wound bed clean, which can shorten treatment times. Supplements, such as citric acid, carboxymethyl cellulose, and curcumin, can be added to the formation of wound dressings to increase this property. Nanofiber dressings have noticeably less swelling capacity than hydrogel dressings, which makes them more suitable for wounds with less exudate (Kaya & Derman, 2023). In a study by Mutlu et al. (2022), swelling ratios were greatly increased from 50% to 332% by adding curcumin to PHBV nanofibers.

Loading efficiency refers to the amount of entrapped compound from the initial loading amount added (Trushina et al., 2022). Optimizing the loading efficiency minimizes the loss of active compounds used in the product while maximizing the amount absorbed.

Nanocellulose as a Mechanical Property Enhancer for Electrospinning

Nanocellulose as a mechanical property enhancer for products such as wound dressings and food packaging provides multiple notable characteristics, including its large surface area, strong mechanical properties, and biocompatibility, while being cost-effective as a bio-based nanomaterial (Goswami et al., 2024). This underlines its importance in integration in synthetic materials as a physical strengthener. As an increasingly researched topic with a wide range of studies, its physical and chemical properties, botanically varying sources, and common and high-yield extraction methods were extensively looked into.

Properties and Applications of Nanocellulose

Nanocellulose has been gaining significant attention due to its low density and remarkable mechanical strength (Kargarzadeh et al., 2018). As defined by Usov et al. (2015), it refers to a group of cellulose-based materials with at least one dimension in the nanoscale range, typically under 100 nanometers. Known for its exceptional tensile strength and stiffness—comparable to synthetic materials like Kevlar—nanocellulose consists of semicrystalline cellulose microfibrils, which contain both crystalline and amorphous regions. These properties make it an attractive material for various advanced applications.

Nanocellulose is typically classified into three main types: cellulose nanocrystals (CNCs), cellulose nanofibrils (CNFs), and bacterial nanocellulose (BNC), each obtained through different processes depending on the cellulose source and extraction method (Kargarzadeh et al., 2018; Patil et al., 2021). CNCs are produced through acid hydrolysis, a chemical process that isolates crystalline cellulosic regions (Shankaran, 2018), resulting in needle-like structures that are particularly effective for reinforcing nanocomposites, especially in biomedical applications (Moon et al., 2016). CNFs, generated through mechanical disintegration with chemical treatment, are valued for their flexibility and viscosity, making them useful in food coatings and as thickening agents (Kargarzadeh et al., 2018). In contrast, BNC is synthesized by bacteria and is known for its high purity and excellent water absorption, which makes it ideal for biomedical uses such as wound dressings (Patil et al., 2021).

Nanocellulose, because of its properties, has been used in different areas of biomedicine. As an effective nanocarrier, nanocellulose can be formulated into aerogels, hydrogels, powders, and capsules for controlled release of therapeutic agents (Leong et al., 2023). Its ability to enhance cellular binding improves drug delivery effectiveness while minimizing systemic exposure. In wound healing, nanocellulose dressings promote moisture retention and support cell proliferation, facilitating rapid healing and infection prevention through slow-release antimicrobial agents (Khan et al., 2021; Singh et al., 2020). In tissue engineering, nanocellulose scaffolds mimic the extracellular matrix (ECM), which is a large network of proteins and other molecules that surround, support, and give structure to cells and tissues in the body, thereby providing an environment conducive to cell growth. Moreover, its antimicrobial properties make it a promising candidate for combating antibiotic resistance by inhibiting bacterial growth when combined with antimicrobial agents (Tamo, 2024).

Nanocellulose as Electrospinning Additive

Electrospinning has become a more common method of converting and incorporating nanocellulose into various materials, particularly in electrospinning wound dressings (Ji et al., 2021). The integration of nanocellulose drastically improves the nanofibers' physical integrity, particularly in morphology, viscosity, and crystallinity. Additionally, it also shows chemical improvements in terms of water vapor transmission rate, conductivity, and thermal ability (Ribeiro et al., 2021).

Several studies on electrospinning nanocellulose in different combinations with polymers such as chitosan, polyvinyl alcohol, polyethylene oxide, and polylactic acid have been conducted. Although there are a number of these studies, the research is still limited and more studies involving optimization of extraction and electrospinning conditions need to be tested, similar to the study conducted by Vergel de Dios et al. (2025). These combinations include Chitosan, polyethylene oxide, and Acacia extract (Ribeiro et al., 2021), polyvinyl alcohol alone (Ji et al., 2021), polyvinyl alcohol and Chitosan (Wang et al., 2018), and polyvinyl alcohol, polyethylene oxide, and polylactic acid (Hsieh, 2018). Polyvinyl alcohol (PVA) is highly documented and has become the preferred polymer with nanocellulose due to its biodegradability and compatibility. The electrospinning conditions, including the voltage and flow rate, vary among different studies. Across these studies, the integration of nanocellulose contributed positively to the resulting spun fibers by enhancing their physical characteristics and complementing the attributes of other polymers.

In Ribeiro et al. (2021), an electrospun wound dressing was made out of Chitosan (CS), polyethylene oxide (PEO), and nanocellulose, with added Acacia extract for antibacterial and antifungal properties. Nanocellulose was tested in different portions of the total solution (0.1, 0.5, 1, 2 %w/v) to determine the most effective ratio of nanocellulose to the CS/PEO polymer. The paper showed that the electrospun solution containing 1% w/v of nanocellulose had the most notable results in terms of morphology and uniform diameter distribution. Overall, the addition of nanocellulose to the solution granted improved thermal stability, conductivity, and better conditions for electrospinning.

Nanocellulose, alongside polyvinyl alcohol (PVA), was incorporated for the development of wound dressings by Ji et al. (2021) in order to address its drawbacks of low physical strength and a lack of absorption capabilities. The results of this study also analyzed the structures of hydrogen alongside the different percentages of nanocellulose in the solution (0, 1, 2, 4, 6, 7, 8 wt%). Across the tests of mechanical strength, hydrogen bond fitting, porosity, contact angle, liquid absorption, and cytotoxicity, the 6 wt% nanocellulose solution performed the best overall. Incorporating nanocellulose into the electrospinning process complemented the weaknesses of PVA, adding to the spun fiber's mechanical strength and water absorption characteristics.

Wang et al. (2018) combined nanocellulose alongside chitosan and polyvinyl alcohol to create a nanofibrous film for water treatment. The purpose of integrating nanocellulose was to identify if it could counteract the negative resultant properties of the combination of the CS/PVA solution. Different nanocellulose concentrations (0, 5, 10, 20 wt%) were tested in this study. Results show that 5 wt% nanocellulose was able to produce the best results in terms of adsorption of metal ions by the films. Overall, the nanocellulose successfully increased conductivity, surface tension, roughness, and diameter, albeit decreasing tensile strength and viscosity.

Hsieh (2018) synthesized a wound dressing using a combination of polyvinyl alcohol, polyethylene oxide, and polylactic acid. Starting with a concentration of 0.5% nanocellulose, increasing the concentration increased viscosity and difficulty in electrospinning. However, limitations are found with this method, with its tendency to form hydrogen bonds leading to aggregation and difficulty in achieving uniform fiber formations.

The summary of polymers enhanced by nanocellulose is highlighted in Table 1. In summary, the integration of nanocellulose has been utilized in numerous applications to augment the mechanical, thermal, and barrier properties of wound dressing materials.

Table 2. Enhancement of electrospun fibers using nanocellulose

Composite Fibers	Polymers Integrated	Solution Preparation	Effect of CNC Integration	Reference
PVA/NC Wound Dressings	• Polyvinyl alcohol (PVA) • Nanocellulose (NC)	• Excluded unstable solutions (1% NC content) before proceeding to electrospinning	• Increased strength • Increased water absorption	Ji et al., 2021
CNC/CS/PVA Composite Nanofibrous Films	• Polyvinyl alcohol (PVA) • Chitosan (CS) • Cellulose nanocrystals (CNC	• CNC preparation by acid hydrolysis • CS powder dissolved in acetic acid and water solution (90:10 vol%) • PVA aqueous solution at 90 °C for 2 h • CS and PVA solution (60:40) under magnetic stirring at room temperature for 10 h	• Increased turbidity/opacity • Increased roughness of the fiber surface • Increased diameter of nanofibers, surface tension, and conductivity • Decreased viscosity and tensile properties increased	Wang et al., 2018
PEO, PLA, and PVA fiber-forming water-soluble polymers	• Polyvinyl alcohol (PVA) • Polyethylene oxide (PEO) • Polylactic acid (PLA)	• Nanocellulose is first extracted and purified. • It is then dispersed in a suitable solvent, such as water or an organic solvent. • The concentration is adjusted to the desired level.	• Enhances the following: mechanical properties, thermal properties, and barrier properties • The CNCs can be: dispersed within the nanocellulose matrix or used as reinforcing agents	Hsieh, 2018

Phycocyanin: A Sustainable Antioxidant from Microalgae for Wound Healing Application

In finding the antioxidant for ideal wound dressings, Phycocyanin is a pigment protein produced by cyanobacteria commonly used as a food colorant, a dietary supplement, and in recent years has been utilized as a nutraceutical compound due to its antioxidant activity (Fernandes et al., 2023). Although Phycocyanin is a rather unutilized component in electrospun products, many studies have proven its antimicrobial, antioxidative, and antibacterial properties as proven in papers by Safari et al. (2020), Izadi and Latifi (2022), Shanmugam et al. (2017), Adli et al. (2020), and summarized by Dranseikienė et al (2022).

Safari et al. (2020) explored the antioxidant and antibacterial properties of phycocyanin extracted from Spirulina platensis. Antioxidant activity was demonstrated and evaluated specifically through the DPPH radical scavenging assay, while antibacterial effects were observed via agar well diffusion and microdilution methods using bacterial strains such as Escherichia coli, Staphylococcus aureus, Listeria monocytogenes, Streptococcus iniae, and Yersinia ruckeri. The results indicated that phycocyanin possesses high in vitro antioxidant potential, making it a viable natural antioxidant for use in foods and cosmetic products. Similarly, Izadi and Latifi (2022) compared the antibacterial properties of pure phycocyanin and phycocyanin-silver nanoparticles (AgNPs). Their study examined the compatibility of these two antibacterial substances by testing their effects on multiple bacterial strains as well as on rat blood cells and liver enzymes. Both formulations exhibited enhanced antibacterial activity against Enterococcus faecalis, Escherichia coli, Serratia marcescens, and Staphylococcus aureus.

Shanmugam et al. (2017) evaluated the antibacterial activity of phycocyanin extracted from Oscillatoria sp., collected from dam water. The extracted compound was compared with the antibiotic Streptomycin against gram-positive bacterial pathogens. Results showed particularly strong antibacterial effects against Klebsiella sp., Pseudomonas aeruginosa, and Staphylococcus aureus, suggesting the potential of phycocyanin as an alternative antimicrobial agent. In addition to its antibacterial efficacy, this study also demonstrated an efficient method for phycocyanin extraction and identified promising implications for future anticancer research.

Further supporting its application in biomedical materials, Adli et al. (2020) developed biodegradable cosmetic patches using a polylactic acid/phycocyanin-alginate composite through a solvent-casting method. The antioxidant activity of phycocyanin in the patches was evaluated using the DPPH radical scavenging assay, which revealed high antioxidant capacity. The study also found that the formulation exhibited no cytotoxicity, indicating its safety for human skin. Overall, the creation of these cosmetic wound patches emphasized phycocyanin's potential as a safe, effective, and multifunctional component in wound healing applications.

Aforementioned benefits and properties of phycocyanin were summarized in the paper by Dranseikienė et al. (2022). This has compiled its many effects on human skin as well as its implications for future medicine. It covers the many previously researched effects of Phycocyanin, such as wound healing capabilities, and antimicrobial, anti-oxidative, anti-inflammatory, anti-melanogenic, and anticancer properties. The summary of the sources, formulations, and therapeutic properties is found in Table 2.

Table 3. Bioactive properties of phycocyanin derived from microalgae

Source	**Formulation**	**Therapeutic Properties**	**Reference**
Spirulina platensis	Pure phycocyanin	Antioxidant Antibacterial	Safari et al., 2020
Spirulina platensis	Pure phycocyanin	Antibacterial	Izadi and Latifi, 2022
Oscillatoria sp.	Pure phycocyanin	Antibacterial Antibiotic Anticancer	Shanmugam et al., 2017
Spirulina sp.	Polylactic acid/phycocyanin-alginate composite	Antioxidant Cytocompatible	Adli et al., 2020
Filamentous cyanobacteria *Arthrospira platensis* Gomont (Spirulina)	Pure phycocyanin	Wound Healing Antimicrobial Anti-oxidative Anti-inflammatory Anti-melanogenic Anticancer	Dranseikienė et al., 2022

Electrospinning Technology for Composite Nanofibers

In creating products using the combination of nanocellulose and Phycocyanin, electrospinning, a process driven by an electro-hydrodynamic occurrence, can be used to reform and integrate polymers to create a singular fused fiber with combined properties of its components. Using this method, a polymer solution is electrified and sprayed through a syringe to form small fibers (Das et al., 2021). When an electric force, usually 10 to 30 kV, is applied to a viscous fluid, the solution will be turned into a jet fluid through a needle towards a collector. When the electric field force overpowers the surface tension force of the solution, a conical shape known as the Taylor cone of fibers will be formed (Aruna et al., 2017). The basic setup includes a reservoir containing a solution, a needle for spraying the solution, a pump, a high-voltage power source, and a collector where the liquid jet will be collected and set as fibers. As the most frequently used method for synthesizing nanofibers, electrospinning is advantageous for its cost-effectiveness, versatility, and the desirable properties of its produced fibers, such as mechanical flexibility and high surface area (Gao et al., 2023).

Effect of Parameters on the Electrospinning of Nanocellulose and Phycocyanin-Loaded Fibers

Numerous factors affect the electrospinning process, which in turn affects the fibers' morphology and production. Specific conditions such as voltage, temperature, humidity, flow rate, and deposition time affect the quality of the resultant fiber and its properties. The summary of current studies that summarized the electrospinning parameters on the resulting electrospun fibers is found in Table 3.

Effect of Flow Rate

Flow rate has a significant effect on the efficiency and quality of the electrospinning process and the electrospun fibers. A low flow rate would lead to a depleted Taylor cone (Khodayari et al., 2025). On the other hand, a high flow rate would cause an excessive electrospinning cone, which causes dripping, wet, and fused fibers. Additionally, it increases the fiber diameter but also leads to bead formation since the nanofiber jet does not completely dry on the way to the collector. To avoid bead formation, Refate et al. (2023) argue to minimize the flow rate, just enough to form a stable jet cone.

Effect of Temperature and Humidity

Environmental conditions such as temperature and humidity create a significant effect in determining fiber morphology (Zahra et al., 2024). Temperature affects solvent evaporation, while humidity may cause excessive water absorption, which slows solidification of hydroscopic polymers (De Vrieze et al., 2009; Tripatanasuwan et al., 2007). According to Yang et al. (2017), increased temperature has both positive and negative consequences on polymer nanofiber formation. Temperature increase negatively affects surface tension and viscosity but improves electrospinnability by accelerating evaporation of solvent from fluid jets.

Effect of Voltage

While electrospinning biopolymers of cellulose and chitosan, Refate et al. (2023) observed that fiber diameter generally increases with higher applied voltage due to reduced Taylor cone size and increased jet velocity. However, this could also cause increased bead formation. The increase of fiber diameter along with the increase of voltage was also observed by Bakar et al. (2018). Lower voltage runs resulted in thinner fiber but also more uniform diameters. This is due to the overall longer flight time of the spun solution, which allows for better elongation and division. Increasing the voltage may also lead to disadvantageous effects like inducing the surface area, resulting in fibers with undesired morphology (Khodayari et al., 2025).

Effect of Needle-to-Collector Distance

When the fiber jet is stretched for a longer period of time, the fiber diameter tends to decrease, which explains how increasing the working distance between the needle and the collector decreases the diameter (Zahra et al., 2024). As the distance increases, the fiber diameter caps and does not decrease further. However, it does improve the uniformity throughout the whole run. Singh et al. (2020) further reinforced the finding of the diameter decreasing as the distance increases, but also found that the diameter begins to increase again after a certain threshold.

Table 4. Parameters that affect the electrospinning of polymer solutions

Product	Voltage	Temperature	Flow Rate	Needle-Collector Distance	Reference
PVA/NC Wound Dressings	22.00 ± 1 kV	34 ± 1 °C	1 mL/h	N/A	Ji et al., 2021
CNC/CS/PVA Composite Nanofibrous Films	17 kV	25 °C	0.4 mL/h	18 cm	Wang et al., 2018
Cellulose acetate (CA) nanofibers filled with cellulose nanocrystals (CNCs)	12.5 kV	25 °C (for solution characterization)	5 mL/h	12 cm	Khodayari et al., 2025
Lower Molecular Weight Polymers (Polyvinylpyrrolidone (PVP))	15 kV	~ 25 °C (room temperature)	0.5 mL/h	12 cm	Zahra et al., 2024
Cellulose Acetate (CA) nanofibers	25–30 kV	~22 °C	1.36–3.0 mL/h	15-20 cm	Refate et al., 2023
Poly-(vinyl alcohol)/wooden utensil nanocellulose (WUNC)/phycocyanin (PC)	25-30 kV	37°C (room temperature)	1 mL/h	15 cm	Vergel De Dios et al., 2025

Among the studies, similarities in the results of nanocellulose integration are notable; a consistent finding is the addition of higher thermal and conductive capacities. However, due to the many differences in electrospinning procedures because of the different polymers and methods used, similarities in terms of electrospinning conditions were not found. Voltage ranged from 29, 22±1, and 17 kV, while the flow rate ranged from 4, 1, and 0.1 mL/h. As for the integration of nanocellulose into the creation of wound dressings, overall, it was found to be a suitable polymer due to its ability to strengthen mechanical properties. The concentrations of nanocellulose ranged from 0 to 20 wt%. The most effective percentages were 5 wt% for Wang et al. (2018) and 6 wt% for Ji et al. (2021).

Challenges in Electrospinning Nanocellulose and Phycocyanin

While nanocellulose and phycocyanin-based electrospun wound dressings show great promise, there are several limitations and gaps in knowledge that hinder their advancement towards mainstream medical use. More prominently, there is a huge gap in the actual experimentation of nanocellulose/phycocyanin wound dressings. To optimize performance and ensure practical application, future research should address the following areas:

Stability and Shelf-life of the Produced Dressing and Phycocyanin in Nanofibers

Despite its wound healing capabilities of antioxidative and antimicrobial properties, phycocyanin has been observed to be unstable under stressful conditions such as light, heat, and pH fluctuations (Dranseikienė et al., 2022; Jaeschke et al., 2021). There is also a lack of high-yield phycocyanin extraction methods, which hinders its path to commercialization. The long-term stability, activity retention, wound healing effectiveness, and biocompatibility of nanocellulose/phycocyanin are still unexplored, which requires future research to focus on testing its shelf-life and effectiveness over time. This also prompts research for protective coatings and encapsulation, a method to entrap phycocyanin within the nanofiber matrix to preserve the phycocyanin bioactivity. Biocompatibility studies, such as sterility or degradation testing, cytotoxicity testing, and antioxidant/antibacterial testing, among others, are necessary to confirm its viability as a medical bioactive patch and to further validate the appropriateness of the biomedical device in the clinical and commercial setting (Zhou et al., 2025).

Scaling and Manufacturing Challenges

While nanocellulose wound dressings could be found in the market, they are far from being recognized in the medical field as an alternative to traditional synthetic dressings. The majority of existing studies in this review paper and to date are confined to laboratory-scale experimentation and characterization with very limited batch sizes (Hsieh, 2018; Ji et al., 2021). Nanocellulose extraction poses issues with sustainability due to the common harsh chemical treatments and high energy consumption required for the processing (Singh et al. 2023; Couret et al., 2021; Raju et al., 2023). Further exploring sustainable and purely physical methods, like steam explosion, is critical in becoming a more environmentally-friendly alternative in the market. Scaling with electrospinning also has challenges with its energy consumption, variability, and traditionally slow flow rates, which make it a time-consuming process (Hao et al., 2024). In summary, optimization of methods such as high-yield extraction of nanocellulose, electrospinning nanocellulose/phycocyanin solutions, and mass manufacturing nanocellulose wound patches may be done to improve the developing methods that are presently available.

Conclusion

Overall, functional properties of wound healing patches, such as tensile strength, swelling capacity, and loading efficiency, play important roles in optimizing dressing quality—particularly in ensuring consistency in wound healing and maintaining structural stability. Reviewed studies highlighted nanocellulose as an adaptable biomaterial with wide-ranging applications in the medical field, including gels, powders, and capsules. This versatility is attributed to its low density, high mechanical strength, and widely documented ability to enhance physical characteristics such as mechanical strength, water absorption, and thermal stability. Phycocyanin was also identified as a promising sustainable additive for wound healing, owing to its consistently reported antioxidant and antibacterial properties across multiple studies. Additionally, four key electrospinning parameters—flow rate, temperature and humidity, voltage, and needle-to-collector distance—were investigated for their effects on the properties of electrospun fibers. Despite these advancements, a research gap remains in the combined application of nanocellulose and phycocyanin in wound dressings.

Material Stability

Future research could address the gap by exploring the stability and shelf life of nanocellulose/phycocyanin composites, especially considering phycocyanin's sensitivity to light, heat, and pH. Future studies should consider encapsulation methods and stabilizing agents, which could help preserve phyocyanin's functional properties. Moreover, evaluating how these materials behave during storage and under different conditions is essential to ensure consistent quality, safety, and commercial viability in real-life applications.

Real-life Application and Commercialization

Possible product concepts to derive from this study mainly involve wound dressing production for advanced and specialized wound healing, revolving around the properties of Phycocyanin. Multiple clinical trials may focus on the applicability and suitability of the product to the skin and its effectiveness over periods of time. Moreover, mass production must overcome the environmental drawbacks of current nanocellulose extraction methods.

Future Recommendations

Beyond the studies reviewed, further research may focus on biochemical evaluations and optimization of physical and chemical properties related to nanocellulose, phycocyanin, electrospinning processes, and sustainable manufacturing approaches.

In summary, to address the gaps, it is recommended for academic institutions to develop stabilization strategies for nanocellulose/phycocyanin composites while optimizing material properties and electrospinning parameters. Research institutions should conduct clinical trials to test the efficacy of products and their compatibility with the skin. Industry stakeholders are responsible for the commercialization of nanocellulose/phycocyanin electrospun fibers into wound dressings, scaling up production, and ensuring product consistency.

References

Abazari, M. F., Gholizadeh, S., Karizi, S. Z., Birgani, N. H., Abazari, D., Paknia, S., Derakhshankhah, H., Allahyari, Z., Amini, S. M., Hamidi, M., & Delattre, C. (2021). Recent Advances in Cellulose-Based Structures as the Wound-Healing Biomaterials: A Clinically Oriented review. *Applied Sciences, 11*(17), 7769. https://doi.org/10.3390/app11177769

Adli, S. A., Ali, F., Azmi, A. S., Anuar, H., Nasir, N. a. M., Hasham, R., & Idris, M. K. H. (2020). Development of biodegradable cosmetic patch using a polylactic Acid/Phycocyanin–Alginate composite. *Polymers, 12*(8), 1669. https://doi.org/10.3390/polym12081669

Ahmed, S., Khan, R. A., & Rashid, T. U. (2025). Cellulose nanocrystal based electrospun nanofiber for biomedical applications–A review. *Carbohydrate Polymers, 348*(Part A), 122838. https://doi.org/10.1016/j.carbpol.2024.122838

Aruna, S. T., Balaji, L. S., Senthil Kumar, S., & Shri Prakash, B. (2017). Electrospinning in solid oxide fuel cells – A review. *Renewable and Sustainable Energy Reviews, 67*, 673–682. https://doi.org/10.1016/j.rser.2016.09.003

Bakar, S. S. S., Fong, K. C., Eleyas, A., & Nazeri, M. F. M. (2018). Effect of voltage and flow rate electrospinning parameters on polyacrylonitrile electrospun fibers. *IOP Conference Series Materials Science and Engineering, 318*, 012076. https://doi.org/10.1088/1757-899x/318/1/012076

Bülbül, E. Ö., Okur, M. E., Okur, N. Ü., & Siafaka, P. I. (2022). Traditional and advanced wound dressings: physical characterization and desirable properties for wound healing. In *Elsevier eBooks* (pp. 19–50). https://doi.org/10.1016/b978-0-323-90514-5.00020-1

Chen, K., Hu, H., Zeng, Y., Pan, H., Wang, S., Zhang, Y., Shi, L., Tan, G., Pan, W., & Liu, H. (2022). Recent advances in electrospun nanofibers for wound dressing. *European Polymer Journal, 178*, 111490. https://doi.org/10.1016/j.eurpolymj.2022.111490

Couret, L., Irle, M., Belloncle, C., & Cathala, B. (2017). Extraction and characterization of cellulose nanocrystals from post-consumer wood fiberboard waste. *Cellulose, 24*(5), 2125–2137. https://doi.org/10.1007/s10570-017-1252-7

Das, S. K., Chakraborty, S., Naskar, S., & Rajabalaya, R. (2021). Techniques and methods used for the fabrication of bionanocomposites. In *Elsevier eBooks* (pp. 17–43). https://doi.org/10.1016/b978-0-12-821280-6.00007-6

De Vrieze, S., Van Camp, T., Nelvig, A. et al. The effect of temperature and humidity on electrospinning. *J Mater Sci 44*, 1357–1362 (2009). https://doi.org/10.1007/s10853-008-3010-6

Dranseikienė, D., Balčiūnaitė-Murzienė, G., Karosienė, J., Morudov, D., Juodžiukynienė, N., Hudz, N., Gerbutavičienė, R. J., & Savickienė, N. (2022). Cyano-Phycocyanin: Mechanisms of action on human skin and future perspectives in medicine. *Plants, 11*(9), 1249. https://doi.org/10.3390/plants11091249

Dumanli, A. G. (2016). Nanocellulose and its Composites for Biomedical Applications. *Current Medicinal Chemistry*, *24*(5), 512–528.

https://doi.org/10.2174/0929867323666161014124008

Fernandes, R., Campos, J., Serra, M., Fidalgo, J., Almeida, H., Casas, A., Toubarro, D., & Barros, A. I. R. N. A. (2023). Exploring the benefits of phycocyanin: from spirulina cultivation to its widespread applications. *Pharmaceuticals, 16*(4), 592. https://doi.org/10.3390/ph16040592

Fu, Y., and Zhu, J. (2021). "Green design and recycling systems for solving the dilemma of disposable chopsticks waste caused by online food delivery: A review," *BioResources 16*(4), 8640-8656.https://doi.org/10.15376/biores.16.4.fu

Gao, M., Yang, Z., Liang, W., Ao, T., & Chen, W. (2023). Recent advanced freestanding pseudocapacitive electrodes for efficient capacitive deionization. Separation and *Purification Technology, 324*, 124577. https://doi.org/10.1016/j.seppur.2023.124577

Ghomi, E. R., Khalili, S., Khorasani, S. N., Neisiany, R. E., & Ramakrishna, S. (2019). Wound dressings: Current advances and future directions. *Journal of Applied Polymer Science, 136*(27). https://doi.org/10.1002/app.47738

Goswami, R., Singh, S., Narasimhappa, P., Ramamurthy, P. C., Mishra, A., Mishra, P. K., Joshi, H. C., Pant, G., Singh, J., Kumar, G., Khan, N. A., & Yousefi, M. (2024). Nanocellulose: A comprehensive review investigating its potential as an innovative material for water remediation. *International Journal of Biological Macromolecules, 254*(Part 3), 127465. https://doi.org/10.1016/j.ijbiomac.2023.127465

Hao, Q., Schossig, J., Davide, T., Towolawi, A., Zhang, C., & Lu, P. (2024). Gravity-Driven Ultrahigh-Speed Electrospinning for the Production of Ethyl Cellulose Fibers with Tunable Porosity for Oil Absorption. *ACS Sustainable Chemistry & Engineering, 13*(1), 507–517. https://doi.org/10.1021/acssuschemeng.4c08259

Hsieh, Y. (2018). Cellulose Nanofibers: Electrospinning and Nanocellulose Self-Assemblies. *Advanced Green Composites*, 67–95. https://doi.org/10.1002/9781119323327.ch4

Izadi, M., & Latifi, E. (2022). Comparison of the antibacterial properties of phycocyanin and its SNPs and their effects on rat blood cells and liver enzymes. *Beni-Suef University Journal of Basic and Applied Sciences, 11*(1). https://doi.org/10.1186/s43088-022-00236-w

Ji, X., Guo, J., Guan, F., Liu, Y., Yang, Q., Zhang, X., & Xu, Y. (2021). Preparation of electrospun polyvinyl Alcohol/Nanocellulose composite film and evaluation of its biomedical performance. *Gels*, *7*(4), 223. https://doi.org/10.3390/gels7040223

Jodnok, S., Choeisai, P., Kruehong, C., & Choeisai, K. (2021b). Recycling disposable bamboo chopstick waste as a renewable energy resource: Case study in Khon Kaen University, Thailand. *Sustainable Environment Research, 31*(1). https://doi.org/10.1186/s42834-021-00101-y

Kargarzadeh, H., Huang, J., Lin, N., Ahmad, I., Mariano, M., Dufresne, A., Thomas, S., & Gałęski, A. (2018). Recent developments in nanocellulose-based biodegradable polymers, thermoplastic polymers, and porous nanocomposites. *Progress in Polymer Science, 87,* 197–227. https://doi.org/10.1016/j.progpolymsci.2018.07.008

Kaya, S., & Derman, S. (2023). İDEAL YARA ÖRTÜSÜNÜN ÖZELLİKLERİ. *Ankara Universitesi Eczacilik Fakultesi Dergisi*, *47*(3), 5. https://doi.org/10.33483/jfpau.1253376

Khandual, S., Sanchez, E. O. L., Andrews, H. E., & De La Rosa, J. D. P. (2021). Phycocyanin content and nutritional profile of Arthrospira platensis from Mexico: efficient extraction process and stability evaluation of phycocyanin. *BMC Chemistry, 15*(1). https://doi.org/10.1186/s13065-021-00746-1

Khodayari, A., Vats, S., Mertz, G., Schnell, C. N., Fuentes Rojas, C., & Seveno, D. (2025). Electrospinning of cellulose nanocrystals: Procedure and optimization. *Carbohydrate Polymers, 347*, 122698. https://doi.org/10.1016/j.carbpol.2024.122698

Kumar, P., Miller, K., Kermanshahi-Pour, A., Brar, S. K., Beims, R. F., & Xu, C. C. (2022). Nanocrystalline cellulose derived from spruce wood: Influence of process parameters. *International Journal of Biological Macromolecules*, *221*, 426–434. https://doi.org/10.1016/j.ijbiomac.2022.09.017

Leong, M., Kong, Y., Harun, M., Looi, C., & Wong, W. (2023). Current advances of nanocellulose application in biomedical field. *Carbohydrate Research, 532*, 108899. https://doi.org/10.1016/j.carres.2023.108899

Luo, C. (2013). China's 80 billion disposable chopsticks a burden on forests. Hong Kong: *South China Morning Post*. https://www.scmp.com/news/china/article/1188299/chinas-80-billion-disposable-chopsticks-burden-forests

Meng, Z., Liu, J., Zhang, R., Ren, Y., Qi, Q., Cui, B., Gou, Y., Zhuang, S., Zhao, T., Liu, Q., Bao, X., & Ren, C. (2025). Phycocyanin-based multifunctional hydrogel with self-healing, hemostatic, antioxidative, and antibacterial activity for wound healing. *International Journal of Biological Macromolecules, 310*(Part 2), 143254. https://doi.org/10.1016/j.ijbiomac.2025.143254

Moon, R.J., Schueneman, G.T. & Simonsen, J. Overview of Cellulose Nanomaterials, Their Capabilities and Applications. *JOM 68*, 2383–2394 (2016). https://doi.org/10.1007/s11837-016-2018-7

Mouro, C., & Gouveia, I. C. (2023). Electrospun wound dressings with antibacterial function: a critical review of plant extract and essential oil incorporation. *Critical Reviews in Biotechnology, 44*(4), 641–659. https://doi.org/10.1080/07388551.2023.2193859

Muraleedharan, M. N., Karnaouri, A., Piatkova, M., Ruiz-Caldas, M., Matsakas, L., Liu, B., Rova, U., Christakopoulos, P., & Mathew, A. P. (2021). Isolation and modification of nano-scale cellulose from organosolv-treated birch through the synergistic activity of LPMO and endoglucanases. *International Journal of Biological Macromolecules*, *183*, 101–109. https://doi.org/10.1016/j.ijbiomac.2021.04.136

Mutlu, B., Çaylak, S., & Duman, Ş. (2022). *Incorporation of cerium oxide into hydroxyapatite/chitosan composite scaffolds for bone repair*. https://doiserbia.nb.rs/Article.aspx?ID=1820-61312203207M

Mutlu, G., Calamak, S., Ulubayram, K., & Guven, E. (2017). Curcumin-loaded electrospun PHBV nanofibers as potential wound-dressing material. *Journal of Drug Delivery Science and Technology*, *43*, 185–193. https://doi.org/10.1016/j.jddst.2017.09.017

Patil, T. V., Patel, D. K., Dutta, S. D., Ganguly, K., Santra, T. S., & Lim, K. (2021). Nanocellulose, a versatile platform: From the delivery of active molecules to tissue engineering applications. *Bioactive Materials, 9*, 566–589. https://doi.org/10.1016/j.bioactmat.2021.07.006

Pellegrino, P., Bramanti, A. P., Farella, I., Cascione, M., De Matteis, V., Della Torre, A., Quaranta, F., & Rinaldi, R. (2022). Pulse-Atomic Force Lithography: a powerful nanofabrication technique to fabricate constant and Varying-Depth nanostructures. *Nanomaterials, 12*(6), 991. https://doi.org/10.3390/nano12060991

Raju, V., Revathiswaran, R., Subramanian, K. S., Parthiban, K. T., Chandrakumar, K., Anoop, E. V., & Chirayil, C. J. (2023). Isolation and characterization of nanocellulose from selected hardwoods, viz., Eucalyptus tereticornis Sm. and Casuarina equisetifolia L., by steam explosion method. *Scientific Reports*, *13*(1). https://doi.org/10.1038/s41598-022-26600-5

Refate, A., Mohamed, Y., Mohamed, M., Sobhy, M., Samhy, K., Khaled, O., Eidaroos, K., Batikh, H., El-Kashif, E., El-Khatib, S., & Mehanny, S. (2023). Influence of electrospinning parameters on biopolymers nanofibers, with emphasis on cellulose & chitosan. *Heliyon, 9*(6), e17051. https://doi.org/10.1016/j.heliyon.2023.e17051

Resch, A., Staud, C., & Radtke, C. (2021). Nanocellulose-based wound dressing for conservative wound management in children with second-degree burns. *International Wound Journal, 18*(4), 478–486. https://doi.org/10.1111/iwj.13548

Ribeiro, A. S., Costa, S. M., Ferreira, D. P., Calhelha, R. C., Barros, L., Stojković, D., Soković, M., Ferreira, I. C., & Fangueiro, R. (2021). Chitosan/nanocellulose electrospun fibers with enhanced antibacterial and antifungal activity for wound dressing applications. *Reactive and Functional Polymers/Reactive & Functional Polymers*, *159*, 104808. https://doi.org/10.1016/j.reactfunctpolym.2020.104808

Safari, R., Amiri, Z. R., & Kenari, R. E. (2020). Antioxidant and antibacterial activities of C-phycocyanin from common name Spirulina platensis. *Iranian Journal of Fisheries and Sciences, 19*(4), 1911–1927. https://doi.org/10.22092/ijfs.2019.118129

Shankaran, D. R. (2018). Cellulose nanocrystals for health care applications. In *Elsevier eBooks* (pp. 415–459). https://doi.org/10.1016/b978-0-08-101971-9.00015-6

Shanmugam, A., Sigamani, S., Venkatachalam, H., Jayaraman, J., & Ramamurthy, D. (2017). Antibacterial activity of extracted phycocyanin from Oscillatoria sp. *Journal of Applied Pharmaceutical Science*. https://doi.org/10.7324/japs.2017.70310

Sihag, S. S., Pal, J., & Yadav, M. (2022). Extraction and Characterization of Nanocellulose from Wheat Straw: Facile Approach. *Journal of Water and Environmental Nanotechnology*, *7*(3), 317-331. https://doi.org/10.22090/jwent.2022.03.007

Singh, H., Verma, A. K., Trivedi, A. K., & Gupta, M. (2023). Characterization of nanocellulose isolated from bamboo fibers. *Materials Today: Proceedings*. https://doi.org/10.1016/j.matpr.2023.02.300

Singh, Y. P., Dasgupta, S., Nayar, S., & Bhaskar, R. (2020). Optimization of electrospinning process & parameters for producing defect-free chitosan/polyethylene oxide nanofibers for bone tissue engineering. Journal of Biomaterials Science, *Polymer Edition, 31*(6), 781–803. https://doi.org/10.1080/09205063.2020.1718824

Suzuki, A., Sasaki, C., Asada, C., & Nakamura, Y. (2018). Production of cellulose nanofibers from Aspen and Bode chopsticks using a high temperature and high pressure steam treatment combined with milling. *Carbohydrate Polymers*, *194*, 303–310. https://doi.org/10.1016/j.carbpol.2018.04.047

Tamo, A. K. (2024). Nanocellulose-Based Hydrogels as Versatile Bio-Based Materials with Interesting Functional Properties for Tissue Engineering Applications. *Journal of Materials Chemistry B*, *12*(32), 7692–7759. https://doi.org/10.1039/d4tb00397g

The Economist. (2014, September 13). Sticks in the gullet. *The Economist*. https://www.economist.com/china/2014/09/13/sticks-in-the-gullet

Tripatanasuwan, S., Zhong, Z., & Reneker, D. H. (2007). Effect of evaporation and solidification of the charged jet in electrospinning of poly(ethylene oxide) aqueous solution. *Polymer, 48*(19), 5742–5746. https://doi.org/10.1016/j.polymer.2007.07.045

Trushina, D. B., Borodina, T. N., Belyakov, S., & Antipina, M. N. (2022). Calcium carbonate vaterite particles for drug delivery: Advances and challenges. *Materials Today Advances,* *14*, 100214. https://doi.org/10.1016/j.mtadv.2022.100214

Usov, I., Nyström, G., Adamcik, J., Handschin, S., Schütz, C., Fall, A., Bergström, L., & Mezzenga, R. (2015). Understanding nanocellulose chirality and structure–properties relationship at the single fibril level. *Nature Communications*, *6*(1). https://doi.org/10.1038/ncomms8564

Vergel De Dios, T. P., Luares, M. A., Arboleda, W., Calibara, M. D. C., & Estrellado, J. R. C. (2025). Multi-Objective Taguchi Optimization of Electrospinning Parameters for the Development of Poly-(vinyl alcohol)/Waste Wooden Utensil Nanocellulose/Phycocyanin Electrospun Fibers. *International Journal of Multidisciplinary: Applied Business and Education Research, 6*(6), 3045-3069. https://doi.org/10.11594/ijmaber.06.06.31

Wang, D., Cheng, W., Yue, Y., Xuan, L., Ni, X., & Han, G. (2018). Electrospun Cellulose Nanocrystals/Chitosan/Polyvinyl Alcohol Nanofibrous Films and their Exploration to Metal Ions Adsorption. *Polymers*, *10*(10), 1046. https://doi.org/10.3390/polym10101046

Wcw-Admin-Support. (2023, April 28). *Types of wound dressings and when to use them*. West Coast Wound & Skin Care. https://westcoastwound.com/types-of-wound-dressings-and-when-to-use-them/

Yang, G.-Z., Li, H.-P., Yang, J.-H., Wan, J., & Yu, D.-G. (2017). Influence of working temperature on the formation of electrospun polymer nanofibers. *Nanoscale Research Letters, 12*(1), 55. https://doi.org/10.1186/s11671-016-1824-8

Zahra, F. T., Zhang, Y., Ajayi, A. O., Quick, Q., & Mu, R. (2024). Optimization of electrospinning parameters for lower molecular weight polymers: A case study on polyvinylpyrrolidone. *Polymers, 16*(9), 1217. https://doi.org/10.3390/polym16091217

Zaman, H. U., Islam, J., Khan, M. A., & Khan, R. A. (2011). Physico-mechanical properties of wound dressing material and its biomedical application. *Journal of the Mechanical Behavior of Biomedical Materials/Journal of Mechanical Behavior of Biomedical Materials, 4*(7), 1369–1375. https://doi.org/10.1016/j.jmbbm.2011.05.007

Zhao, J., Zhang, W., Zhang, X., Zhang, X., Lu, C., & Deng, Y. (2013). Extraction of cellulose nanofibrils from dry softwood pulp using high shear homogenization. *Carbohydrate Polymers*, *97*(2), 695–702. https://doi.org/10.1016/j.carbpol.2013.05.050

Zhou, R., Ma, Y., Yang, M., Cheng, Y., Ma, X., Li, B., Zhang, Y., Cui, X., Liu, M., Long, Y., & Li, C. (2025). Wound dressings using electrospun nanofibers: mechanisms, applications, and future directions. *European Polymer Journal,* 113900. https://doi.org/10.1016/j.eurpolymj.2025.113900